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Environmental and Social Life Cycle Assessment (LCA) in Transport Infrastructure

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Environmental and Social Life Cycle Assessment (LCA) in Transport Infrastructure

By

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DISSERTATION

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DEDICATION

To my husband and best friend, Hadi,

my parents, my sister, and my brothers

for all their love, patience, endless support, and encouragement.

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I would like to express my deepest appreciation to those who have supported me in this long journey of completing my doctoral study.

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ABSTRACT

Sustainability principles aim to bring key environmental, social, and economic factors into the decision-making process. The main goal of this dissertation is to develop representative frameworks, models, and databases for transportation infrastructure in California to quantify the environmental and socio-economic impacts needed to support data-driven and integrated decision-making. This study was proposed to ponder the environmental impacts according to the life cycle of the transportation infrastructure, using reliable, up-to-date, and representative data in terms of materials, energy sources, production technologies, design methods, and transport modes.

The three main parts of this doctoral research include:

1. Development of a representative life cycle inventory (LCI) database for California and an appropriate life cycle assessment (LCA) model in transportation infrastructure management in the state, including i) crude oil and asphalt binder inventories and a case study, ii) an inventory for warm mix asphalt additives and a case study, and iii) an inventory and case studies for bonded concrete overlay on asphalt (BCOA);
2. Evaluation of complete streets as a modern design philosophy for urban streets aiming to reach social and environmental benefits, including defining socio-economic performance measures for complete streets, developing a social life cycle assessment framework for complete streets, applying the proposed complete streets LCA framework for calculating environmental impacts, and demonstrating the use of social LCA for three complete street case studies;

3. Development of a proposed strategy for integrating sustainability measures in the planning and conceptual design phase of transportation infrastructure in California using LCA methodology.

Through the first part of this research study, an up-to-date and representative (regional) LCI database was developed for transportation infrastructure to quantify their environmental impacts, and an appropriate LCA was modeled in transportation infrastructure management in California for those elements for which data inventories do not yet exist. Literature reviews, surveying of the local contractors, local governments' data, Caltrans' data and interviews, databases such as GaBi and ecoinvent, and observations were used to collect the data. The UCPRC LCI, which is a comprehensive pavement dataset developed and calibrated for California, including a comprehensive list of materials, sources of energy, transport modes, and pavement surface treatments were also used. The electricity grid mix and other energy sources used in different life cycle stages were modified using California-specific data. Mix designs were defined based on specifications enforced by Caltrans. The three LCIs developed and the three case studies covered in this dissertation study were:

1 Crude oil and asphalt binder

This part of the study aimed to quantify the environmental impacts of the production of asphalt binder used in California. The cradle-to-gate approach used for this study included the material extraction and production stages as well as the transportation of the materials up to the point of leaving the refinery's gate. A life cycle inventory dataset of crude oil and asphalt binders was developed using data from PADD 5 (Petroleum Administration for Defense Districts) and was narrowed to the refineries in California. In addition, a LCA framework development to model asphalt binder production inventory data and environmental impacts for PADD5 and California is described.

2 Warm mix asphalt additives (WMAA)

Warm mix asphalt (WMA) is considered a potential means for reducing energy consumption and emissions during the material and construction stages of asphalt concrete by allowing reduced mixing temperatures in the asphalt plant. This study quantifies the potential environmental impacts that occur during the material production stage of WMA. A comparative attributional LCA approach was adopted where life cycle environmental impacts from the production of WMA using different WMAAs were compared with the conventional Hot Mix Asphalt. The framework considers the reduced natural gas use that may occur when WMA is used and the environmental impacts of the WMAA developed using proxy data.

3 Bonded concrete overlay of asphalt (BCOA).

BCOA is a rehabilitation alternative that consists of placing a hydraulic cement concrete overlay on an existing asphalt pavement. While the technology for thin BCOA has been common on highways and conventional roads in several U.S. states and other countries, its use has been very limited in California. As with any pavement rehabilitation, the materials and construction stages of thin BCOA result in significant environmental impacts in terms of energy use, material resource consumption, waste generation, and emissions during the life of the BCOA pavement. This study presented an LCA that quantifies the potential environmental impacts due to the material and construction stages of a BCOA pilot project implemented in a case study in California.

The second segment of this research focused on complete streets as a modern design philosophy for urban streets. This study aimed to determine social and environmental benefits, define socio-economic performance measures, and develop a social life cycle assessment framework for complete streets.

“Complete street” is a design concept for primarily urban streets and intersections (existing and/or new) intended to encourage active transportation by making streets safer, convenient, and more attractive. Motorized transportation and parking are also accommodated in the design concept. Performance measures have been proposed to address these goals. One gap identified in current LCA impact indicators is lack of socio-economic indicators to complement the existing environmental indicators. To address the gaps in performance metrics, this study developed a framework for LCA of complete street projects, including the development of socio-economic impact indicators that also consider equity of outcomes with regard to complete streets and the locations supporting quality of life that they connect. Another critical question addressed in this study was what social goals (economic, health, safety, etc.) should be considered and how to consider equity in performance metrics for social goals. This project laid the foundation for creating guidelines for social LCAs for complete streets.

The social life cycle assessment (SLCA) framework developed in this study was based on five categories of concerns and 17 performance measures or indicators. The indicators were tested in the project and evaluated for final recommendations for use in future studies. The results were compared with the existing streets that had been configured to be vehicle-centric. The case studies were solicited in more and less advantaged neighborhoods so that the framework could also be evaluated in different contexts. The use of the CalEnviroScreen tool from the California Environmental Protection Agency was also investigated to assess the exposure of neighborhoods and their vulnerability to environmental impacts in conjunction with the performance indicators when evaluating the potential benefits for disadvantaged neighborhoods (also called priority population areas). Recommendations were made for dropping some indicators because of difficulties collecting data or interpreting the results, modifying other indicators, and adding new indicators to fill important gaps.

In the last part of this research, a strategy for integrating sustainability measures in the planning phase of transportation infrastructure in California using an LCA methodology was proposed. Recommendations are made for future studies to develop an up-to-date and representative (regional) LCI database for generic road infrastructure elements in California to quantify their environmental impacts during the planning and conceptual design phases.

Transport infrastructure planning and delivery is a long and complex process implemented at different levels. Transportation infrastructure is crucial to the economy and every aspect of our social lives, and environmental impacts during the life cycle stages of transport infrastructure are substantial. The first step for managing the environmental impacts of such a system is to quantify them. While increased efforts to quantify sustainability effects can be observed in recent years, quantification of the full-system and life cycle quantification following LCA principles in the planning process is in the early stages of development. This part of the dissertation (Chapter 5) aimed to identify ideas for when and how considerations of life cycle impacts following LCA principles can be integrated into the transport infrastructure planning process, what decisions should be taken, and which data should be used. LCA should be conducted to improve the ability to quantify the system, the life cycle effects of decisions, and changes in systems, without design details which usually needs in LCA for quantifying the system precisely. The proposed methodology focused on the conceptual and early design stages in which the choices should be made regarding rehabilitation, reconstruction, retrofit, or repurposing of a road corridor and its basic scope and dimension, and the corresponding choice of road elements. This study considered the use of LCA during the planning phase of transport infrastructure at the state-level and local government-level in California to fill the gaps in the quantification of environmental impacts.

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CHAPTER 1. INTRODUCTION

1.1. Background

1.1.1. Transport Infrastructure in the U.S. and California and legislative mandates improving sustainability

The U.S. has 4.11 million lane-miles of roads, of which 2.75 million lane-miles are paved. Each year, this network supports more than three trillion vehicle-miles-traveled, which leads to 70 percent of the U.S. annual petroleum consumption of more than 213 billion gallons. Almost 320 million tonnes of raw materials, which cost more than 150 billion dollars, are required to maintain and expand such vast infrastructure each year. The United States spent $87.7 billion on the construction of highways and streets in 2021. (Bureau of Transportation Statistics website, 2021; Davis et al., 2017; Santero, 2009)

In California, the Road Repair and Accountability Act of 2017 (Senate Bill 1 [SB1]) invests $54 billion over the next decade to repair California’s transportation infrastructure. According to this legislative package, $27 billion is allocated to Caltrans (California Department of Transportation), and $27 billion is assigned to local agencies to repair and maintain roads, freeways, and bridges in communities across California and to invest more in public transit and safety (Caltrans, 2018). These new investments are expected to substantially increase the number of construction projects and the quantities of materials used for pavement infrastructure in the state. These numbers show the network's high cost and depict the transportation network's massive impacts on the environment. Proper management of such impacts begins with their quantification.

California is one of the pioneering states in environmental stewardship in the U.S., with increasingly ambitious regulations and legislative mandates for combating climate change and reducing global warming by drastic cuts in statewide greenhouse gas (GHG) emissions. The overarching bill in California's climate change effort is Assembly Bill 32 (AB32: California Global Warming Solutions Act of 2006) which mandated California's statewide GHG emissions to 1990 levels by the year 2020 and to 80 percent below 1990 levels by 2050. Senate Bill 375 (SB 375: the Sustainable Communities and Climate Protection Act of 2008) is another primary legislation that requires specific GHG reductions in the transportation sector for each metropolitan planning organization (MPO) in California. SB 375 mandates should be met by various strategies such as reducing vehicle-miles-traveled and improving active modes of transport through land-use changes such as complete streets and improved public transit. Using the regional transportation planning process to reach GHG emission reductions is one of the significant components of SB 375 (ILG, 2018).

The construction sector and the highway construction industry in the U.S. employed 11.2 million and 8.6 million people, respectively (Bureau of Transportation Statistics website, 2021). Transport infrastructure and roadways provide accessibility, connectivity, and freight movement with positive and negative impacts on public health, safety, mobility, job creation, and livability.

1.1.2. Complete Streets, as modern design philosophy for urban streets, to meet the SB 375

"Complete streets" (CS) is a set of design concepts for urban streets and intersections intended to encourage active modes of transportation (primarily biking and walking) and reduce vehicle miles traveled, by making the streets safer, more comfortable, and more appealing for active modes of transportation compared to conventional streets, while also accommodating motorized transportation and parking. Complete streets are typically developed by transforming existing streets, which were built mainly focused on serving motorized vehicle movement and parking, by implementing the CS design concepts. Complete streets are currently being advocated mainly for urban areas and offer the potential for environmental, social, and economic benefits (Harvey et al., 2018, Smith et al. 2010; NACTO 2013; Wendell 2015.)

One of the goals of implementing complete streets is to produce social and environmental benefits. However, quantitative analysis of these benefits is still a major challenge (Evans et al., 2008; Rosenbaum, 2014). Since the proportion of state revenue shared with locals is roughly one-third of the state's transportation revenues, which was $1.3 billion in 2016-2017 (Taylor, 2017), it is important to fully understand the current gaps in knowledge in quantifying and implementing social and environmental LCA of urban streets and the models and databases needed to address such gaps. Funding for complete street projects is also becoming much more widely available in California and across the U.S. Therefore, the development of project evaluation metrics that consider project-specific quantitative environmental and social impacts (when assessing, prioritizing, and designing projects) has increasing importance.

1.1.3. Life cycle assessment methodology for quantification of the environmental impacts of services

Environmental Life cycle assessment (ELCA) is a technique to analyze and quantify the environmental impacts of a product, system, or process throughout its entire life cycle. Figure 1-1 shows a generic model of a product system during various life cycle stages, from the extraction of raw materials from the ground (cradle) all the way to the end of life (grave.) LCA can identify hotspots and where the most significant improvements can be made while identifying potential trade-offs.

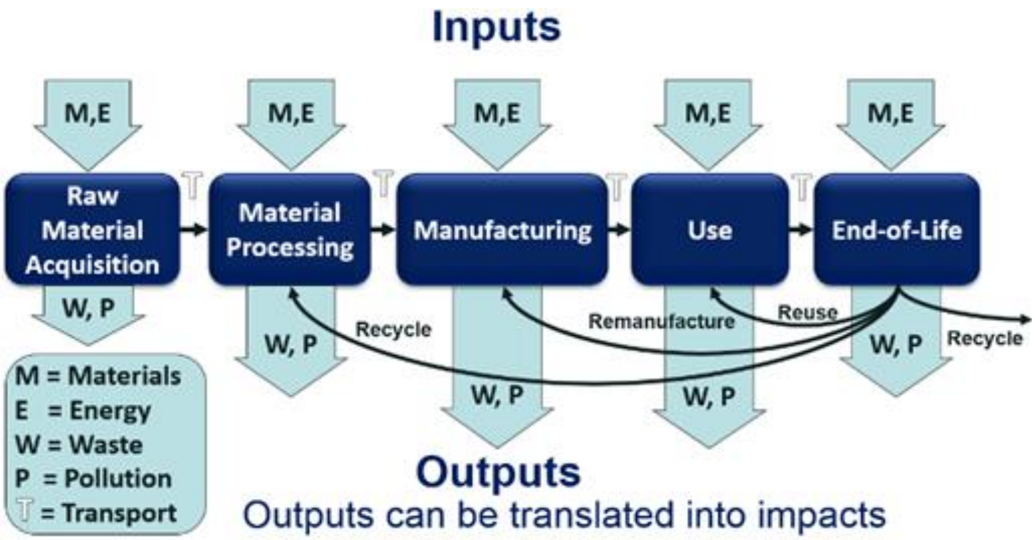


Figure 1-1. General life cycle of a system (Kendall, 2012)

According to the International Organization for Standardization (ISO 2006), the general LCA framework (Figure 1-2) consists of four major steps, including (1) the goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. LCA can provide quantitative information for decision-makers to evaluate the direct and indirect impacts of transportation systems (Chester et al., 2012). Construction and maintenance of road infrastructure involve the consumption of significant amounts of materials and energy sources, especially considering their long service life. Therefore, it is critical to explore solutions to minimize their life cycle environmental impacts (Miliutenko, 2016). Although LCA has broad applications in various industries, its implementation in planning is rare and needs more investigation (Harvey et al., 2018).

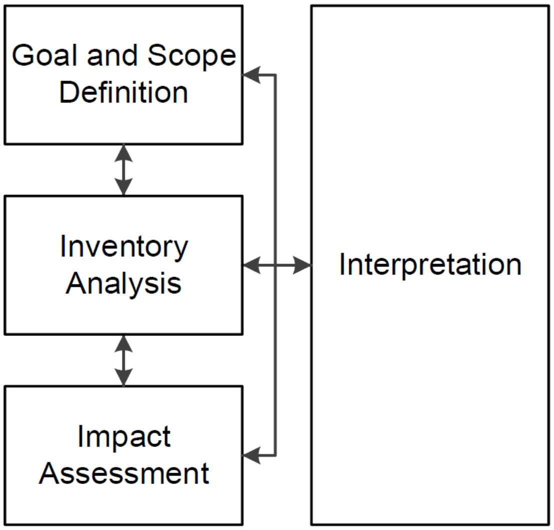


Figure 1-2. General Life Cycle Assessment Framework (ISO 14040, 2006)

1.1.4. Social life cycle assessment for quantification of the social impacts of services

Social LCAs quantify the social and sociological aspects related to a system. Social life cycle assessment (SLCA) is still at the early stage of development, unlike environmental LCA and life cycle cost analysis (LCCA) which already have established measurement approaches (Haaster et al., 2017, and Benoit et al., 2010). The United Nations Environment Program (UNEP) published methodological sheets to complement the SLCA guidelines published in 2009 by UNEP and support the development of SLCA case studies. The UNEP sheets were intended to clarify the concepts of sub-categories, recommended data sources, and existing policies for SLCA (UNEP, 2013). The proposed framework by UNEP followed the four LCA phases, including goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. Regarding this framework, SLCA, as a standalone tool or in combination with LCA, can be applied and complements LCA with social and socio-economic indicators (UNEP, 2013). Although UNEP developed a framework guideline for SLCA (UNEP, 2013), there is still an absence of a foundation of empirical experience in SLCA due to a lack of general standardized indicators to measure the social impacts during the supply chain and product life cycle (Ostovar et al., 2021, Harvey et al., 2018, Kuhnen and Hahn, 2017, Corona et al. 2017, and Arcese et al. 2018). According to the literature reviews, no study has considered social LCA (SLCA) in the road and transport infrastructure area.

1.1.5. Planning and the importance of integrating sustainability measures to meet the legislative mandates

Environmental impact consideration is typically introduced in transportation decisions through transportation planning and the environmental review processes. Planning is the process of deciding how a community uses its land and other resources, including analyzing the environmental impacts of development and infrastructure projects to reach its development goals. Planning decisions usually require local political approval and reflect the desires and interests of the community. The process for making planning decisions is defined by local and state laws (OPR, 2005), and analyzing the environmental impacts of development and infrastructure projects is a central part of the planning process.

Road infrastructure planning is often a long and complex process implemented at different levels of government (Miliutenko, 2016). The legislation mentioned in the previous section and their aggressive requirements for GHG cutbacks point to the importance of objective quantification of sustainability measures in the planning phase of transportation infrastructure.

1.2. Problem Statement

The United States has a vast transportation infrastructure, vital to its economic prosperity and way of life, but its maintenance and expansion come with staggering environmental and social impacts. Transport infrastructure and roadways provide positive and negative impacts on public health and safety, mobility, and livability. Even though transport and road infrastructure have significant social impacts, evaluating and quantifying these aspects of transport infrastructure are still in their infancy.

Life cycle assessment is a holistic approach in which the environmental sustainability of a product, project, process, or system can be assessed and quantified. Environmental LCA quantifies the energy, resource use, and emissions to air, water, and land for a product or a system. A reliable and representative LCI database to quantify the environmental consequences of decisions in transportation infrastructure is always a gap and always needs to be updated.

One of the main approaches to complete streets, as a design concept for streets and intersections, is to reach social and environmental benefits. The quantitative analysis of the potential benefits is lacking in the CS concept. Life Cycle Assessment is an appropriate tool to quantify the analysis, and Social LCA quantifies the social and sociological aspects related to a system. The advantage of using an LCA methodology is that it is a systems approach, with system boundaries depending on the goal of the assessment study applying to the life cycle to account for long-term impacts rather than only initial outcomes. However, a gap in transport infrastructure LCA impact indicators is a shortage of socio-economic performance measures to complement the existing environmental indicators. Therefore, performance measures are indicators defined in terms of socio-economic and environmental impacts to evaluate the social equity of project selection, which is a critical issue for CS, and critical for understanding the efficacy of CS. In addition, there was no established framework, models, and database for quantifying the social impacts and environmental impacts of complete street measures and comparing them with conventional design methods to allow quantification of the efficacy of complete streets in meeting the sustainability of urban streets.

There are legislative mandates, with specific deadlines to reach predefined milestones, in the state of California for improving the sustainability of the transportation sector and minimizing its environmental impacts. However, there is currently no available methodology for the integration of sustainability measures in the earliest stages of a development project (planning and conceptual phases) to optimize transportation infrastructure management. Road infrastructure planning can be a long and complex process implemented at different levels, and the early stages of planning and conceptual design present the most significant opportunity to reduce GHG emissions in the lifetime of infrastructure projects. In addition, the early stage of planning has the highest effect on impacts since the major scoping decisions are made at this stage. However, there are few studies considering LCA in the planning phase, and also there is still a shortage of work for the appropriate use of LCA in the conceptual design and early stage of the planning phase in transport infrastructure projects at the state-level and local-government-level in the U.S, and California.

1.3. Research Objectives and Contributions to the State of Knowledge

The objectives of the work presented in this doctoral thesis are:

- Development of an up-to-date and representative (regional) LCI database for transportation infrastructure in California for quantification of their environmental impacts, by filling gaps in current LCIs for crude oil and asphalt binder, warm mix asphalt additives, and bonded concrete overlay on asphalt, and considering case studies to evaluate the environmental life cycle impact for them.

- Develop a Social LCA framework for complete streets as a transport infrastructure considering appropriate socio-economic performance measures and relevant and reliable data sources.
- Conduct several case studies to test the framework by using it to quantify the environmental and socio-economic impacts of those case studies and compare them with leaving the street in its vehicle-centric configuration.
- Propose a strategy for integrating sustainability measures in the planning and conceptual design phases of transportation infrastructure in California to fill the currently existing gaps in practice.
- Identify a framework for an up-to-date and representative (regional) LCI database for generic road infrastructure elements in California to quantify their environmental impacts during the planning and initial design phases.

1.4. Research Scope and General Methodologies

Figure 1-3 shows the scope of the research presented in this dissertation. The first main part of this dissertation is to develop a representative life cycle inventory (LCI) database for the California region and an appropriate life cycle assessment model in transportation infrastructure management in California, including i) Crude Oil and Asphalt Binder and Case study, ii) Warm Mix Asphalt Additives and Case study, and iii) Bonded Concrete Overlay of Asphalt and Case study (Chapter 2). The second main part of the current dissertation study describes complete streets as a modern design philosophy for urban streets aiming to reach social and environmental benefits, defines socio-economic performance measures for complete streets, and develops social life cycle assessment framework for complete streets (Chapter 3). The next chapter involves the application of LCA to calculate environmental impacts for complete street case studies and to demonstrate the use of social LCA for complete streets for three case studies in northern California (Chapter 4). The last main chapter proposes a strategy for integrating sustainability measures in the planning and conceptual design phases of transportation infrastructure in California using LCA methodology (Chapter 5). Create an outline for a future study to develop an up-to-date and representative (regional) LCI database for generic road infrastructure elements in California to quantify their environmental impacts during the planning and initial design phases (Chapter 5).

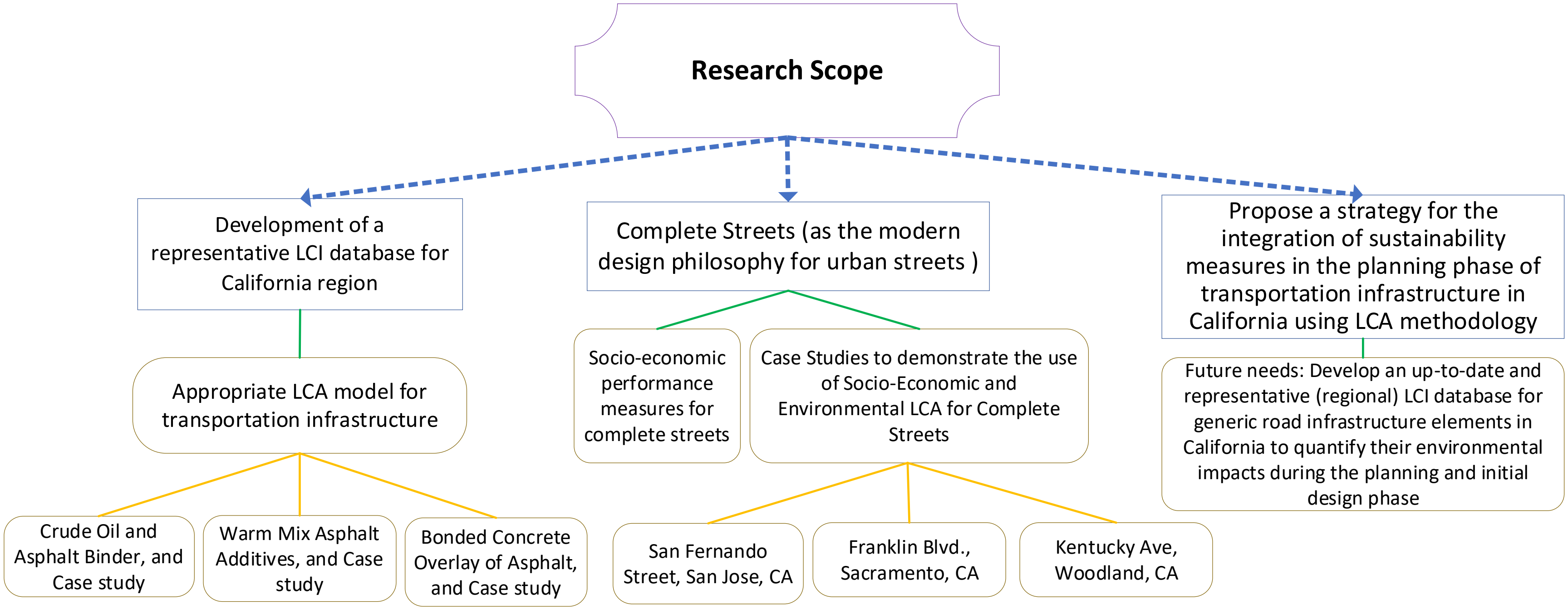


Figure 1-3. Research scope, main topics, and projects covered under each topic

The following general methodologies have been conducted to address the gaps in the knowledge and the issues discussed in the previous sections.

1.4.1. Development of a representative LCI database and appropriate LCA model for road infrastructure

The approaches for implementing LCA include identifying questions to achieve environmental goals, defining system boundaries, functional units, required approaches for sensitivity analysis, identifying input of the system and how they change the system, and identifying appropriate environmental LCI data, and life cycle impact assessment. LCA has done a comprehensive job in terms of collecting precise, regionally relevant, and more updated data (time comprehensive).

Literature reviews, surveying of the local contractors, local government, Caltrans' data, and databases such as GaBi and ecoinvent, and observations were used to collect the data. UCPRC LCI, a comprehensive pavement dataset developed and calibrated for California, was also used, including a comprehensive list of materials, energy sources, transport modes, and pavement surface treatments. Representative (regional) LCI databases for those elements for which data inventories do not yet exist has been developed for California. The three newly developed LCIs that are covered in this dissertation study are:

1. Asphalt binder,
2. Warm mix asphalt technologies and
3. Bonded concrete overlay of asphalt (BCOA).

1.4.2. Socio-economic performance measures, developing a Social LCA framework for complete streets, and case studies

A framework for LCA of complete streets projects was developed based on the SLCA framework (UNEP 2009 and UNEP 2013). Different systems of social impact indicators and performance measures were compared, and appropriate categories (e.g., accessibility, jobs, connectivity/mobility, safety/public health, and livability) were defined to screen and select the best indicators among a large number of potential indicators considering clarity, data availability, relevance, applicability, overlap, and simplicity of calculation or estimation. The framework developed in the previous studies did not include a method for considering environmental justice concerns in minority and low-income neighborhoods. Hence, an equity of outcomes point of view, which evaluates and compares indicators and measures, was applied to the initial set of performance measures. The LCA framework was evaluated in terms of its practicality of data collection, usefulness, and rationality of the results to quantify the socio-economic impacts of CS, and to compare them with the conventional streets. The SLCA framework is based on five categories of concerns and 17 performance measures or indicators.

The indicators were tested and evaluated for final recommendations. The results are compared with the existing streets that were configured to be vehicle-centric. The case studies were solicited in both high and low-resource neighborhoods on corridors in three cities with different infrastructure and socio-economic characteristics. This permitted the evaluation of changes in how users of complete street improvements gain access to public resources and how and where public infrastructure investments are deployed. Using the CalEnviroScreen tool from the California Environmental Protection Agency is also investigated to assess the exposure of neighborhoods and their vulnerability to environmental impacts in conjunction with the performance indicators when evaluating the potential benefits for disadvantaged neighborhoods.

Recommendations are made for dropping some indicators because of difficulties collecting data or interpreting the results, modifications of other indicators, and adding some new indicators to fill important gaps.

1.4.3. Strategies for using LCA at the conceptual design stage and early design stage of road improvement

The current dissertation defined the conceptual design stage and the early design stage as part of the planning and design process of transportation infrastructure, respectively, and considers them at the state-level and local government-level in California. The conceptual design stage is defined as an early stage of the transportation infrastructure planning phase when an initial project estimate is developed based needs, identification of alternative solutions, and historical costs of similar projects. The information in the conceptual design stage and during the preparation of the initial plan is required to decide if, how, and when to fund a particular project. The applicability of LCA or similar methodologies in quantifying the environmental impacts in the conceptual design stage depends on the availability of sufficient data and information in this stage. Using LCA improves the ability to quantify the -system, life cycle effects of decisions, and changes in systems.

The early design stage covers more inventories compared to the conceptual design stage. The conceptual design stage gives practitioners a general idea for a rough estimation of 10% of the design details, while the early design stage covers more details (expect to cover 30% details of the design). Reconstruction, retrofit, rehabilitation, and repurposing of existing infrastructure should be investigated in addition to the corresponding choice of road elements (e.g., changes or addition or removal of pavements). In these proposed stages, generic alternative designs should be developed for each infrastructure type for different contexts.

CHAPTER 2. LIFE CYCLE INVENTORIES AND ASSESSMENT FOR CRUDE OIL AND ASPHALT BINDER, WARM MIX ADDITIVES, AND BONDED CONCRETE OVERLAYS FOR CALIFORNIA

This chapter aims to develop a representative life cycle inventory (LCI) database for the California region and an appropriate life cycle assessment (LCA) model in transportation infrastructure management in California for the following: asphalt binder, warm mix additives and bonded concrete overlays.

2.1. Introduction

Sustainability cannot be addressed without consideration of the environmental impacts of the systems, products, activities and processes that support quality of life. The life cycle assessment (LCA) methodology, which identifies and quantifies the energy use, materials consumption, and emissions (land, air and water), can be used for environmental analysis for a life cycle perspective of a system. The University of California Pavement Research Center (UCPRC) and the California Department of Transportation (Caltrans) developed a Pavement LCA Roadmap for California which is a living document that gets updated every three years. Caltrans vision is to be able to quantitatively assess the social, economic and environmental impacts of transportation infrastructure. The UCPRC has been collecting data for different pavement materials, construction processes, transport methods, energy sources and other variables important for California that gives the Caltrans capability of performing LCAs for decision support for project-level design, network analysis for pavement management, benchmarking and reporting, and policy evaluation (specifications, directives, etc.).

The UCPRC has earlier developed life cycle inventories (LCIs) for several infrastructure materials and construction activities for Caltrans (Wang et al., 2015; Saboori et al., 2022; Ostovar et al., 2023). The current study continues to update California specific LCIs and develop new ones for the materials and processes that have not been covered earlier. Once they have been reviewed, LCIs are uploaded into the environmental life cycle assessment of pavement tool (*eLCAP*) which has also been developed for Caltrans.

The three new developed LCIs that are covered in this chapter are:

1. Crude Oil and Asphalt Binder,
2. Warm mix asphalt technologies and
3. Bonded concrete overlay of asphalt (BCOA).

2.2. LCA of Crude Oil and Asphalt Binder, and Case study

2.2.1. Background

Several pavement studies have used databases and life cycle assessment (LCA) for evaluating the environmental impacts of an asphalt binder in pavements. The Eurobitume life cycle inventories (Eurobitume, 2012) were pioneering works that have been used extensively in LCA. Eurobitume used a fictional refinery using characteristics from several refineries in northern Europe and a representative average crude slate. LCA models of petroleum refineries for North America have also used an average crude slate for all refinery products (thinkstep mode refinery model in GaBi software (Schuller, 2016), Petroleum Refinery Life Cycle Inventory Model (Abella, 2016), and National Renewable Energy Laboratory of the United States Life Cycle Inventory (NREL, 2003). Yang evaluated average crude slates for different Petroleum Administration for Defense Districts (PADD) in the USA when evaluating the impacts of materials extraction for different crude sources used for all refinery products in each PADD (Yang, 2014). The U.S. was divided into five PADDs to help organize fuel distribution during World War II as shown in Figure 2-1: East Coast (PADD 1), Midwest (PADD 2), Gulf Coast (PADD 3), Rocky Mountain Region (PADD 4), and West Coast (PADD 5). California is included in PADD 5 along with six other west coast states. The PADDs help users of the Energy Information Administration's (EIA) petroleum data evaluate regional petroleum product supplies as well as analyze patterns of crude oil and petroleum product movements throughout the nation (EIA, 2020).

The 2019 Asphalt Institute LCA for North American asphalt binders (Wildnauer et al., 2019) used data for the refineries that produce asphalt and were willing to participate in the data collection effort. The LCA therefore is based on the crude slate that is representative of those refineries. The participating refineries provided data for the LCA that were representative of when the refineries were producing asphalt, as opposed to other times when they were not producing asphalt. The current NREL USLCI data prepared by Mukherjee uses the results from the Asphalt Institute LCA and Yang's studies (NREL, 2003; Wildnauer et al., 2019; Yang, 2014).

California is in PADD 5 (West Coast), which also includes six other western states as shown in Figure 2-1. The average crude slate in the Asphalt Institute LCA is heavily weighted toward use of crude from oil sands from western Canada. California is not connected to the Canadian oil sands by pipeline, and only one pipeline—the Trans Mountain pipeline to Vancouver, British Columbia—connects the Canadian oil sands to the sea. Canadian oil sands are classified as heavy, meaning that they contain more bitumen used to make asphalt than lighter constituents that are used to make transportation fuels, and they are classified as sour, meaning that they are high in sulfur, requiring extraction to make transportation fuels. The average slate used in the Asphalt Institute LCA was thought by the UCPRC to not be representative of crude used in PADD 5. It was expected that there are also large differences between California and the other states in the PADD and that a study was needed to produce a more representative regionalization of the Asphalt Institute LCA to better calculate asphalt binder environmental impacts in California for use in pavement LCA.

No study on the environmental impacts of asphalt binder has been performed previously for California, thus the UCPRC set out to develop a life cycle inventory dataset of asphalt binders by using data from PADD 5 and to further narrow that to the refineries in California. This chapter describes the framework that was developed to model asphalt binder production inventory data and environmental impacts for PADD5 and California. Data sources and supporting methodologies with assumptions are also discussed in detail in the following sections.

It should be noted that the Trans Mountain pipeline is currently being expanded to increase its capacity from 300,000 barrels per day (bpd) to 890,000 bpd, with construction originally scheduled to be completed in 2022, with a likely finish in the fall of 2023 (Transmountain, 2020). It is not certain how much the pipeline expansion will change the crude slates used by California refineries in the future. Future updates to this study will likely be warranted as the economics of California asphalt production and importation of crude used to produce asphalt change.

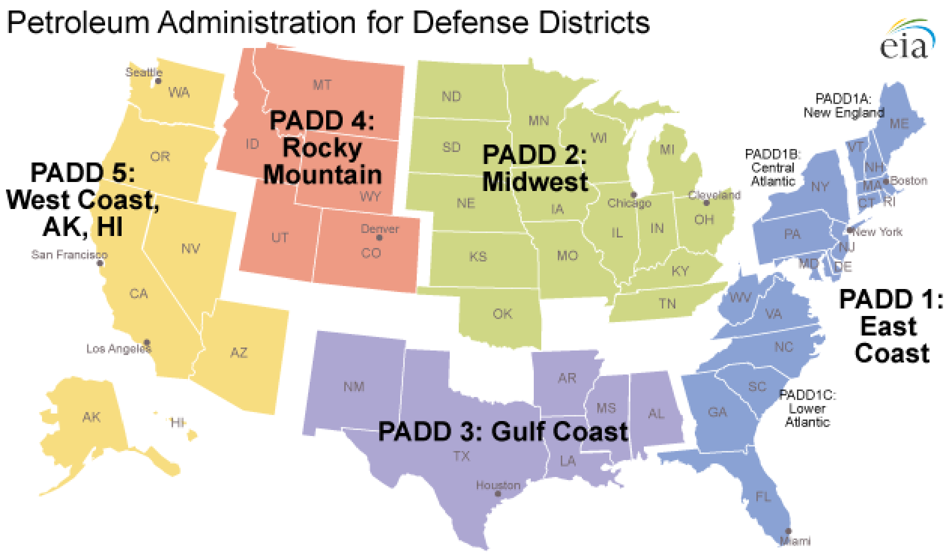


Figure 2-1. The U.S. Petroleum Administration for Defense Districts (PADDs) (EIA, 2020)

2.2.2. Goal and Scope

2.2.2.1. Goal

The goal of this study is to quantify the environmental impacts from the production of the asphalt binder used in California. This study focuses on LCA of the asphalt binder production in PADD 5 and California in the years 2017 and 2018. Additionally, a comparison to the Asphalt Institute's (AI) study, LCA of Asphalt Binder of North America, has also been performed.

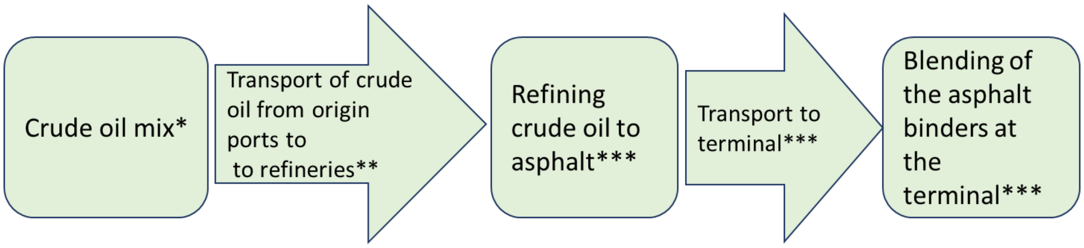
2.2.2.2. Declared Unit

A declared unit is typically used instead of a functional unit when the application and function of the product are uncertain. A declared or defined unit is used for pavement materials such as asphalt binder, aggregate, etc. to define mass, volume, area or length in pavement design and construction (Harvey, 2016). The declared unit defined for this study is the production of 1 kg of asphalt binder (also referred to as bitumen in European literature).

2.2.2.3. System boundary

The cradle-to-gate approach used for this study includes the material extraction and production stages as well as the transportation of the materials up to the point of leaving the gate of the refinery. This study covers the complete supply chain for asphalt binder for PADD 5 and California as presented in Figure 2-2, including

- Crude oil mix: well drilling, exploration, production, and processing, the long-distance transport and the regional distribution to the port (modeled based on crude oil mix of GaBi software).
- Transportation of crude oil from origin port to the destination port and refineries. (modeled in Gabi based on data collected from EIA, CEC, NEB, Oil Sands Magazine, Oil& Gas Journal, NACEI, Enerdata, CEC, NASEO, and Government of Canada)
- Refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders (using AI study model and data). (Figure 2-2)



**Crude oil mix: modeled based on crude oil mix of GaBi software*
***Transportation of crude oil from origin port to the destination port and refineries: modeled in Gabi based on data collected from EIA, CEC, NEB, Oil Sands Magazine, Oil& Gas Journal, NACEI, Enerdata, CEC, NASEO, and Government of Canada*
****Refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders: using AI study model and data*

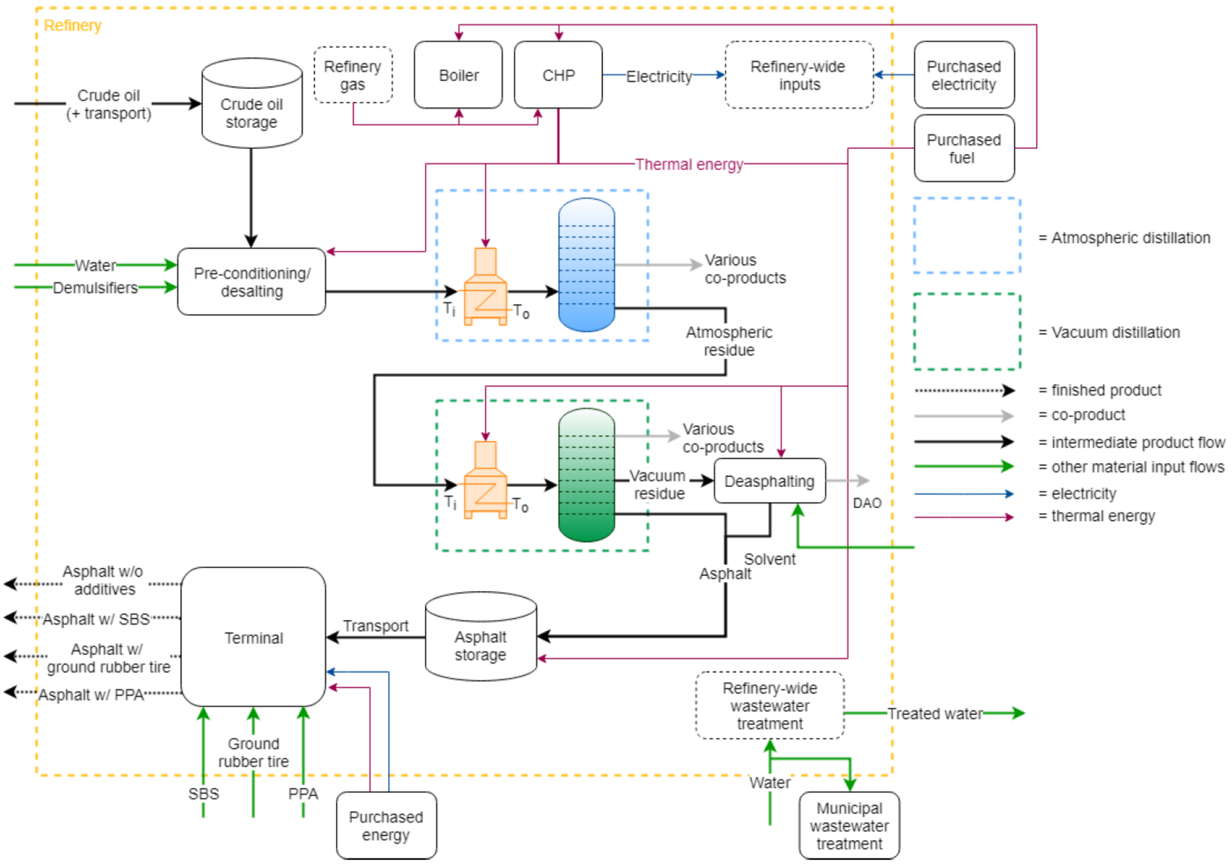
Figure 2-2. System boundary of asphalt binder covered in this study

In this study, crude oil for each source is modeled based on the crude oil mix dataset of that specific source available in GaBi that covers the entire supply chain of crude oil. Crude oil mix, as reported in the GaBi dataset's documentation, includes well drilling, crude oil production and processing, long-distance transport, and the regional distribution to the final consumers.

In the crude oil mix model, all known transport processes, including ocean freighter, barge, rail, truck, and pipeline transport of bulk commodities are included (Thinkstep, 2020). Data for transportation of crude oil from origin port to destination port and to refineries were collected from EIA, CEC, NEB, Oil Sands Magazine, Oil& Gas Journal, NACEI, Enerdata, CEC, NASEO, and Government of Canada.

In the LCA of asphalt binder study by AI, as the main reference of the current study, inventories were supplied by twelve AI member refineries and eleven terminals (from four companies) in North America (Yang, 2014). Due to the lack of other sources of information, it was assumed that the refineries and terminals of the current study and AI study are similar, and the AI study's data are used for refining of crude oil into asphalt, transport to a terminal, and the final blending process.

The system boundary of the AI study includes "raw material sourcing and extraction, transportation to refineries, refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders at the terminal". Only processes at the refinery associated with asphalt production were included in the AI refinery system boundary, as seen in Figure 2-3, and processes for producing other products after extraction of asphalt from the crude were not included.



**DAO: deasphalted oil*

Figure 2-3. Asphalt Institute (AI) cradle-to-gate system boundary (Yang, 2014, p16)

2.2.2.4. Crude Oil

The asphalt binder production starts with extraction of crude oil followed by delivery to the refinery.

In this study, crude oil is modeled based on the crude oil mix dataset available in GaBi that covers the entire supply chain of crude oil starting with the extraction of crude oil and delivery to the refinery. *Crude oil mix*, as reported in the GaBi dataset's documentation, includes well drilling, crude oil production and processing, long-distance transport, and the regional distribution to the final consumer. Losses occurring during transportation via pipeline or vessel are also included in GaBi. (Eurobitume, 2012)

The most important technologies used for crude oil extraction, such as conventional (primary, secondary, tertiary) and unconventional production (oil sands, oil shale), which include parameters such as energy consumption, transport distances, and crude oil processing technologies, are independently considered for each crude oil production country in the GaBi dataset as shown in Figure 2-4 (Thinkstep, 2020). In the crude oil mix model, all known transport processes including ocean freighter and barge transport as well as rail, truck, and pipeline transport of bulk commodities are included (Schuller et al., 2019).

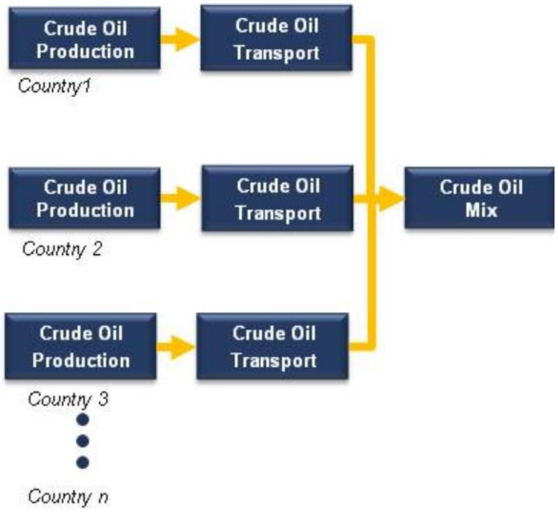


Figure 2-4. Typical pictogram of crude oil mix (Thinkstep, 2020)

2.2.2.4.a. Crude oil type and production technologies

There are two classifications of crude oil, conventional and unconventional, as shown in Table 2-1 and Figure 2-5. There are three conventional crude oil development and production technologies in U.S. oil reservoirs called primary, secondary, and tertiary (Figure 2-5). During primary recovery, about 10 percent of a reservoir's original oil in place is produced. During this technology, the natural pressure of the reservoir, combined with artificial lift techniques (such as pumps) bring the oil to the surface. During secondary technology, about 20 to 40 percent of a reservoir's original oil in place is produced by extending a field's productive life by injecting gas or water to displace oil and drive it to a production wellbore. During tertiary or enhanced oil recovery (EOR) technology, which is the most popular technique in the U.S., more than 30 to 60 percent of a reservoir's original oil in place is brought to the surface. EOR usually uses three major technologies: thermal recovery, gas injection, and chemical injection (Office of Fossil Energy, 2020).

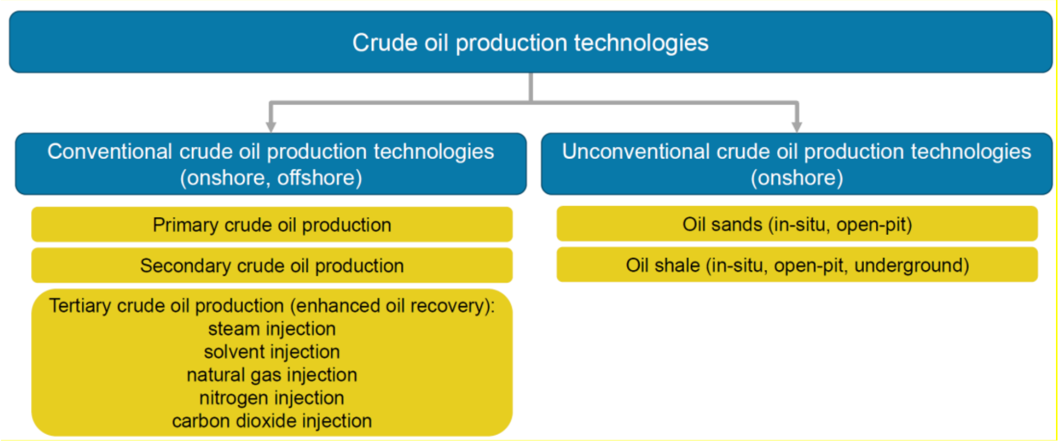


Figure 2-5. Crude oil production technologies (Schuller et al., 2019, p11)

Table 2-1 presents the crude oil types from conventional and unconventional extraction which are explained in greater detail in the following section.

Table 2-1. Crude oil types from different conventional and unconventional extraction methods

Conventional	**Unconventional** (Oil Sand or Bitumen)
Light (API*>30)	Upgraded Bitumen (Synthetic: upgraded bitumen from the oil sands (light/ sweet))
Medium (25<API≤30)	Bitumen (Non-upgraded (diluted oil sands)) (heavy/ sour):
Heavy (API*≤25)	i. Dilbit: Diluted with distillates
	ii. Synbit: Diluted with synthetic crude

** American Petroleum Institute (API) gravity method, which is an inverse of the petroleum liquid's density relative to water, is used to classify different crude types. Heavier crudes will have a larger percentage of asphalt.*

2.2.2.4.b. Crude oil quality and properties

To compare the quality of different crude oils, sulfur content and density are two of the most important attributes. The EIA defines crude oil with less than 1 percent sulfur as sweet and crude oil with greater than 1 percent sulfur as sour (EIA, 2019). The American Petroleum Institute (API) gravity method, which is an inverse of the petroleum liquid's density relative to water, is used to classify different crude types. API gravity is commonly grouped as heavy, medium, or light. API gravity higher than 30 is defined as light crude oil, and any crude oil with the API gravity less than 30 would be classified as heavy and medium crude oil (EIA, 2019). Table 2-2 shows data from the AI LCA that compares the percent of crude oil of each gravity category in crude slates in that LCA with the crude slates in different regions.

The same information for California is also shown in the table from data from the EIA (EIA, 2020). In 2018, California refineries received 31.1 percent of their crude from California wells, 11.4 percent from Alaska, and 57.5 percent from foreign sources. Top foreign sources that year were Saudi Arabia, Ecuador, and Iraq. Foreign sources of crude are increasing because California and Alaska oil fields are aging. Many of California's fields have been developed for a century, and the Alaskan fields for a half century. California crude oil production in 2018 breaks down into the following API gravity categories: 68 percent of crude oil is heavy, 24 percent is medium, and the remaining 8 percent is light. Although the crude slate used by California's refineries resembles that of the AI LCA in terms of gravity, less than two percent of that slate is imported from Canada (California Energy Commission (CEC), 2020a).

Table 2-2. Gravity of crude slates from several sources in 2017 (Wildnauer, 2019; EIA, 2020)

Gravity of Crude Oil (Percentage by mass)	Asphalt Institute (Eurobitume, 2012)	North American Average (Wildnauer, 2019)	U.S. Average (EIA, 2020)	PADD 5 (EIA, 2020)	California (EIA, 2020)
Heavy & Medium (API≤30)	90%	65%	39%	40%	91%
Light (API>30)	10%	35%	61%	60%	9%

2.2.2.5. Refinery

In the LCA of asphalt binder study by AI, as the main reference of the current study, inventories were supplied by twelve AI member refineries and eleven terminals (from four companies) in North America (Wildnauer, 2019). Due to the assumed similarity to considered refineries and terminals of this study and the AI study, the AI study's data were used for refining crude oil into asphalt, transport to a terminal, and the final blending process. Hence, the following paragraphs explain the methodology and assumptions used in the AI study.

Process-specific electricity, thermal energy, water usage, and emission were the preferred data in the AI study, but they were unavailable. Therefore, the AI study collected refinery-level data for site-wide consumption of electricity, thermal energy, and direct emissions.

Regarding the allocation method considered in the AI study, electricity was allocated based on the total mass of the co-products, the sensible heat allocation method was selected for thermal energy, and the total thermal energy use allocation was used for direct emissions from refinery processes (i.e., fuel combustion). The mass allocation method was considered for crude oil extraction and transportation. This study assumed the same allocation method as the AI study used.

In AI study, the thermal energy input was calculated using the following equation:

$$\frac{C \times \Delta T}{\eta} = Thermal\ Energy\ Required$$

Where,

C = heat capacity (J/K)

ΔT = temperature difference between crude oil input and asphalt run down (K)

η = efficiency of heating system (unitless)

L = losses (J)

It should be mentioned that each refinery considered in the AI study was modeled individually based on their own data and then combined to create the production-weighted average.

2.2.2.6. Asphalt Binder Production

Crude oil is the raw material that is extracted from the ground and transported to crude oil refineries mainly through ports and pipelines, although rail is used by some refineries. At the refinery, crude oil is partially heated and mixed with water to dissolve salts (a process called de-salting) followed by separating and removing the water from the crude oil. The de-salted crude oil is further heated in the atmospheric distillation unit where fractional distillation takes place. All products lighter than heavy gas oil are vaporized and captured outside the unit. The resulting atmospheric residue then enters the vacuum distillation unit, where the residue is heated and distilled under a vacuum. Gas oils and diesel are vaporized in the vacuum distillation unit, and asphalt, as a remaining hot liquid is left at the bottom of the vacuum distillation tower. Before asphalt goes to the asphalt rundown line and asphalt storage, it goes through heat exchangers in conjunction with other refinery feeds, in the crude and vacuum distillation units, to return heat energy in the asphalt to the process (Wildnauer, 2019; Schuller, 2019). This complete process is presented in Figure 2-3.

Looking at data in the AI LCA indicates that approximately 93 percent of the non-renewable energy consumption and 63% of the global warming potential from the production of asphalt binder comes from the crude oil mix extraction (Wildnauer, 2019). Production of asphalt binder in this study focuses on crude oil production and transportation in PADD 5 and California, and assumes the same impacts of asphalt binder refineries and terminals as the AI study (Figure 2-2). Two of the twelve refineries in the AI LCA are in California, and one of the twelve is in Washington State. Because crude oil extraction and transportation are heavily dependent on the crude oil source, expected differences in the crude oil slates used in California compared with PADD 5 and the rest of the U.S. are expected to result in large differences in non-renewable energy use, global warming potential and other environmental impacts of asphalt binder production.

2.2.3. Life Cycle Inventory and Life Cycle Impact Assessment

2.2.3.1. Life Cycle Inventory

This study to develop an LCI of asphalt binder for PADD 5 and California considers all components of the material stage: crude oil mix (i.e., well drilling, exploration, production, and processing, the long-distance transport and the regional distribution to the port of the crude oil source), transportation of crude oil from origin port to the destination port and refineries, refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders. As mentioned before (Figure 2-2), production of asphalt binder in this study focuses on crude oil mix and transportation in PADD 5 and California, and assumes the same impacts of asphalt binder refineries and terminals as the AI study. The AI LCA report collected information from twelve AI member refineries and terminals in North America. In the LCA of asphalt binder study by AI, as the main reference of the current study, inventories were supplied by twelve AI member refineries and eleven terminals (from four companies) in North America (Wang et al., 2015). Due to the assumed similarity to considered refineries and terminals of the current study and the AI study, the AI study's data are used for refining crude oil into asphalt, transport to a terminal, and the final blending process. The geographical coverage of the AI study is the U.S. and Canada. As crude oil sources vary significantly among different regions, the current study collects data for crude oil in PADD 5 and California, specifically.

The framework developed in this study is mainly based on available crude oil mix data updated by the Energy Information Administration (EIA) (EIA, 2019) and California Energy Commission (CEC) (California Energy Commission (CEC), 2020b). The model can be updated and adjusted in the future as trends change. The procedure developed can be used to calculate more precisely the environmental impacts of asphalt binder production more precisely for other parts of the U.S as well compared with the averaged data in the AI study.

2.2.3.1.a. Data collection, software, and database

Most of the data for this study were extracted from the following references, with citations included in the text where specific sources were used:

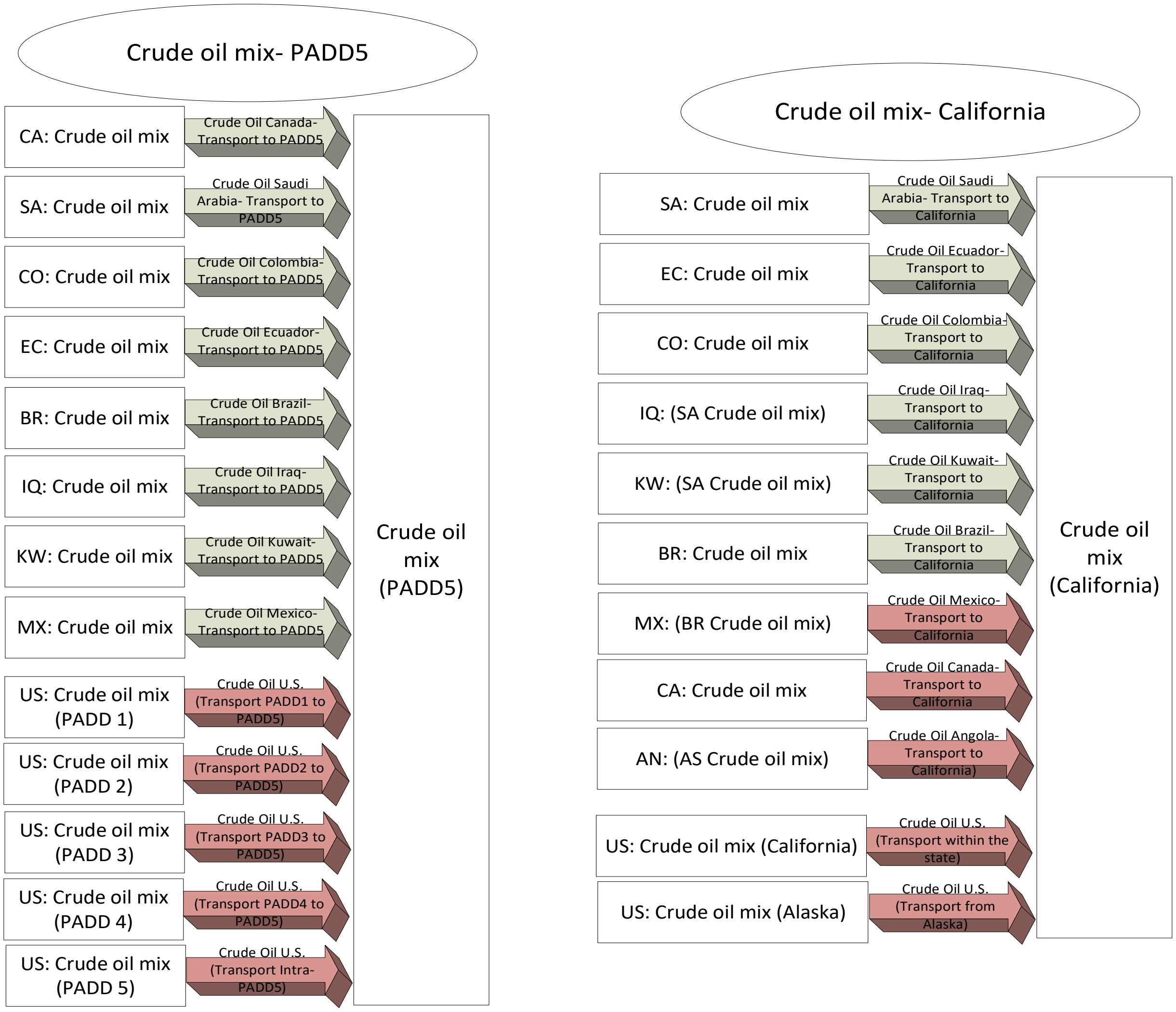
- EIA (U.S. Energy Information Administration) website

- NEB (National energy board)
- Oil Sands Magazine (OSM)
- Oil and Gas Journal (OGJ)
- NACEI (North American cooperation on energy information)
- Enerdata
- Government of Canada
- California Energy Commission (CEC)
- National Association of State Energy Officials (NASEO)

GaBi software, developed by Thinkstep and now owned by Sphera Solutions GmbH, was used to create the asphalt binder models. The secondary LCI data for the background system were extracted from the 2019 GaBi life cycle inventory database (Schuller, 2016). Because the most recent and most complete data that were obtained from most of the sources belonged to 2017, that was considered as the reference year.

2.2.3.1.b. Crude oil mix calculation

The crude slate data used specifically for the production of the PADD 5 and California asphalt binders were mainly collected from EIA, CEC, NEB, Oil Sands Magazine, Oil& Gas Journal, NACEI, Enerdata, CEC, NASEO, and Government of Canada (EIA, 2019; EIA, 2011; Schremp, 2016; Schremp, 2017; California Energy Commission (CEC), 2020a; California Energy Commission (CEC), 2020b; Government of Canada, 2019; Enerdata, 2019; OSM, 2019a; OSM, 2019b; OSM, 2019c; OGC, 2019; Congressional Research Service, 2012; NACEI, 2019; NEB, 2019). Crude oil mix data and the data for the transportation of crude oil from the origin port to the destination port and to refineries were collected from the mentioned resources. Figure 2-6 depicts the process diagram of crude oil for PADD 5 and California.



Note: US = United States, CA = Canada, SA = Saudi Arabia, CO = Colombia, EC = Ecuador, BR = Brazil, IQ = Iraq, KW = Kuwait, MX = Mexico, and AN = Angola

Figure 2-6. Crude Oil Mix Process Diagram for PADD 5 and California

PADD 5 Crude oil calculation and assumptions

The foreign and domestic crude oil sources supplied to PADD 5 were determined based on EIA data from 2017 (EIA, 2020). Based on assumptions of the current study, only the countries that provided more than 5 percent of PADD 5 crude oil imports were considered in the calculations, and the smaller sources of crude oil are distributed among them considering the similarity between the country of origin and the countries that contributed more than 5 percent. Major countries that export their crude oil to PADD 5 include Saudi Arabia (SA), Canada (CA), Ecuador (EC), Colombia (CO), and Brazil (BR) (EIA, 2020). The percentage of heavy, medium, and light oil for comparison was unavailable for some countries. For the countries that did not have crude oil data available, the assumption was to substitute them with the countries which have similar extraction and transportation and crude oil quality acquired from EIA (EIA, 2020). For instance, the crude oil mix of Saudi Arabia, which includes five types from heavy to super light, is assumed as a substitution for Iraq’s crude oil mix and Kuwait’s crude oil mix based on regional similarities and that the Iraqi and Kuwaiti crudes are in between Arabian Heavy to Extra Light with respect to average API gravity and sulfur content similarity (EIA, 2020; California Energy Commission (CEC), 2020b). Mexico’s crude oil mix is substituted with Brazil's crude oil mix due to the similarity of the crude’s API gravity, offshore production, and geographical locations, although sulfur contents differ (EIA, 2020; California Energy Commission (CEC), 2020b). The production from smaller producers of oil for the PADD (shown as Crude Oil from Other Countries) was prorated across the assumed suppliers. Table 2-3 shows the crude oil imports to PADD 5 as reported by EIA, and the study’s calculated percentages also consider data from the California Energy Commission.

Table 2-3. PADD 5 crude oil imports from foreign countries in 2017 (EIA, 2020)

Country of origin	EIA percentage (by mass)	Calculated PADD5 Percentage Smaller Sources with Assumed Similar Production and Crude (by mass)
Crude oil from Saudi Arabia (SA)	25	40=25+3+3+(18*(25+3+3)/82)
Crude oil from Canada (CA)	18	22=18+ (18*(18/82)
Crude oil from Ecuador (EC)	15	18=15+(18*(15/82)
Crude oil from Colombia (CO)	10	12=10+(18*(10/82)
Crude oil from Iraq (IQ)	4	-
Crude oil from Kuwait (KW)	4	-
Crude oil from Brazil (BR)	3	7=3+3+(18*((3+3)/82)
Crude oil from Mexico (MX)	3	-
Crude oil from other countries	18	-
Crude oil from all foreign countries	100	100

The domestic crude oil resources used in PADD 5 include PADD 5 field production crude oil (Intra-PADD) in addition to the crude oil coming from other PADDs to PADD 5. Table 2-4 depicts the amount of foreign crude oil and domestic crude oil resources refined in the U.S. and in PADD 5. (EIA, 2020)

Table 2-4. Amount of foreign and domestic crude oil resources refined in U.S. and in PADD 5 in 2017 (EIA, 2020)

Crude oil resources used	In U.S. (Million barrels)	In U.S. (Percentage by mass)	In PADD5 (Million barrels)	In PADD5 (Percentage by mass)
Domestic (produced within the U.S.)	3,413.4	54	410.2	47
Foreign	2,908.6	46	462.6	53

As mentioned before, there are two main sources of crude oil refined in PADD 5: 1) 47% Domestic (PADD 2, PADD 3, PADD 4, and intra-PADD 5) and 2) 53% Foreign (imported from foreign countries into PADD 5). To estimate the sources of the domestic crude oil mix brought into and refined in PADD 5 (i.e., PADD 2, PADD 3, PADD 4, and intra-PADD 5), the U.S. average crude oil mix database, as a national average for domestic crude oil sources derived from Gabi, is multiplied by 47% (domestic portion (Table 2-4). The portion of the foreign crude oil brought into PADD 5 from each foreign country (Table 2-3) is multiplied by 53% (Table 2-4). The impacts of the crude oil mix for each foreign country were also taken from the Gabi database. The crude oil mix and its impacts on PADD 5 were calculated from the summation of these numbers. A pictorial demonstration of this process is shown in Figure 2-7.

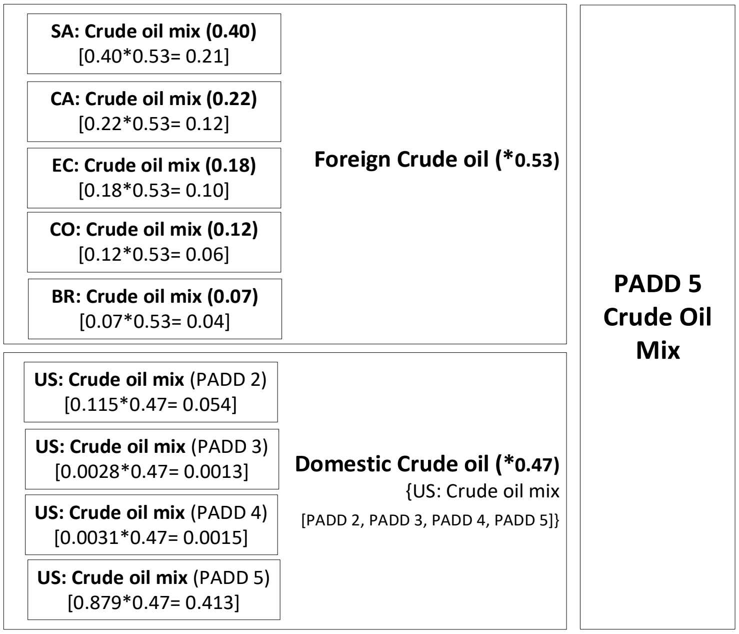


Figure 2-7. PADD 5 Crude Oil Mix Calculations using 2017 data (EIA, 2020)

California crude oil calculation and assumptions

The crude oil mix calculations performed to estimate a California average mix are similar to the ones done for PADD 5. All inventories were extracted from EIA and California Energy Commission information for 2017 (EIA, 2020; California Energy Commission (CEC), 2020b). The calculated percentages based on the assumptions made in Section 2.2.1.1.1 and imported from foreign countries are depicted in Table 2-5. Table 2-6 indicates domestic and foreign crude oil percentages for the U.S., PADD 5, and California. It should be mentioned that domestic crude oil for California is defined as crude oil mix in California, plus the crude oil brought into California from inside the U.S. (nearly all from Alaska, which is in PADD 5, there are no pipelines connecting California to the other 48 continental states). The same substitutions made for PADD 5 for Iraqi, Kuwaiti, Mexican crudes and crudes from other countries were also made for California. Figure 2-8 shows the process diagram presenting the California crude oil calculations.

Table 2-5. Assumed California crude oil imports from foreign countries in 2017 (EIA, 2020; California Energy Commission (CEC), 2020b)

Country of origin	EIA and CEC percentage (by mass)	Assumed Percentage (by mass)
Crude oil from Saudi Arabia (SA)	29	48
Crude oil from Ecuador (EC)	20	22
Crude oil from Colombia (CO)	14	16
Crude oil from Canada (CA)	3	4
Crude oil from Iraq	8	-
Crude oil from Kuwait	7	-
Crude oil from Brazil	4	10
Crude oil from Mexico	4	-
Crude oil from other countries	10	-
Crude oil from all foreign countries	100	100

Table 2-6. Foreign and domestic crude oil resources of U.S., PADD 5, and California in 2017 (EIA, 2020; California Energy Commission (CEC), 2020b)

Crude oil resource	Thousand barrels			Percentage by mass		
	U.S.	PADD5	California	U.S.	PADD5	California
Domestic	3,413,376	410,191	274,748	54%	47%	44%
Foreign	2,908,670	462,589	355,150	46%	53%	56%

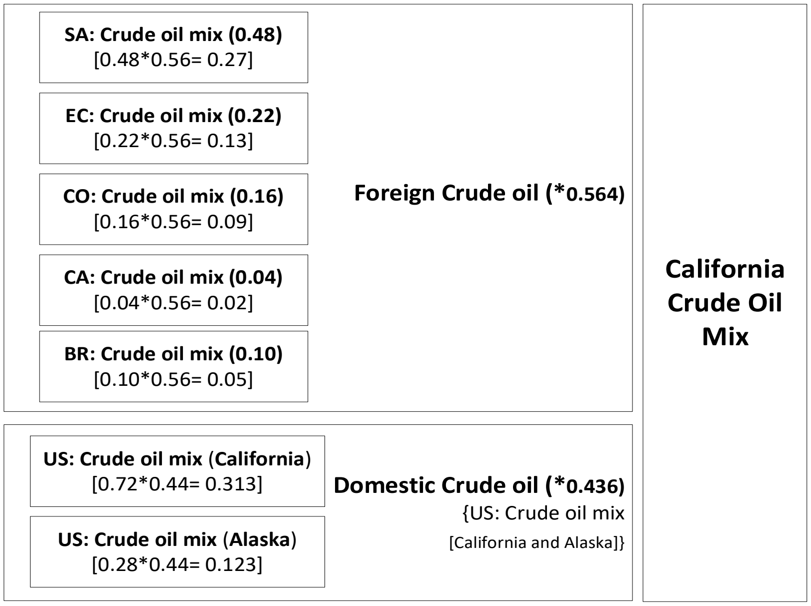


Figure 2-8. California Crude Oil Mix Calculations for the year 2017 (EIA, 2020; California Energy Commission (CEC), 2020b)

2.2.3.1.c. Crude oil transportation

Crude oil is transported from the origin ports/wells to the destination ports and refineries by pipeline, rail, ocean freighter, barge, truck, or combination of them. The crude oil transport was calculated based on the information on the location of the port/well, mode of transport, and distance as summarized in Table 2-7 and Table 2-8. The sea distances online tool was used to calculate distances between origin seaports and destination ports travelled by the ocean freighter (oil tanker) (Sea Distances online tool, 2019). The distances for other modes of transport were calculated based on the U.S., PADD 5 and California fuel resiliency, West Coast fuels markets, and petroleum and other liquids' inventory by EIA (EIA, 2014a; EIA, 2014b; EIA, 2015). Table 2-7 and Table 2-8 show the portion of each mode of transportation based on the crude oil origin-destination distances for PADD 5 and California, respectively. The Gabi 2019 database was used to model transportation (Schuller, 2019).

Table 2-7. Crude oil transportation distances and quantities for different transport modes to PADD5 locations (EIA, 2020)

	Origin Port	Destination Port	PADD5 Import (MBL/d)	Distance (mile)	Multiply of mass and distance (MBL*miles/d)
Transport Mode: Pipeline					
Canada to PADD 5	Edmonton, CAN	Puget Sound, WA	279	793	221,105
PADD3 to PADD 5	Elpaso, TX	Phoenix, AZ	34	402	13,520
PADD4 to PADD 5	Salt lake city, UT	Spokene, WA	32	721	22,777
PADD4 to PADD 5	Salt lake city, UT	Las Vegas, NV	8	421	3,325
PADD4 to PADD 5	Billings, MT	Moses lake	8	645	5,094
PADD 5 to PADD 5	LA, CA	San Fransisco, CA	84	382	32,088
PADD 5 to PADD 5	Bakersfield, CA	Los Angeles, CA	79	113	8,927
PADD 5 to PADD 5	Blaine, WA	Portland, OR	284	285	80,940
Pipeline					387,775 **(4.56%)**
Transport Mode: Rail					
PADD 2 to PADD 5	Bakken Play	Tacoma, WA	38	1,026	39,034
PADD4 to PADD 5	Salt lake city	Los Angeles, CA	16	688	10,867
PADD5 to PADD 5	Tacoma, WA	San Fransisco, CA	54	777	41,958
PADD5 to PADD 5	SF, CA	Long Beach, CA	57	405	23,085
Rail					114,944 **(1.35%)**
Transport Mode: Tanker					
SA to PADD 5	Saudi Arabia, Ras Tanura	Los Angeles, CA	507	11,370	5,763,986
EC to PADD 5	Ecuador, Balao terminal	Los Angeles, CA	228	3,005	685,519
CO to PADD 5	Colombia, Barranquilla	Los Angeles, CA	152	3,289	500,204
BR to PADD 5	Belem, Brazil	Los Angeles, CA	89	5,267	467,266
PADD 5 to PADD 5	Valdez, AK	Anacortez, WA	119	202	142,681
PADD 5 to PADD 5	Valdez, AK	San Fransisco, CA	98		168,070
PADD 5 to PADD 5	Valdez, AK	Los Angeles, CA	103	2,056	211,768
PADD 5 to PADD 5	SF, CA	Portland, OR	97	645	62,565
Tanker					8,002,059 **(94.03%)**
Transport Mode: Barge					
PADD5 to 5	Valdez, AK	Anacortez, WA	1	1,199	1,199

	Origin Port	Destination Port	PADD5 Import (MBL/d)	Distance (mile)	Multiply of mass and distance (MBL*miles/d)
PADD5 to 5	Valdez, AK	San Fransisco, CA	1	1,715	1,715
Barge					2,914 **(0.03%)**
Transport Mode: Truck					
PADD5 to PADD 5	Assumed Average Intra-PADD Distance		17	150	2,580
Truck					2,580 **(0.03%)**

MBL: thousand barrels of petroleum liquids

Table 2-8: Crude oil transportation distances and quantities for different transport modes to California locations (EIA, 2020)

	Origin Port	Destination Port	PADD5 Import (MBL/d)	Distance (mile)	Multiply of mass and distance (MBL*miles/d)
Transport Mode : Pipeline					
PADD 5 to PADD 5	LA, CA	San Fransisco, CA	84	382	32,088
PADD 5 to PADD 5	Bakersfield, CA	Los Angeles, CA	79	113	8,927
Pipeline					41,015 **(0.56%)**
Transport Mode: Rail					
PADD4 to PADD 5	Salt Lake City	Los Angeles, CA	16	688	11,008
PADD5 to PADD 5	Tacoma, WA	San Fransisco, CA	54	777	41,958
PADD5 to PADD 5	SF, CA	Long Beach, CA	57	405	23,085
Rail					76,051 **(1.05%)**
Transport Mode: Tanker					
SA to PADD 5	Saudi Arabia, Ras Tanura	Los Angeles, CA	453	11,370	5,146,921
EC to PADD 5	Ecuador, Balao terminal	Los Angeles, CA	207	3,005	623,466
CO to PADD 5	Colombia, Barranquilla	Los Angeles, CA	151	3,289	496,283
BR to PADD 5	Belem, Brazil	Los Angeles, CA	89	5,267	467,266
PADD 5 to PADD 5	Valdez, AK	San Fransisco, CA	98	1,715	168,070
PADD 5 to PADD 5	Valdez, AK	Los Angeles, CA	103	2,056	211,768
Tanker					7,115,271 **(98.31%)**
Transport Mode: Barge					
PADD5 to 5	Valdez, AK	Anacortez, WA	1	1,199	1,199
PADD5 to 5	Valdez, AK	San Fransisco, CA	1	1,715	1,715
Barge					2,914 **(0.04%)**

	Origin Port	Destination Port	PADD5 Import (MBL/d)	Distance (mile)	Multiply of mass and distance (MBL*miles/d)
Transport Mode: Truck					
PADD5 to PADD 5	Assumed Average Intra-PADD Distance		17	150	2,550
Truck					2,550 **(0.04%)**

MBL: thousand barrels of petroleum liquids

Table 2-9. Transportation and fuel datasets from GaBi (Schuller, 2020)

Mode	Database (EIA, 2020)	Fuel
Pipeline	GLO: Pipeline average	Electricity power
Ocean Freighter (Oil tanker)	US: Transport, ocean freighter, average fuel mix	Diesel power, Residual fuel oil
Barge Transport	US: Transport, barge, average fuel mix	Diesel power, Residual fuel oil
Rail	US: Transport, train, diesel-powered	Diesel power
Heavy Truck	US: Heavy Heavy-duty Diesel Truck/ 53,333 lb payload- 8b	Diesel power

Table 2-10. Summary of crude oil transportation GWP per transport mode type to PADD5

Transportation Mode	Fuel	GWP per 1000 kg-km [kg CO2e]	Mass-distance allocation (percent of total mass * distance)	Average GWP per mass-distance allocation [kg CO2e per 1000 kg-km]
Pipeline	Electricity power	2.87E-03	4.56%	1.31E-04
Rail	diesel powered	2.20E-02	1.35%	2.97E-04
Oil tanker	Diesel power, Residual fuel oil	1.83E-02	94.03%	1.72E-02
Barge Transport	Diesel power, Residual fuel oil	3.31E-02	0.03%	1.13E-05
Heavy Truck	Diesel power	7.80E-02	0.03%	2.36E-05
Total GWP per 1000 kg-km per all transportation modes				**1.78E-02**

Table 2-11. Summary of crude oil transportation GWP per transport mode type to California

Item	Fuel	GWP per 1000 kg-km [kg CO2e]	Mass-distance allocation (percent of total mass * distance)	Average GWP per mass-distance allocation [kg CO2e per 1000 kg-km]
Pipeline	Electricity power	2.87E-03	0.56%	1.62E-05
Rail	diesel powered	2.20E-02	1.05%	2.30E-04
Oil tanker	Diesel power, Residual fuel oil	1.83E-02	98.31%	1.80E-02
Barge Transport	Diesel power, Residual fuel oil	3.31E-02	0.04%	1.33E-05
Heavy Truck	Diesel power	7.80E-02	0.04%	2.74E-05
Total GWP per 1000 kg-km per all transportation modes				**1.83E-02**

An example of calculating crude oil transportation emission (GWP) can be seen in Table 2-10 and Table 2-11.

2.2.3.1.d. Life Cycle Impact Assessment

TRACI 2.1, which is a Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (Bare, 2008), was selected as impact assessment methodologies so that a comparison of results could be made with the AI report. TRACI 2.1 includes U.S. average conditions to establish characterization factors.

The life cycle impact assessment (LCIA) environmental categories selected in this study include:

- Global Warming Potential (GWP): in kg of CO_{2e}. The evaluation of GWP is based on the characterization factors from Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5), which is currently the most commonly used metric, for a 100-year timeframe (GWP100) (Eurobitume. 2012).
- Ozone depletion potential: in kg CFC-11 eq (A measure of air emissions that contribute to the depletion of the stratospheric ozone layer resulting in higher levels of UVB ultraviolet rays that arrives in the earth) (Butt et al., 2019).

- Photochemical Ozone Creation Potential: in POCP: in kg of O3e in TRACI (a measure of smog formation (SFP)).
- Human Health (PM2.5): in kg of PM2.5 (particulate matters smaller than or equal to 2.5 micrometers in diameter).
- Acidification Potential: in kg SO2 eq (A measure of emissions leading to acidifying effects to the environment.)
- Eutrophication Potential: in kg N eq (A measure of the pollution state of aquatic ecosystems) (Tagliaferri and Lettieri, 2019)
- Water Consumption: in kg (A measure of the net intake and release of freshwater)
- Renewable Primary Energy Demand: used as fuel from renewable resources (net calorific value excluding feedstock energy) in MJ.
- Non-renewable Primary Energy Demand: used as fuel from nonrenewable resources (net calorific value excluding feedstock energy) in MJ.
- Feedstock Energy is Primary Energy Demand" used as a material from nonrenewable resources (also called PED (non-fuel)) in MJ.

Non-renewable and renewable primary energy demand, and feedstock energy were used for reporting energy consumption. According to ISO 14040, feedstock energy is defined as "the heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value" (ISO, 2006). Because asphalt (bitumen) is an oil-based product that is used as a material (not as an energy source), it has high feedstock energy content and is recommended to be reported in LCA studies separately (ISO, 2006; Butt et al., 2019; Ostovar et al., 2020). It should be mentioned that global warming, ozone depletion, and use of non-renewable primary energy demand are impact categories that have global effects (Butt et al., 2019; Butt et al., 2021).

2.2.3.2. LCI and LCIA Results

The asphalt binder LCI covers crude oil mix (material stage) and crude oil transportation (transport from origin well/port to the destination port and refinery, which is collected and calculated in the current study), and refinery processes, transport to the terminal (taken from AI), and terminal storage (taken from AI study (Wildnauer, 2019)). Table 2-12 shows the LCI (energy and water consumption) and LCIA results of the material stage of 1 kg of asphalt binder for PADD 5, and Table 2-15 presents the results for California. Table 2-13, Table 2-14 show the LCI and LCIA results from the transportation of asphalt binder in 2017 for PADD5 and Table 2-16 and Table 2-17 presents the transportation results for California.

Table 2-12. LCI and LCIA results from the material stage of 1 kg of asphalt binder for PADD 5 (data from 2017)

Impact Category and Unit	**U.S. (47%)**	**CAN (53%* 22%= 0.12)**	**SA (53%* 40%= 0.21)**	**CO (53%* 12%= 0.06)**	**EC (53%* 18%= 0.10)**	**BR (53%* 7%= 0.04)**	**Avg. PADD 5**
	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	**Asphalt binder, Crude oil**
IPCC AR5							
Global warming potential [GWP100] kg CO2 eq	3.05E-01	4.22E-01	8.08E-02	1.84E-01	2.60E-01	2.45E-01	2.58E-01
Global warming potential [GWP20] kg CO2 eq	4.06E-01	5.08E-01	8.88E-02	3.08E-01	4.52E-01	3.92E-01	3.50E-01
TRACI 2.1							
Ozone depletion potential kg CFC-11 eq	-8.48E-15	-2.85E-14	-4.46E-16	-3.25E-16	-2.83E-16	-4.39E-16	-7.56E-15
Acidification potential kg SO2 eq	1.28E-03	1.15E-03	3.00E-04	5.20E-04	9.30E-04	9.03E-04	9.63E-04
Eutrophication potential kg N eq	7.30E-05	6.45E-05	1.36E-05	3.12E-05	2.81E-05	5.05E-05	5.16E-05
Smog formation potential kg O3 eq	2.50E-02	2.19E-02	4.49E-03	8.59E-03	8.26E-03	1.62E-02	1.73E-02
Human health particulate effects kg PM2.5 eq	9.21E-05	7.50E-05	1.80E-05	4.07E-05	6.51E-05	6.57E-05	6.77E-05
Resource Use							
Primary Energy (Non-Renewable) (MJ)	4.66E+01	5.03E+01	4.38E+01	4.40E+01	4.50E+01	4.54E+01	4.61E+01
Primary Energy (Renewable) (MJ)	1.40 E-01	3.85 E-01	1.7 E-03	8.43 E-02	7.24 E-02	6.98 E-02	1.28 E-01
Water Consumption (kg)	1.09 E+00	1.62 E+00	8.35 E-01	1.36 E-01	1.18 E-01	2.32 E-01	9.12 E-01

Note: US = United States, CA = Canada, SA = Saudi Arabia, CO = Colombia, EC = Ecuador, and BR = Brazil

Table 2-13. LCI and LCIA results from the transportation for 1 tonne-km functional unit of asphalt binder in 2017 for PADD5

Impact Category and Unit	Transport LCIA for 1 tonne-km functional unit				
	Pipeline-	Ocean Freighter (oil tanker)	Barge Transport	Rail-train	Truck
IPCC AR5					
Global warming potential [GWP100] kg CO2 eq	2.91E-03	1.84E-02	3.33E-02	2.21E-02	7.88E-02
Global warming potential [GWP20] kg CO2 eq	3.36E-03	1.97E-02	3.54E-02	2.36E-02	8.51E-02
TRACI 2.1					
Ozone depletion potential kg CFC-11 eq	1.63E-13	6.85E-13	1.24E-12	8.35E-13	3.31E-12
Acidification potential kg SO2 eq	6.48E-06	3.80E-04	3.79E-04	3.93E-04	4.98E-04
Eutrophication potential kg N eq	3.61E-07	2.05E-05	1.83E-05	2.38E-05	2.86E-05
Smog formation potential kg O3 eq	8.17E-05	1.11E-02	9.58E-03	1.29E-02	9.86E-03
Human health particulate effects kg PM2.5 eq	3.52E-07	1.87E-05	1.96E-05	1.88E-05	2.59E-05
Global Warming Air [kg CO2 eq.]	2.87E-03	1.83E-02	3.31E-02	2.20E-02	7.82E-02
Resource Use					
Primary Energy (Non-Renewable) (MJ)	4.50E-02	2.31E-01	4.17E-01	2.82E-01	1.12E+00
Primary Energy (Renewable) (MJ)	1.50E-02	0	0	0	0
Water Consumption (kg)	6.23E-01	0	0	0	0

Table 2-14. LCI and LCIA results from the transportation of asphalt binder in 2017 for PADD5

Impact Category and Unit	**Transport LCIA for mass-distances allocation for each transport mode**					
	Pipeline	Ocean Freighter (oil tanker)	Barge Transport	Rail-train	Truck	**Total Crude Transport**
IPCC AR5						
Global warming potential [GWP100] kg CO2 eq	1.33E-04	1.73E-02	1.14E-05	2.99E-04	2.36E-05	**1.78E-02**
Global warming potential [GWP20] kg CO2 eq	1.53E-04	1.85E-02	1.21E-05	3.19E-04	2.55E-05	**1.90E-02**
TRACI 2.1						
Ozone depletion potential kg CFC-11 eq	7.44E-15	6.45E-13	4.23E-16	1.13E-14	9.92E-16	**6.65E-13**
Acidification potential kg SO2 eq	2.95E-07	3.57E-04	1.30E-07	5.31E-06	1.49E-07	**3.63E-04**
Eutrophication potential kg N eq	1.65E-08	1.93E-05	6.27E-09	3.22E-07	8.57E-09	**1.96E-05**
Smog formation potential kg O3 eq	3.72E-06	1.05E-02	3.28E-06	1.74E-04	2.95E-06	**1.07E-02**
Human health particulate effects kg PM2.5 eq	1.60E-08	1.76E-05	6.72E-09	2.54E-07	7.77E-09	**1.79E-05**
Global Warming Air [kg CO2 eq.]	1.31E-04	1.72E-02	1.13E-05	2.97E-04	2.34E-05	**1.77E-02**
Resource Use						
Primary Energy (Non-Renewable) (MJ)	2.05E-03	2.17E-01	1.43E-04	3.81E-03	3.34E-04	**2.24E-01**
Primary Energy (Renewable) (MJ)	6.83E-04	0	0	0	0	**6.83E-04**
Water Consumption (kg)	2.84E-02	0	0	0	0	**2.84E-02**

Table 2-15. LCI and LCIA results from the material stage of 1 kg of asphalt binder for California (data from 2017)

Impact Category and Unit	**U.S. (47%)**	**CAN (53%* 22%= 0.12)**	**SA (53%* 40%= 0.21)**	**CO (53%* 12%= 0.06)**	**EC (53%* 18%= 0.10)**	**BR (53%* 7%= 0.04)**	**Avg. PADD 5**
	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	Asphalt binder, Crude oil	**Asphalt binder, Crude oil**
IPCC AR5							
Global warming potential [GWP100] kg CO2 eq	3.05E-01	4.22E-01	8.08E-02	1.84E-01	2.60E-01	2.45E-01	2.25E-01
Global warming potential [GWP20] kg CO2 eq	4.06E-01	5.08E-01	8.88E-02	3.08E-01	4.52E-01	3.92E-01	3.15E-01
TRACI 2.1							
Ozone depletion potential kg CFC-11 eq	-8.48E-15	-2.85E-14	-4.46E-16	-3.25E-16	-2.83E-16	-4.39E-16	-4.51E-15
Acidification potential kg SO2 eq	1.28E-03	1.15E-03	3.00E-04	5.20E-04	9.30E-04	9.03E-04	9.00E-04
Eutrophication potential kg N eq	7.30E-05	6.45E-05	1.36E-05	3.12E-05	2.81E-05	5.05E-05	0.00E+00
Smog formation potential kg O3 eq	2.50E-02	2.19E-02	4.49E-03	8.59E-03	8.26E-03	1.62E-02	1.53E-02
Human health particulate effects kg PM2.5 eq	9.21E-05	7.50E-05	1.80E-05	4.07E-05	6.51E-05	6.57E-05	1.00E-04
Resource Use							
Primary Energy (Non-Renewable) (MJ)	4.66E+01	5.03E+01	4.38E+01	4.40E+01	4.50E+01	4.54E+01	4.54E+01
Primary Energy (Renewable) (MJ)	1.40E-01	3.85E-01	1.70E-03	8.43E-02	7.24E-02	6.98E-02	8.98E-02
Water Consumption (kg)	1.09E+00	1.62E+00	8.35E-01	1.36E-01	1.18E-01	2.32E-01	7.85E-01

Note: US = United States, CA = Canada, SA = Saudi Arabia, CO = Colombia, EC = Ecuador, and BR = Brazil

Table 2-16. LCI and LCIA results from the transportation for 1 tonne-km functional unit of asphalt binder in 2017 for California

Impact Category and Unit	**Transport LCIA for 1 tonne-km functional unit**				
	Pipeline-	Ocean Freighter (oil tanker)	Barge Transport	Rail-train	Truck
IPCC AR5					
Global warming potential [GWP100] kg CO2 eq	2.91E-03	1.84E-02	3.33E-02	2.21E-02	7.88E-02
Global warming potential [GWP20] kg CO2 eq	3.36E-03	1.97E-02	3.54E-02	2.36E-02	8.51E-02
TRACI 2.1					
Ozone depletion potential kg CFC-11 eq	1.63E-13	6.85E-13	1.24E-12	8.35E-13	3.31E-12
Acidification potential kg SO2 eq	6.48E-06	3.80E-04	3.79E-04	3.93E-04	4.98E-04
Eutrophication potential kg N eq	3.61E-07	2.05E-05	1.83E-05	2.38E-05	2.86E-05
Smog formation potential kg O3 eq	8.17E-05	1.11E-02	9.58E-03	1.29E-02	9.86E-03
Human health particulate effects kg PM2.5 eq	3.52E-07	1.87E-05	1.96E-05	1.88E-05	2.59E-05
Global Warming Air [kg CO2 eq.]	2.87E-03	1.83E-02	3.31E-02	2.20E-02	7.82E-02
Resource Use					
Primary Energy (Non-Renewable) (MJ)	4.50E-02	2.31E-01	4.17E-01	2.82E-01	1.12E+00
Primary Energy (Renewable) (MJ)	1.50E-02	0	0	0	0
Water Consumption (kg)	6.23E-01	0	0	0	0

Table 2-17. LCI and LCIA results from the transportation of asphalt binder in 2017 for California

Impact Category and Unit	**Transport LCIA for considering mass import and distances for each transport mode**					
	Pipeline	Ocean Freighter (oil tanker)	Barge Transport	Rail-train	Truck	**Total Crude Transport**
IPCC AR5						
Global warming potential [GWP100] kg CO2 eq	1.65E-05	1.81E-02	1.34E-05	2.33E-04	2.78E-05	**1.84E-02**
Global warming potential [GWP20] kg CO2 eq	1.90E-05	1.93E-02	1.43E-05	2.48E-04	3.00E-05	**1.97E-02**
TRACI 2.1						
Ozone depletion potential kg CFC-11 eq	9.25E-16	6.74E-13	4.98E-16	8.78E-15	1.17E-15	**6.85E-13**
Acidification potential kg SO2 eq	3.67E-08	3.73E-04	1.53E-07	4.13E-06	1.75E-07	**3.78E-04**
Eutrophication potential kg N eq	2.05E-09	2.02E-05	7.37E-09	2.50E-07	1.01E-08	**2.04E-05**
Smog formation potential kg O3 eq	4.63E-07	1.10E-02	3.86E-06	1.36E-04	3.47E-06	**1.11E-02**
Human health particulate effects kg PM2.5 eq	1.99E-09	1.84E-05	7.90E-09	1.98E-07	9.14E-09	**1.86E-05**
Global Warming Air [kg CO2 eq.]	1.63E-05	1.80E-02	1.33E-05	2.31E-04	2.76E-05	**1.83E-02**
Resource Use						
Primary Energy (Non-Renewable) (MJ)	2.55E-04	2.27E-01	1.68E-04	2.96E-03	3.93E-04	**2.31E-01**
Primary Energy (Renewable) (MJ)	8.50E-05	0	0	0	0	**8.50E-05**
Water Consumption (kg)	3.53E-03	0	0	0	0	**3.53E-03**

Table 2-18 and Table 2-19 present the life cycle impact results for 1 kg of the asphalt binder for all stages for PADD 5 and California, respectively. As mentioned earlier, LCIAs from the refinery processes and terminal storage are taken from the AI report (Saboori, 2022).

Table 2-18: LCIA results for PADD 5 for 1 kg of asphalt binder (data from 2017)

Impact Category and Unit	**Crude oil extraction-PADD5**	**Transport from crude oil well/port to PADD5 refinery**	**Refinery**	**Transport to terminal**	**Terminal**	**Total PADD5**
IPCC AR5						
Global warming potential [GWP100] kg CO2 eq	2.58E-01	1.78E-02	7.69E-02	3.30E-02	1.01E-01	**4.87E-01**
Global warming potential [GWP20] kg CO2 eq	3.50E-01	1.90E-02	8.70E-02	3.51E-02	1.17E-01	**6.08E-01**
TRACI 2.1						
Ozone depletion potential kg CFC-11 eq	-7.56E-15	6.65E-13	6.79E-12	4.97E-12	6.41E-12	**1.88E-11**
Acidification potential kg SO2 eq	9.63E-04	3.63E-04	1.68E-04	2.04E-04	1.36E-04	**1.83E-03**
Eutrophication potential kg N eq	5.16E-05	1.96E-05	7.30E-05	9.85E-06	1.76E-05	**1.72E-04**
Smog formation potential kg O3 eq	1.73E-02	1.07E-02	1.76E-03	4.82E-03	3.44E-03	**3.80E-02**
Human health particulate effects kg PM2.5 eq	6.87E-05	1.79E-05	2.21E-05	1.14E-05	1.93E-05	**1.39E-04**

Table 2-19: LCIA results for California for 1 kg of asphalt binder (data from 2017)

Impact Category and Unit	**Crude oil-California**	**Transport from crude oil well/port to California refinery**	**Refinery**	**Transport to terminal**	**Terminal**	**Total California**
IPCC AR5						
Global warming potential [GWP100] kg CO2 eq	2.25E-01	1.84E-02	7.69E-02	3.30E-02	1.01E-01	**4.55E-01**
Global warming potential [GWP20] kg CO2 eq	3.15E-01	1.97E-02	8.70E-02	3.51E-02	1.17E-01	**5.74E-01**
TRACI 2.1						
Ozone depletion potential kg CFC-11 eq	-4.51E-15	6.85E-13	6.79E-12	4.97E-12	6.41E-12	**1.89E-11**
Acidification potential kg SO2 eq	9.00E-04	3.78E-04	1.68E-04	2.04E-04	1.36E-04	**1.79E-03**
Eutrophication potential kg N eq	0.00E+00	2.04E-05	7.30E-05	9.85E-06	1.76E-05	**1.21E-04**
Smog formation potential kg O3 eq	1.53E-02	1.11E-02	1.76E-03	4.82E-03	3.44E-03	**3.64E-02**
Human health particulate effects kg PM2.5 eq	1.00E-04	1.86E-05	2.21E-05	1.14E-05	1.93E-05	**1.71E-04**

2.2.4. Interpretation

Figure 2-9 to Figure 2-12 present the results of the environmental impacts of three stages of asphalt binder production to the gate of the refinery or terminal for PADD 5 and California. The three steps are: a) crude oil extraction and transportation, b) refinery operations and transportation, and c) terminal storage and operations. Figure 2-9 and Figure 2-10 separates the three steps into five steps of asphalt binder supply chain including crude oil extraction and production, transport from the origin port to the destination port and refinery, refinery operations, terminal storage, and transport to the terminal for PADD 5 and California, respectively. Figure 2-11 and Figure 2-12 show the overall contribution at each step in the supply chain for all impacts from the material stage of asphalt binder.

Within the cradle-to-gate life cycle, crude oil extraction and transportation has the highest environmental impacts and energy consumption in most categories, followed by terminal storage. The only impact category showing a different behavior is ozone depletion potential (ODP). The terminal storage has the highest ODP, while ODP from the crude oil has the lowest impact on both PADD 5 and California. A high amount of consumed carbon monoxide in terminals is the reason for the higher amount of ODP in terminals compared to crude oil extraction and refineries. As mentioned in Section 2.2.3.1, the current study has used the refinery and terminal inventories of AI study. According to the AI study, unless terminals can be either co-located with the refinery or off-site, all participating companies were considered off-site, because there is no data available for co-located terminals in AI study.

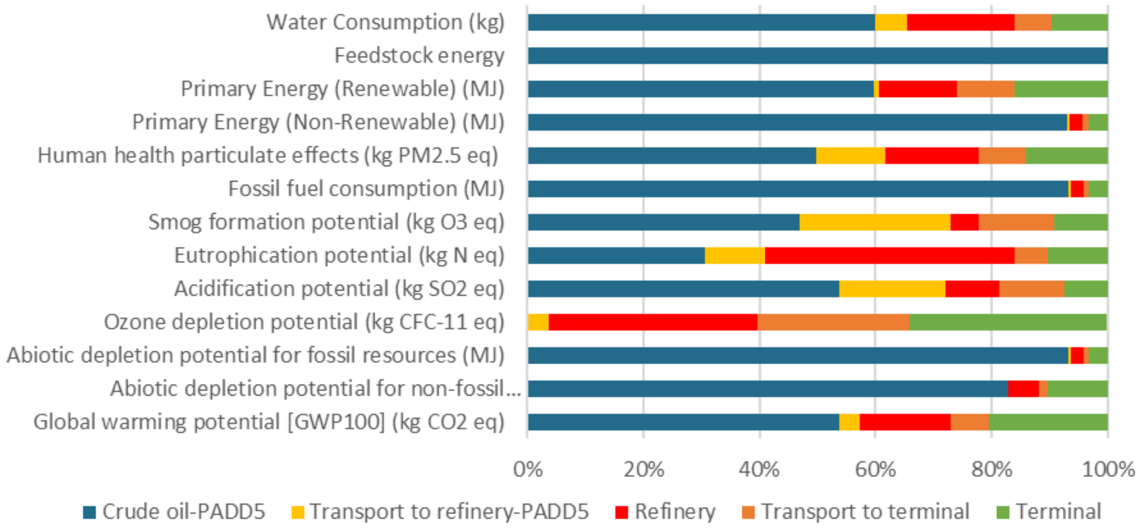


Figure 2-9: Environmental impacts from the asphalt binder material stage for PADD 5

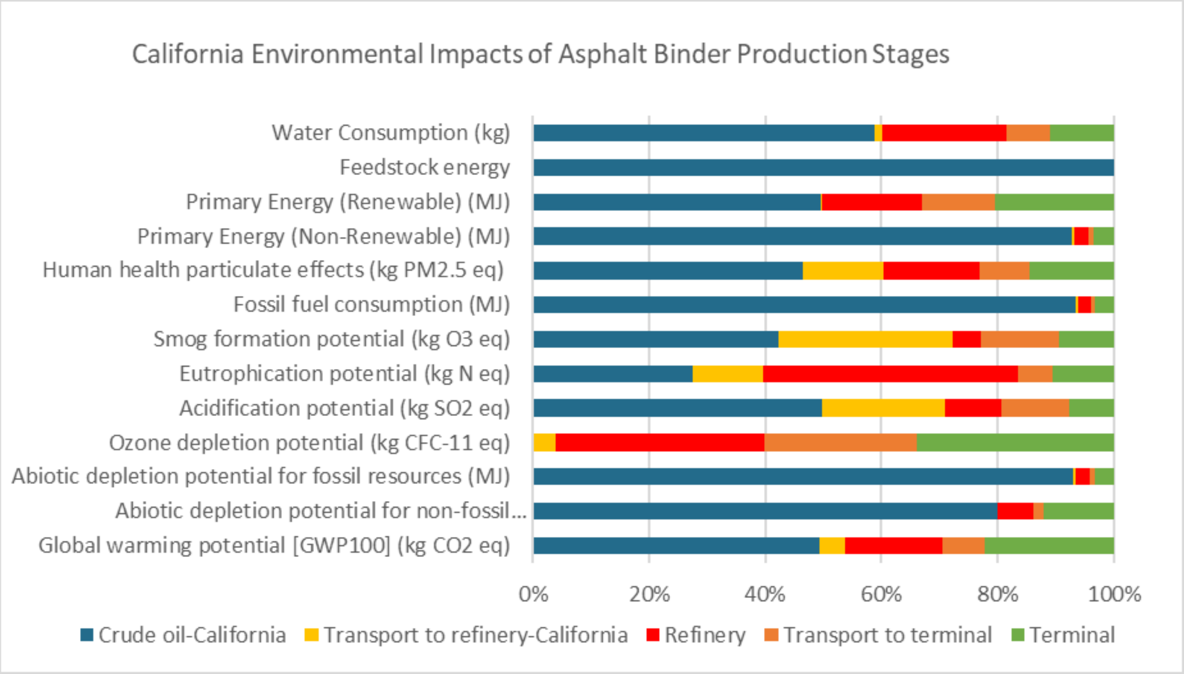


Figure 2-10. Environmental impacts from the asphalt binder material stage for California

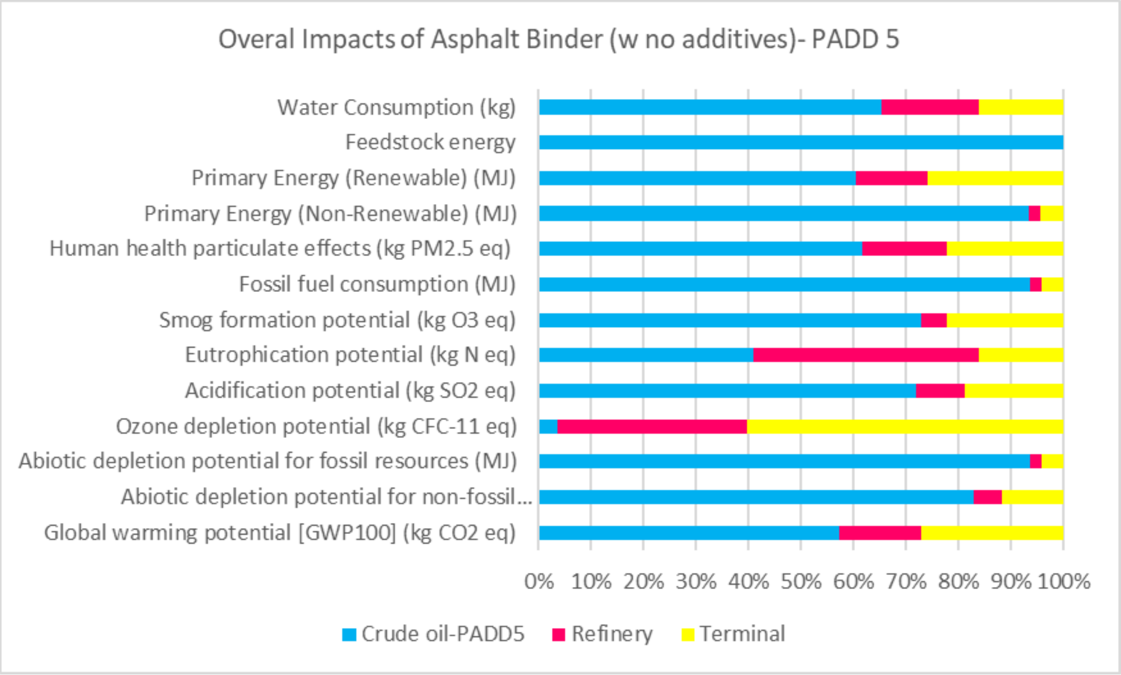


Figure 2-11. PADD 5 overall impacts of asphalt binder

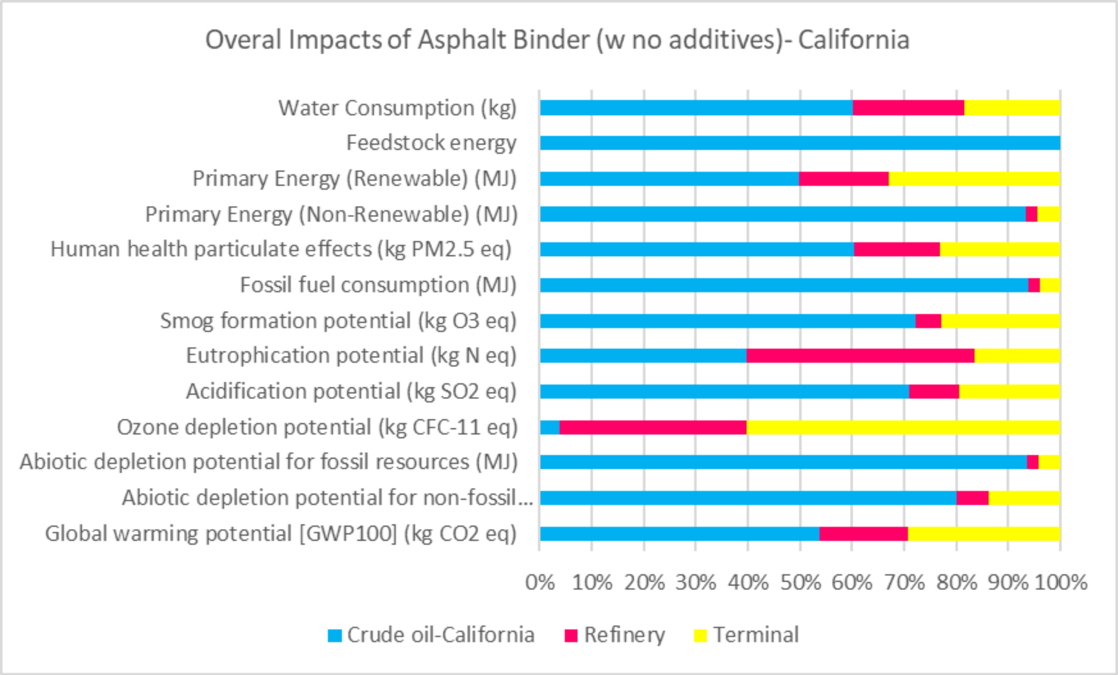


Figure 2-12. California overall impacts of asphalt binder

Figure 2-13 shows the comparison of global warming potential (GWP), as a global impact category, for 1 kg of asphalt binder for different steps for PADD 5, California, and the AI study. California has the lowest GWP, while AI study has the highest GWP results. This difference is due to the percentage of heavy Canadian oil sands in the crude mixes in the AI study compared to PADD5 and California. The heavy oil imported from Canada is 53% of crude input in the AI study (Wildnauer, 2019), 18% in PADD 5 (Table 2-3), and 3% in California (Table 2-5). This difference also causes a difference in Ozone Depletion Potential (ODP), which also is a global impact category (Figure 2-14). Figure 2-15 through Figure 2-21 show the regional environmental impacts and energy consumption for 1 kg of asphalt binder in California, PADD 5, and AI study. In addition, the difference in oil-sand percentage is a notable factor that causes regional emissions and energy consumption changes (Figure 2-15 through Figure 2-21).

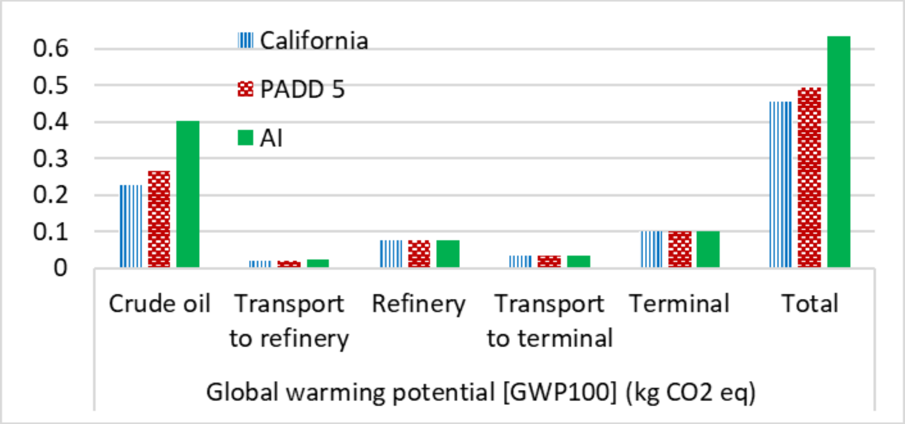


Figure 2-13. Global Warming Potential results for 1 kg of Asphalt binder in California, PADD 5, and AI

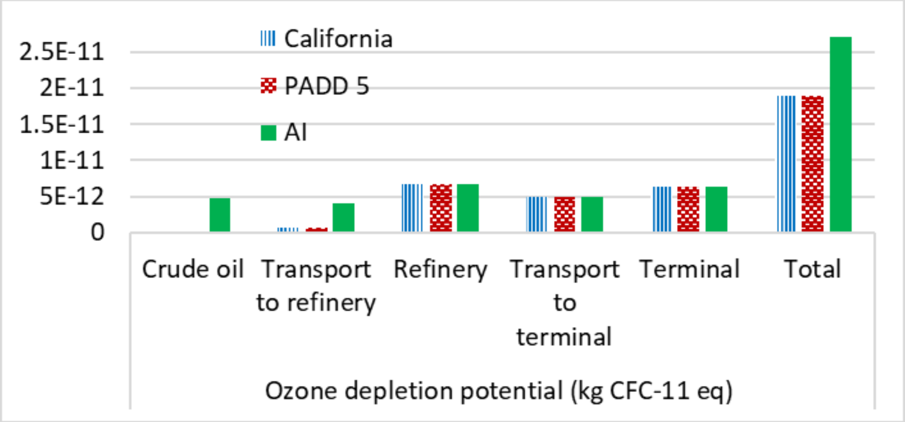


Figure 2-14. Ozone Depletion Potential results for 1 kg of Asphalt binder in California, PADD 5, and AI

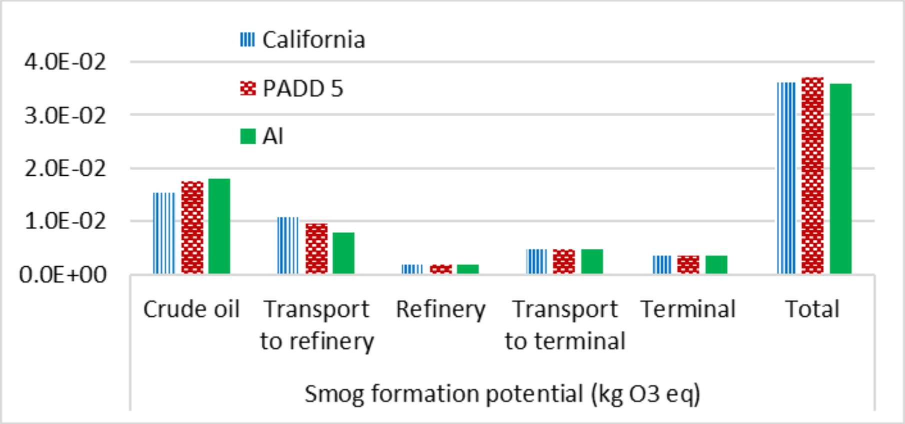


Figure 2-15. Smog Formation Potential results for 1 kg of Asphalt binder in California, PADD 5, and AI

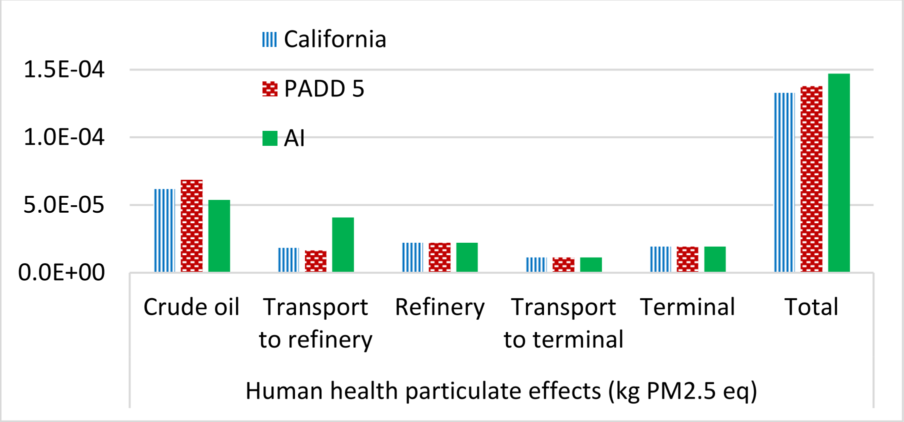


Figure 2-16. Human Health Particulate Effects results for 1 kg of Asphalt binder in California, PADD 5, and AI

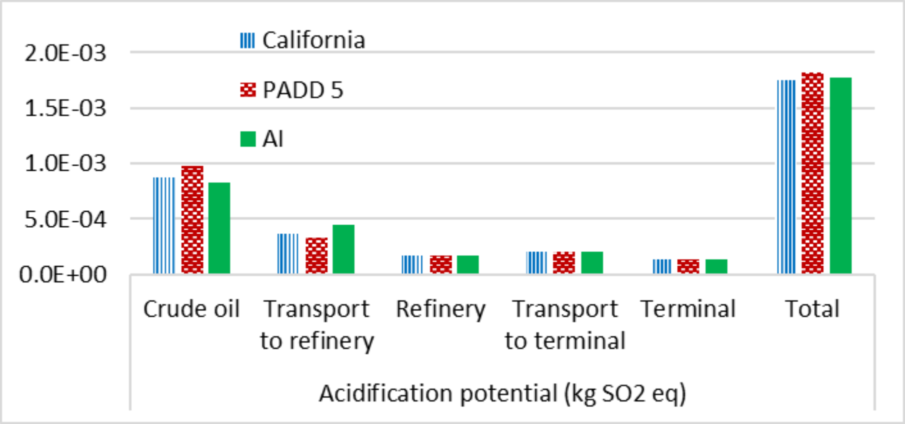


Figure 2-17. Acidification Potential results for 1 kg of Asphalt binder in California, PADD 5, and AI

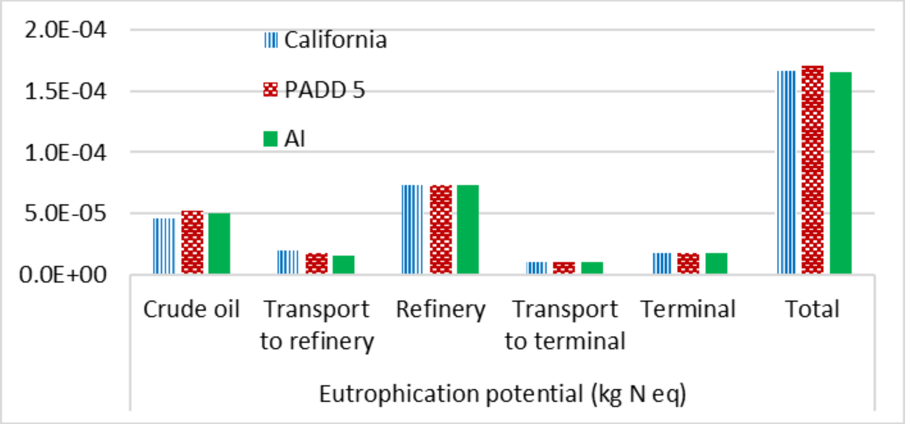


Figure 2-18. Eutrophication Potential results for 1 kg of Asphalt binder in California, PADD 5, and AI

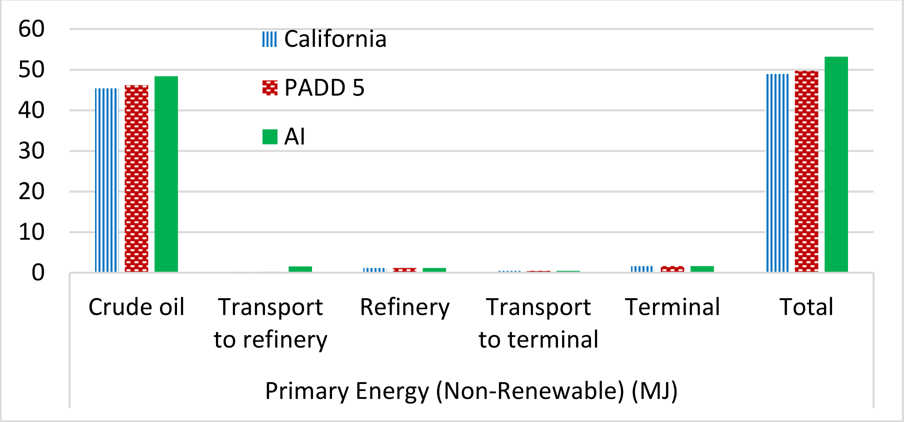


Figure 2-19. Non-Renewable Energy results for 1 kg of Asphalt binder in California, PADD 5, and AI

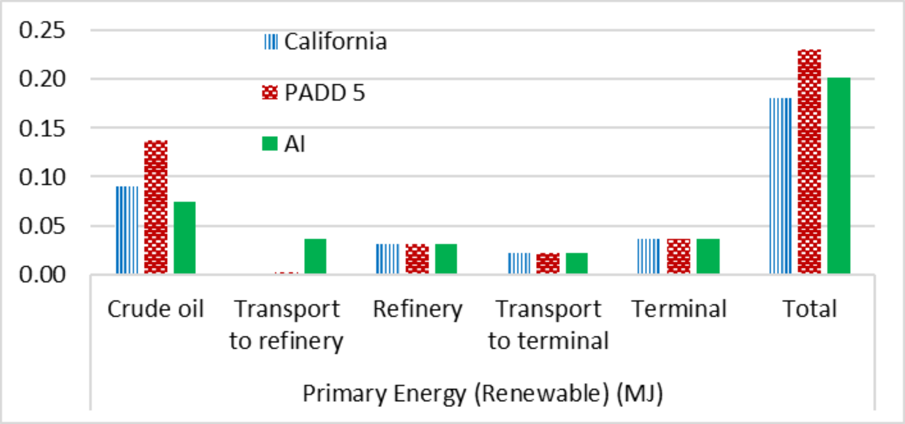


Figure 2-20. Renewable Energy results for 1 kg of Asphalt binder in California, PADD 5, and AI

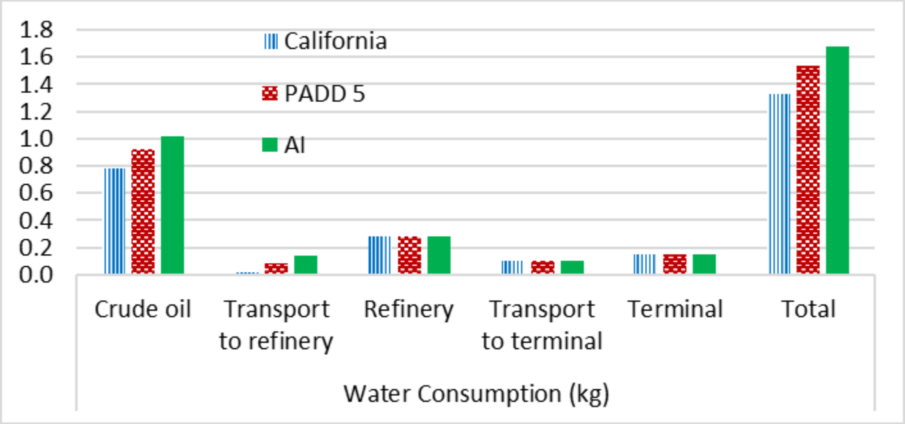


Figure 2-21. Water Consumption results for 1 kg of Asphalt binder in California, PADD 5, and AI

2.2.4.1. Sensitivity Analysis considering Extraction Method

This section presents the differences between California heavy crude oil and the average U.S. heavy crude oil because of the availability of data for California.

According to EIA and CEC (2017), 44% of crude oil brought into California belongs to domestic (inside the U.S.) production, including crude oil production in California and Alaska. Due to a lack of data on the crude oil production of California and Alaska, this study's model used the average U.S. crude oil production data instead of California and Alaska crude oil production data. Since heavy crude oil in California & Alaska is different from the average U.S. heavy crude oil assumed in the current study's model, the percentage of heavy oil in the U.S. average is compared to California& Alaska, and sensitivity analysis is used for the GWP value (Figure 2-8).

Most of California's crude oil is heavy, and 91 percent has an API gravity of less than 30 (EIA, 2020). California's heavy crude oil causes heavy environmental damage because of energy-intensive extraction techniques used to pump oil from the ground (Wolf et al., 2017). The crude oil fields have become more depleted and waterlogged over time. Therefore, extreme extraction technologies are used to loosen the viscous heavy crude oil and push it toward production wells. Common extraction techniques used in California include cyclic steam injection, steam flooding and waterflooding, and fracking (Wolf et al., 2017).

In a cyclic steam injection, steam is injected into the oil well repeatedly. It requires steam generators (huge boilers burning natural gas or other fossil fuels) and the transportation of massive quantities of water to heat the crude within the underground formation and flow up the well more easily (Wolf et al., 2017). In the steam flooding and waterflooding technique, large volumes of steam or water, respectively, are pumped into injection wells to loosen the oil and push it toward the production wells (Wolf et al., 2017). Hydraulic fracturing or fracking is an oil and gas well development process in which large volumes of water, sand, and chemicals are pumped at high pressures into the rock formation, causing it to crack and release oil and gas. In 2016, 3,045 out of 57,000 wells in California used fracking techniques (6 percent fracking) (EIA, 2020; Wolf et al., 2017; Aczel and Makuch, 2017; Ridington et al., 2016; Pacific Institute, 2016; EIA, 2018).

Seventy-five percent of California’s crude oil uses these extreme extraction techniques (Wolf et al., 2017) and is considered as heavy oil ($API \leq 25$). Sixteen percent of California’s crude oil is medium ($25 < API \leq 30$), and 9 percent is light ($API > 30$) based on the data from 2019 (EIA, 2020). In the average U.S. model, almost half of the crude oil extraction is done by fracking technology (EIA, 2020), which uses a tertiary method of extraction, and the other half is extracted using primary and secondary techniques.

Figure 2-22 shows the process diagram presenting the percentage of heavy crude oil brought into California from foreign countries (Foreign) and brought into California from within the U.S. (Domestic). The figure shows how domestic crude oil calculated based on the current study's calculation is different from the domestic crude oil extracted from EIA and CEC in 2017.

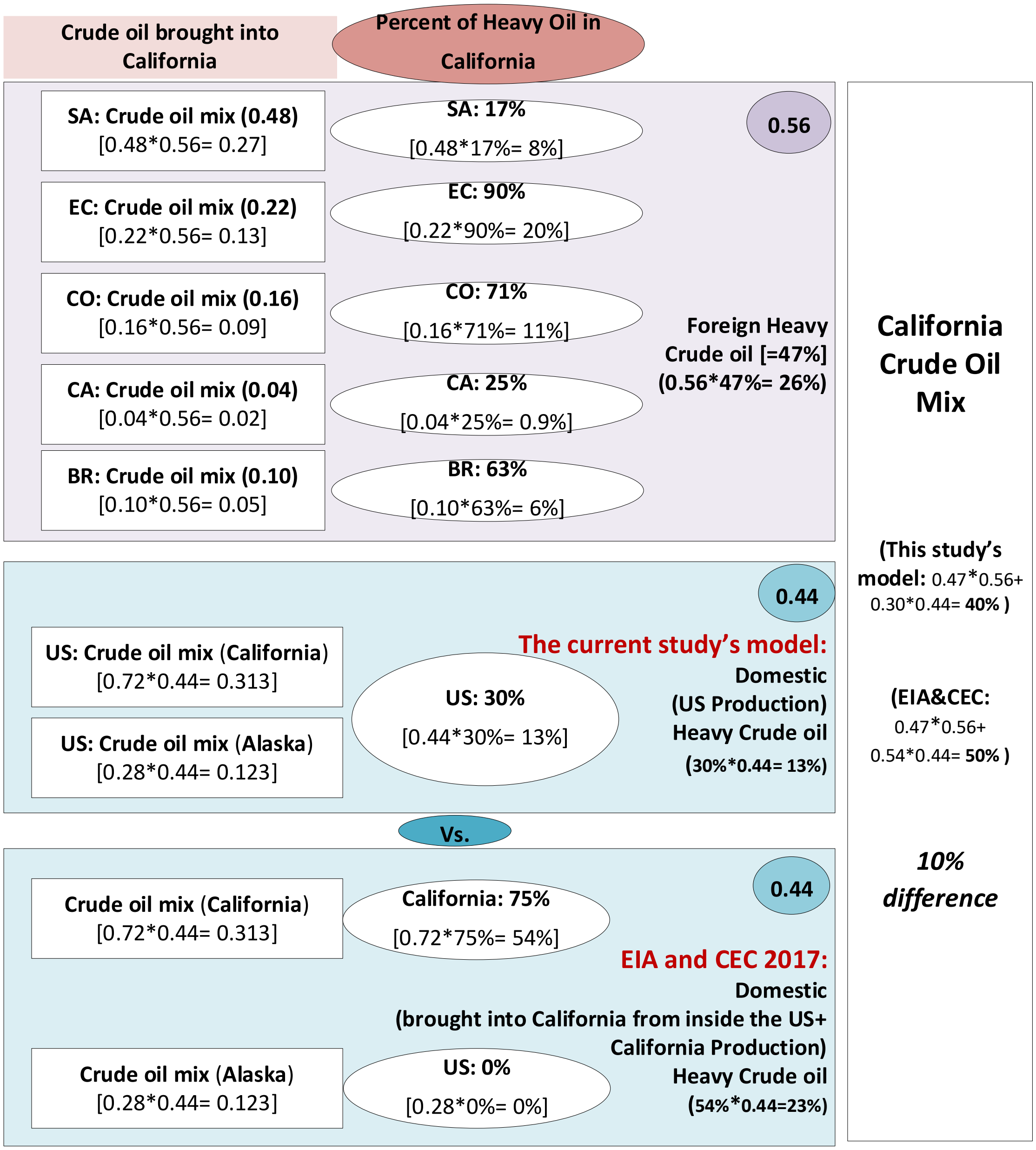


Figure 2-22. California heavy crude oil calculation process diagram

As shown in Figure 2-22, the percentage of heavy crude oil in the U.S. is 30 percent. Hence, the percentage of California heavy crude oil based on the assumptions of this study is calculated to be 13 percent. Based on EIA and CEC (EIA, 2020; California Energy Commission (CEC), 2020b) data, heavy crude oil brought into California from domestic locations (California and Alaska) is calculated to be 23 percent.

Based on the data from Table 2-18, it can be concluded that there is a 10 percent (23%-13%=10%) difference between the heavy crude oil brought into California from domestic locations (California and Alaska) considering the average U.S. crude oil production compared to California's crude oil production.

Table 2-20: California domestic (within the U.S.) heavy crude oil production in 2017

California Domestic heavy crude oil (EIA&CEC)	California Domestic heavy crude oil (This study's model considers the U.S. average)
*0.44*54%*= 23%	*0.44*30%*= 13%

Table 2-21: Crude oil extraction methods as reported in the AI report (Wildnauer et al., 2019)

Crude oil extraction methods	**GWP (kgCO2e)/kg**
Primary extraction	0.1
Secondary extraction	0.2
Tertiary extraction- Natural gas injection	0.25
Tertiary extraction- CO2 injection	0.29
Tertiary extraction- Steam injection	0.59

Table 2-21 compares the Crude oil extraction methods as reported in the AI report. Steam injection is used in most of California's extraction (94%), while the U.S. half uses the primary and secondary extraction methodologies and the other half uses the tertiary extraction methodologies (Wildnauer et al., 2019). Using the extraction impacts shown in Table 2-21 and the calculations shown in the following paragraphs, the GWP reported from the California extraction is almost twice the GWP from the U.S. extraction. The calculation can be seen in the following equation:

*California extraction: [0.94*0.59+ 0.06* (0.59+0.29+0.25)/3]*

U.S. extraction: [(0.5(0.59+0.29+0.25)/3)+ (0.5 * (0.2+0.1)/2)]*

California extraction / U.S. extraction = 2.19

Table 2-20 shows a 10% difference between California's heavy crude oil production assumed in the current study model, considering the U.S. average, and California's heavy crude oil production based on the statistics from CEC and EIA in 2017. Therefore, since the California extraction is almost twice the GWP from the U.S. extraction, the final GWP should be multiplied by 1.22 (*[1+(2.19*10%)= 1.22]*).

Table 2-22 compares the asphalt binder GWP in California, considering two different assumptions explained in the sensitivity analysis. Assumption 1 assumes the U.S. average heavy oil data, while assumption 2 regards the heavy crude oil for California& Alaska.

Table 2-22. California global warming potential before sensitivity analysis vs. after sensitivity analysis

	Impact Category and Unit	**Crude oil-PADD5**	**Transport from crude oil well/port to PADD5 refinery**	**Refinery**	**Transport to terminal**	**Terminal**	**Total PADD5**
Assumption 1	Global warming potential kg CO2 eq	0.2254	1.96E-02	0.0769	0.033	0.101	0.4559
Assumption 2	Global warming potential kg CO2 eq	0.2525	1.96E-02	0.0769	0.033	0.101	0.4829

2.3. LCA of Warm Mix Asphalt Additives, and Case Study

2.3.1. Background

Warm mix asphalt (WMA) is considered a potential means for reducing energy consumption and emissions during the material and construction stages of asphalt concrete (Jones et al., 2011a; Nabizadeh et al., 2017) by allowing for reduced mixing temperatures in the asphalt plant. WMA can also be used with the same mixing temperatures to allow for compaction at lower temperatures at the construction site, which does not reduce energy and emissions from mixing, but can result in better compaction and longer pavement life. When used to reduce mixing temperatures, there are fewer emissions at the construction site as well as the plant, which produces better conditions for workers and neighbors. According to the findings of the UCPRC (Jones et al., 2011a; Jones et al., 2014), the use of warm mix asphalt additives (WMAA) in asphalt mixes, especially in asphalt rubber projects, is encouraged. Studies conducted in European countries and the US have revealed the possibility of reductions in the asphalt concrete mixing and placement temperatures and of potentially related emissions (Cheraghian et al., 2020; Nabizadeh et al., 2022; Hui et al., 2019; Vidal et al., 2013; Tatatri et al., 2012).

In conventional hot mix asphalt (HMA), the asphalt viscosity reduction and aggregate dryness required for thorough coating of aggregates by asphalt binder during the mixing are gained by using heat. Increasing the heat during the mixing reduces the asphalt viscosity and moisture content of the aggregate (dryness); however, in WMA, water, special organic additives, chemical additives, or a combination of the aforementioned are added to the mixture to reduce the viscosity, resulting in an adequate coating of asphalt binder on the aggregate surfaces. The reduction in mixture viscosity also improves workability and compaction at lower temperatures (Jones et al., 2011a; Nabizadeh et al., 2022; Tatatri et al., 2012).

Several studies have been conducted globally to assess the environmental impacts of WMA; however, there are many unanswered questions pertaining to the environmental benefits of WMA. In this study, the life cycle environmental impacts of different types of WMA containing different WMAAs were evaluated and compared to conventional HMA. There is no study on the environmental impacts of WMA performed in California; thus, the UCPRC took the initiative by developing LCI datasets of different WMAA. There are no definitive ingredient lists and proportions, so this study has used the best available knowledge and created proxies. There were also no EPDs for WMA until December 2021, when one was produced by Ingevity (Ingevity, 2022).

2.3.2. Goal and Scope of the Study

This study aims to quantify the potential environmental impacts that occur during the material production stage of WMA. Thus, the scope of the study is from cradle-to-gate, including the materials extraction to transportation to plants, and all the processes conducted in the plant to prepare the final mix. A comparative attributional LCA approach is adopted where life cycle environmental impacts from the production of WMA using different WMAAs are compared with the conventional HMA. The asphalt mix designs are mainly reflecting California specific mix designs. The chemical components of WMAA technologies were obtained from their material safety data sheets (MSDS) and online published materials. The different WMAAs that have been studied and evaluated for environmental impacts include Evotherm DAT (A1), Cecabase RT, Sasobit, Rediset LQ, Advera, Gencor Ultrafoam GX2, SonneWarmix, and Astec Double Barrel

Green. A complete list of WMAA that are authorized to be used in WMA by Caltrans in 2020 (Caltrans, 2020) is shown in Table 2-23 and section 2.3.2.1.

The declared unit defined for this study is 1 kilogram of warm mix asphalt. The intended audience of the study includes local governments, pavement researchers and practitioners, and pavement designers. The transportation stage is considered for WMAAs production plant to the asphalt mix plant. Apart from the transportation of WMAAs to the asphalt mix plant, all the other material transports are not considered in this study as they are common for both HMA and WMA. In order to determine the quantity of natural gas used/consumed to produce different types of WMAs, a sensitivity analysis was conducted in which different data and methods were used.

Figure 2-23 shows the system diagram for calculating WMA impacts.

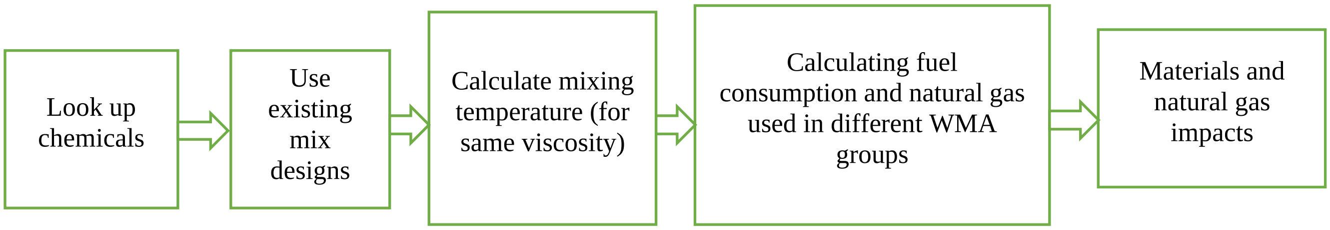


Figure 2-23. System diagram for calculating WMA impacts

2.3.2.1. Product System

Life cycle environmental impacts from three different groups of asphalt mixes are compared in this study:

A. Conventional HMA in which no WMAA is used.
B. WMAAs are added to the asphalt mixtures, but the asphalt mixing temperatures remain the same as conventional HMA.
C. WMAAs are added to the asphalt mixtures, and the asphalt mixing temperatures are reduced due to the addition of additives. The WMAAs are evaluated in terms of their softening points to ensure that the mixing temperature does not go over the WMAAs'

softening points. Reducing the heat during the mixing increases the asphalt viscosity and moisture content of the aggregate. In addition, in WMA, water, special organic additives, chemical additives, or a combination of the these are added to the mixture to reduce the viscosity, resulting in an adequate coating of asphalt binder on the aggregates surface. The reduction in mixture viscosity also improves workability and compaction at lower temperatures (Tagliaferri and Lettieri, 2019; Pacific Institute, 2016).

2.3.2.2. WMA Additives

Caltrans has approved a number of additives that can be used in the production of WMA. The authorized list includes additive technologies and water injection technologies (Ingevity, 2022) as can be seen in Table 3-1.

Table 2-23. Caltrans authorized list for WMAAs (2020) (Ingevity, 2022)

Additive Technologies
Evotherm DAT (A1)
Evotherm 3G (J1, M1)
Rediset LQ
Advera
Cecabase RT
Sasobit
SonneWarmix
Zycotherm SP
Water Injection Technologies
Astec Double Barrel Green
Gencor Ultrafoam GX2
MAXAMA AQUABLACK System

2.3.2.3. Data Collection, Software, and Database

The chemical components of WMAA, were obtained from material safety data sheets (MSDS) and online published materials. UC Davis researcher Dr. Peter Green, an environmental chemistry expert, was consulted for the additives that did not have enough information available online and for the final chemical components' decisions. The WMAAs that are considered in the current study include:

- **Additive Technologies**
  - Evotherm DAT (A1), chemical surfactant technology, referred to as Evotherm in this study
  - Cecabase RT, chemical surfactant technology, referred to as Cecabase in this study
  - Sasobit, organic wax technology, referred to as Sasobit in this study
  - Rediset LQ, chemical surfactant technology referred to as Rediset in this study.
  - Advera, chemical water foaming technology, referred to as Advera in this study
  - SonneWarmix, organic wax technology, referred to as SonneWarmix in this study
- **Water Injection Technologies**
  - Astec Double Barrel Green, water injection technology, referred to as Astec in this study
  - Gencor Ultrafoam GX2, water injection technology, referred to as Gencor in this study

Table 2-24 presents each WMA additive's chemical components, dosage by weight of asphalt binder, and mixing temperature according to each additive's Material Safety Data Sheet (MSDS). The second column of this table shows the exact chemical components derived from the additives' MSDS (PQ Corporation, 2015; Astec Industriees, Inc., 2017; CECA ARKEMA Group, 2017; Vance Brothers, 2017; Sasol, 2016; Nouryon, 2017; Sonneborn Refined Product, 2015). The third column presents those ingredients found in Gabi, which are reviewed and confirmed by Dr. Peter Green (UC Davis environmental chemist faculty member). The GaBi model was developed for each WMA technology based on the chemical components as well as the dosage of each component in the additive.

Table 2-24. Assumed chemical components of WMAA from material safety sheets, their dosage by weight of asphalt binder, and asphalt mixing temperatures (Schuller et al., 2019)

WMAA	**WMAA's ingredients based on MSDS**	**WMAAs' ingredients found in GaBi (2019)**	**Dosage by Weight of Asphalt Binder (%)**	**Asphalt Concrete Mixing Temperatures**
Additive Technologies				
Advera	Zeolite	Aluminum silicate (Zeolite type A) (80%)	4.5	295 F (145 C)
	Water	Water (20%)	(Range: 0.2-5)	
Evotherm	Hydrochloride Salt of Fatty Amine derivatives	Hexamethylenediamine (HMDA) (30%)	0.5	248 F (125 C)
	Water	Water (70%)	(Range: 0.375-0.5)	Range: 125-135 C
SonneWarmix	Paraffineic Hydrocarbons	Wax/Paraffins	0.7 (Range: 0.50-1)	295 F (145 C) >230 ˚C
CECABASE	Tetraethylenepentamine	HMDA (96.9%)	0.5	295 F (145 C)
	Propanol, 1(or 2)-[methyl-2-(methyl-2-propoxyethoxy)ethoxy]	Propylene glycol (3%)	(Range: 0.2-0.5)	
	Potassium hydroxide	Potassium hydroxide (KOH) (0.1%)		
Sasobit	Wax	Wax/ Paraffins	1.5 (Range: 1-3)	300 F (149 C) < 230˚F/ 446˚C
Rediset	Including Amine	HMDA	2 (Range: 0.3-3)	285 F (140 C) 20-35°C lower than HMA
Water Injection Technologies				
Astec	Water	Water	1.5 (Range: 0.0012-1.5)	295 F (145 C)
Gencor	Water	Water	1.5 (Range: 0.0012-1.5)	285 F (140 C)

GaBi was also used for modeling the different groups of mix types. Figure 2-24 through Figure 2-31 show the process diagram used for modeling the different groups of mix types.

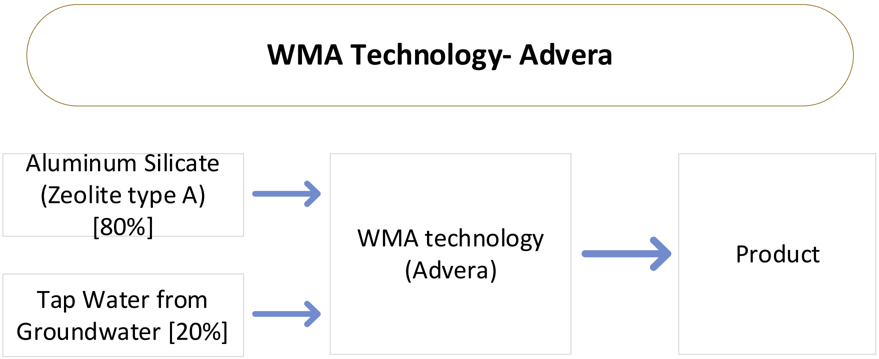


Figure 2-24. Process diagram used for modeling WMA technology- Advera

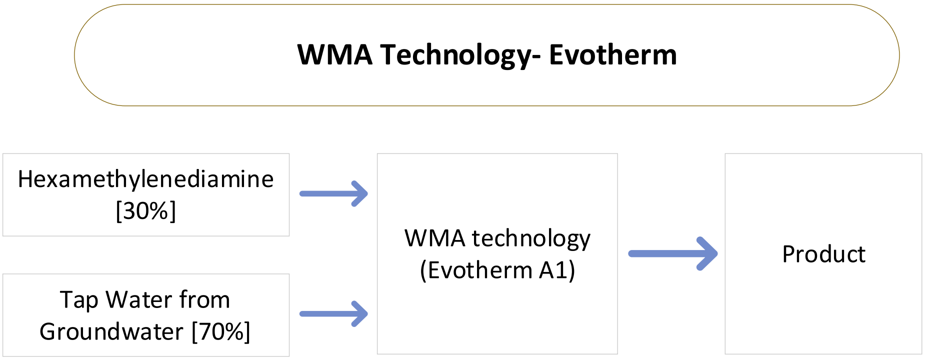


Figure 2-25. Process diagram used for modeling WMA technology- Evotherm

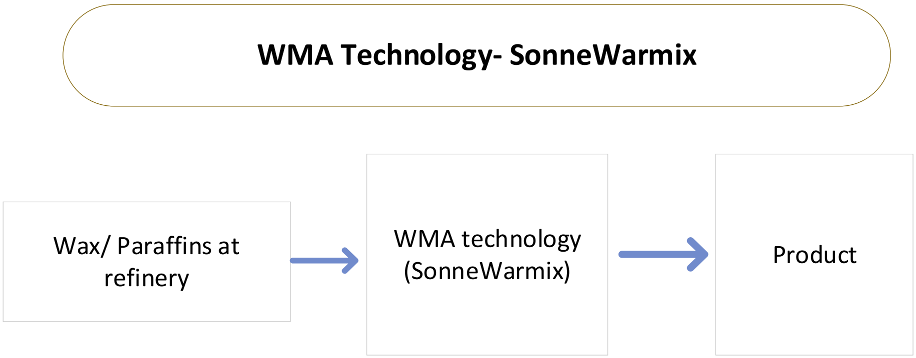


Figure 2-26. Process diagram used for modeling WMA technology- SonneWarmix

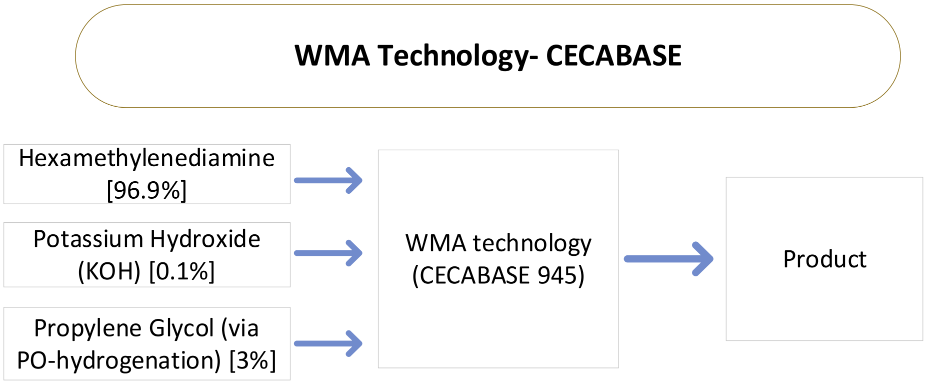


Figure 2-27. Process diagram used for modeling WMA technology- CECABASE

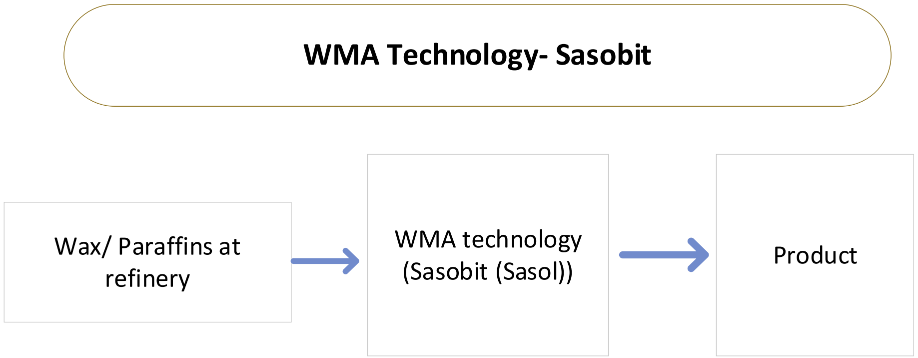


Figure 2-28. Process diagram used for modeling WMA technology- Sasobit

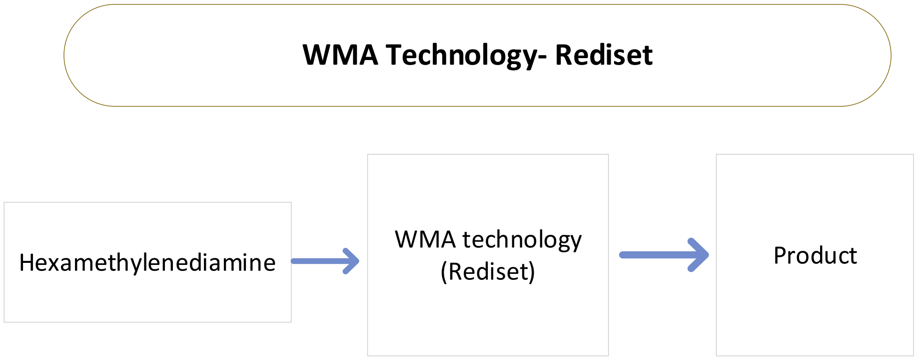


Figure 2-29. Process diagram used for modeling WMA technology- Rediset

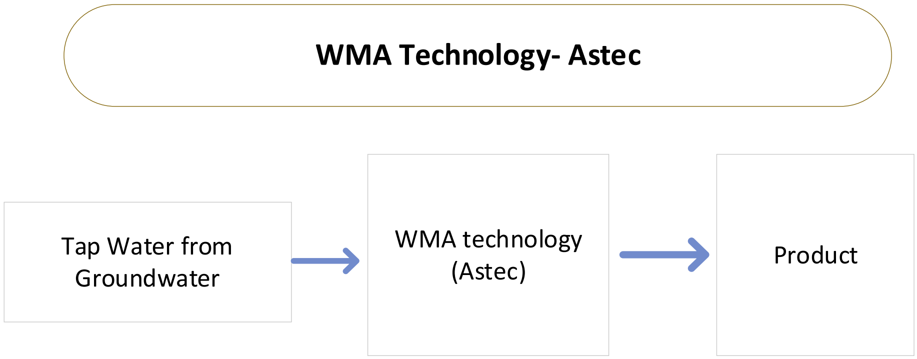


Figure 2-30. Process diagram used for modeling WMA technology- Astec

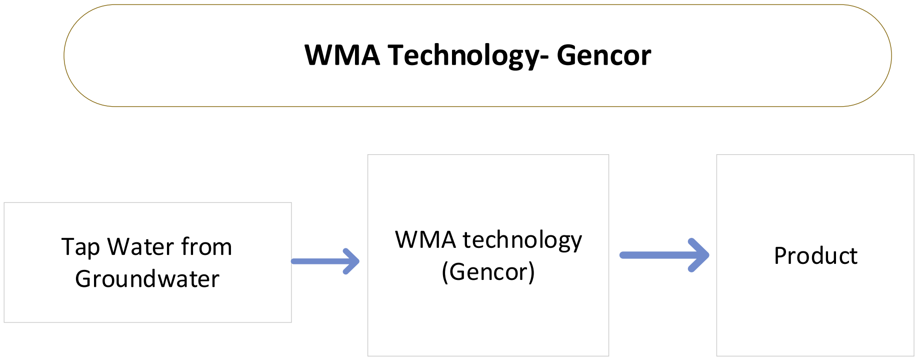


Figure 2-31. Process diagram used for modeling WMA technology- Gencor

2.3.3. Life Cycle Inventory and Life Cycle Impact Assessment

2.3.3.1. Life Cycle Inventory

This study used the GaBi software to develop models for different asphalt mixes. Different non-rubberized and rubberized asphalt concrete mix designs are presented in Table 2-25 and Table 2-26, respectively, based on a UCPRC research report that evaluated the mix properties and performance under accelerated pavement testing of the WMA technologies shown (Jones et al., 2011b; Jones et al., 2014).

Table 2-27, Table 2-28, Table 2-29, and Table 2-30 present the asphalt concrete mixing temperatures that are used to calculate the natural gas consumption, unit conversion tables for fuel consumption, and the calculation of natural gas for the different WMAs, respectively. Three different groups of asphalt mixes are considered in this study, including:

A. Conventional hot mix asphalt: There is no WMA technology additive, and the mixing temperature does not change.
B. WMA technologies are added, but the mixing temperature does not change.
C. WMA technologies are added, and the mixing temperature is reduced.

Table 2-25. Mix designs for different groups of non-rubberized asphalt concrete mixes (Dosage by weight of asphalt concrete mix) in percentages

Asphalt Concrete Mix Types	Aggregate	Virgin Asphalt Binder	WMAA	Total Asphalt Binder in the Mix
Conventional HMA	93.46%	6.54%	-	6.54%
WMA-Advera	93.18%	6.52%	0.29%	6.82%
WMA-Evotherm A1	93.43%	6.54%	0.033%	6.57%
WMA-SonneWarmix	93.42%	6.54%	0.046%	6.59%
WMA-CECABASE	93.43%	6.54%	0.0266%	6.57%
WMA-Sasobit	93.37%	6.54%	0.0986%	6.63%
WMA-Rediset	93.34%	6.53%	0.131%	6.66%
WMA-Gencor	93.37%	6.54%	0.098%	6.63%
WMA-Astec	93.37%	6.54%	0.098%	6.63%

Table 2-26. Mix designs for different groups of rubberized asphalt concrete mixes (Dosage by weight of asphalt concrete mix) in percentages

Asphalt Concrete Mixe Types	Aggregate	Virgin Asphalt Binder	Crumb Rubber	Extender oil	WMAA	Total Asphalt Binder in the Mix
Conventional RHMA	92.19%	6.453%	1.226%	0.13%	-	7.80%
RWMA-Advera	91.92%	6.435%	1.223%	0.13%	0.290%	8.08%
RWMA-Evotherm A1	92.13%	6.449%	1.225%	0.16%	0.032%	7.87%
RWMA-SonneWarmix	92.15%	6.451%	1.226%	0.13%	0.045%	7.85%
RWMA-CECABASE	92.14%	6.450%	1.225%	0.16%	0.026%	7.86%
RWMA-Sasobit	92.10%	6.447%	1.225%	0.13%	0.097%	7.90%
RWMA-Rediset	92.07%	6.445%	1.225%	0.13%	0.129%	7.93%
RWMA-Gencor	92.10%	6.447%	1.225%	0.13%	0.097%	7.90%
RWMA-Astec	92.10%	6.447%	1.225%	0.13%	0.097%	7.90%

Table 2-27. Asphalt concrete mix temperature used to calculate natural gas consumption

Group	Asphalt Concrete Mix Types	Aggregate Temperature F° (˚C)	Binder Temperature F° (˚C)	Mix Temperature F° (˚C)
A	HMA	358 (181)	331 (166)	-
B	WMA-Advera	358 (181)	331 (166)	356 (180)
	WMA-Evotherm A1	347 (175)	320 (160)	346 (174)
	WMA-SonneWarmix	358 (181)	331 (166)	356 (180)
	WMA-CECABASE	347 (175)	320 (160)	346 (174)
	WMA-Sasobit	358 (181)	331 (166)	356 (180)

	WMA-Rediset	358 (181)	331 (166)	356 (180)
	WMA-Gencor	358 (181)	331 (166)	356 (180)
	Astec Double Barrel	358 (181)	331 (166)	356 (180)
C	WMA-Advera	320 (160)	293 (145)	318 (159)
	WMA-Evotherm A1	284 (140)	257 (125)	282 (139)
	WMA-SonneWarmix	320 (160)	293 (145)	318 (159)
	WMA-CECABASE	293 (145)	266 (130)	291 (144)
	WMA-Sasobit	327 (164)	300 (149)	325 (163)
	WMA-Rediset	311 (155)	284 (140)	309 (154)
	WMA-Gencor	311 (155)	284 (140)	309 (154)
	Astec Double Barrel	320 (160)	293 (145)	318 (159)

Table 2-28. Unit conversion tables for fuel consumption

Volume	1 ft^3	0.0283 m^3
Energy	1 BTU	1.0550 kJ

Table 2-29. Energy content of natural gas and diesel

Natural Gas (NG)	1 ft^3	1037 Btu
Diesel	1 Gallon	135 ft^3 of NG
Natural Gas (NG)	1 m^3	38,637.7 kJ
Electricity*	1 kg	0.00618 MJ

**The electricity input to produce 1 kg of WMA is reported to be 0.00618 MJ.*

2.3.3.1.a. Example of calculation of natural gas use for mixing: WMA with Advera in group C

WMA with Advera is shown here as an example to show how to calculate natural gas consumption. The first step is to calculate the final mixing temperature, including the aggregate temperature and WMA mix temperature, considering the amounts of aggregate and total asphalt binder in the mix. It should be mentioned that Aggregate and asphalt binder do not heat at the same temp to minimize the aging of the binder.

Mix temperature= Aggregate temperature (160˚C) * Aggregate content in the mix (0.9318) + Binder temperature (145 ˚C) * Total Asphalt binder content in the mix (0.0682)= 159 ˚C

Then, the following equation is used to calculate the energy (E) for each type of WMA. Specific heat (C) is the energy needed to raise a unit mass of a substance by one unit of temperature kJ/kg•C. The specific heat of asphalt is about 900 J/kg•˚C or (0.9 kJ/kg•˚C).

$$E= m.c.\Delta\theta \qquad \text{Eq. (1)}$$

m: the mass of the material heated up (in kg)
c: the specific heat capacity (in kJ/kg•˚C)
$\Delta\theta$: the difference in temperature due to the work done on the substance (in degrees Celsius (˚C))

Another factor to be considered in the calculation of the used natural gas is energy for vaporization of water, which is 2,260 kJ/kg (NREL, 2004). Assuming 3% moisture meaning 30 kg water per tons of aggregate, 67.8 KJ/kg, as an energy for vaporization of water, is added to the energy from Eq (1). Then 75% of natural gas fired burners efficiency (Jay, 2019) is assumed to calculate the natural gas for different WMAs.

Next, cubic meter of natural gas used in the production of WMA with Advera is calculated as an example.

WMA Energy (*Cubic meter of Natural Gas / kg*)= [(0.9 *kJ/kg•˚C* * 180 °*C*) + 2260* 0.03]/ 0.75 / 38,637.7423 *kJ* (Table 2-28) = 0.00793 m^3/kg

This study used the 2017 electricity grid mix for California to calculate the environmental impacts of asphalt concrete mixes. The electricity input to produce 1 kg of WMA is reported to be 0.00618 MJ (Department of Industrial Ecology, 2016).

Table 2-30. The calculation of natural gas for the different WMAs

Group	**Asphalt Concrete Mix Types**	**HMA/WMA Mix Temperature F˚ (˚C)**	**HMA/WMA Fuel (kJ NG/kg)**	**HMA/WMA NG (m^3)/ kg**	**HMA/WMA NG (ft^3)/ lb**
A	HMA	180	162.02	0.00793	0.12704
B	Advera	180	162.02	0.00793	0.12704
	Evotherm	174	156.62	0.00774	0.12405
	SonneWarmix	180	162.02	0.00793	0.12704
	CECABASE	174	156.62	0.00774	0.12405
	Sasobit	180	162.02	0.00793	0.12704
	Rediset	180	162.02	0.00793	0.12704
	Gencor	180	162.02	0.00793	0.12704
	Astec	180	162.02	0.00793	0.12704
C	Advera	159	143.12	0.00728	0.11659
	Evotherm	139	125.12	0.00666	0.10664
	SonneWarmix	159	143.12	0.00728	0.11659
	CECABASE	144	129.62	0.00681	0.10913
	Sasobit	163	146.72	0.00740	0.11858
	Rediset	154	138.62	0.00712	0.11410
	Gencor	154	138.62	0.00712	0.11410
	Astec	159	143.12	0.00728	0.11659

2.3.3.2. Life Cycle Impact Assessment

In

Table 2-31, the life cycle impact results per 1 kg of the WMAAs during the material production as well as the transport to the plant are presented. As mentioned before, there were lso no EPDs for WMA until December 2021, when one was produced by Ingevity (Vidal et. al., 2018). The EPD's GWP, which shows 5.64 kgCO2e for GWP of Evotherm M, is comparable with Evotherm A shown in

Table 2-31.

In Table 2-32 and Table 2-33, the life cycle impact results per 1 kg of the non-rubberized and rubberized mix asphalt are presented for different groups of asphalt concrete in California, respectively.

Table 2-31. Impacts of Material and transport for Functional Unit (1 kg of WMA additive) during WMAA Production

Item	Unit	Material Production					Transport to the Plant				
		GWP [kg CO$_2$e]	**Smog** [kg O$_3$e]	**PM 2.5 [kg]**	**PED-R [MJ]**	**PED-NR [MJ]**	**GWP [kg CO$_2$e]**	**Smog [kg O$_3$e]**	**PM 2.5 [kg]**	**PED-R [MJ]**	**PED-NR [MJ]**
Advera	1 kg	2.83E+00	1.36E-01	7.51E-04	1.18E+00	4.01E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Evotherm	1 kg	2.16E+00	7.95E-02	1.70E-04	4.01E-01	4.32E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
SonneWarmix	1 kg	1.12E+00	3.93E-02	2.00E-04	4.63E-01	5.47E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
CECABASE	1 kg	7.09E+00	2.63E-01	5.71E-04	1.38E+00	1.42E+02	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Sasobit	1 kg	1.12E+00	3.93E-02	2.00E-04	4.63E-01	5.47E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Rediset	1 kg	7.19E+00	2.65E-01	5.68E-04	1.34E+00	1.44E+02	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Gencor	1 kg	2.26E-04	9.56E-06	4.53E-08	1.30E-04	2.38E-03	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Astec	1 kg	2.26E-04	9.56E-06	4.53E-08	1.30E-04	2.38E-03	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01

Table 2-32. Life Cycle Impacts from the Material Stage of 1 kg of Non-Rubberized Asphalt Concrete Mixtures

Group	Asphalt Concrete Mix types	GWP [kg CO_{2e}]	POCP [kg O_{3e}]	$PM_{2.5}$ [kg]	PED-R [MJ]	PED-NR [MJ]	PED-FS [MJ]
Group A (No Additives-No Temperature Change)	HMA	5.21E-02	6.26E-03	3.84E-05	8.05E-02	3.57E+00	4.14E+01
Group B (Additives- No Temperature Change)	WMA-Advera	5.21E-02	6.26E-03	3.83E-05	8.03E-02	3.56E+00	4.14E+01
	WMA-Evotherm	5.22E-02	6.27E-03	3.82E-05	8.05E-02	3.57E+00	4.14E+01
	WMA-SonneWarmix	5.26E-02	6.28E-03	3.85E-05	8.07E-02	3.59E+00	4.14E+01
	WMA-CECABASE	5.16E-02	6.25E-03	3.82E-05	8.04E-02	3.56E+00	4.14E+01
	WMA-Sasobit	5.20E-02	6.26E-03	3.84E-05	8.04E-02	3.56E+00	4.14E+01
	WMA-Rediset	6.14E-02	6.61E-03	3.91E-05	8.21E-02	3.75E+00	4.14E+01
	WMA-Astec	5.20E-02	6.26E-03	3.84E-05	8.04E-02	3.56E+00	4.14E+01
	WMA-Gencor	5.20E-02	6.26E-03	3.84E-05	8.04E-02	3.56E+00	4.14E+01
Group C (Additives- Lower Temperature)	WMA-Advera	5.05E-02	6.22E-03	3.75E-05	8.03E-02	3.53E+00	4.14E+01
	WMA-Evotherm	4.96E-02	6.21E-03	3.68E-05	8.05E-02	3.53E+00	4.14E+01
	WMA-SonneWarmix	5.10E-02	6.25E-03	3.76E-05	8.07E-02	3.57E+00	4.14E+01
	WMA-CECABASE	4.94E-02	6.20E-03	3.69E-05	8.04E-02	3.52E+00	4.14E+01
	WMA-Sasobit	5.07E-02	6.23E-03	3.77E-05	8.04E-02	3.54E+00	4.14E+01
	WMA-Rediset	5.94E-02	6.56E-03	3.81E-05	8.21E-02	3.72E+00	4.14E+01
	WMA-Astec	5.05E-02	6.22E-03	3.75E-05	8.04E-02	3.54E+00	4.14E+01
	WMA-Gencor	5.01E-02	6.22E-03	3.73E-05	8.04E-02	3.53E+00	4.14E+01

Table 2-33. Life Cycle Impacts from the Material Stage of 1 kg of Rubberized Asphalt Concrete Mixtures

Group	Asphalt Concrete Mix types	GWP [kg CO_{2e}]	POCP [kg O_{3e}]	$PM_{2.5}$ [kg]	PED-R [MJ]	PED-NR [MJ]	PED-FS [MJ]
Group A (No Additives- No Temperature Change)	RHMA	5.25E-02	6.21E-03	3.90E-05	9.52E-02	3.56E+00	4.14E+01
Group B (Additives- No Temperature Change)	RWMA-Advera	5.25E-02	6.20E-03	3.89E-05	9.50E-02	3.53E+00	4.14E+01
	RWMA-Evotherm	5.27E-02	6.22E-03	3.88E-05	9.53E-02	3.54E+00	4.14E+01
	RWMA-SonneWarmix	5.30E-02	6.23E-03	3.91E-05	9.54E-02	3.56E+00	4.14E+01
	RWMA-CECABASE	5.20E-02	6.20E-03	3.87E-05	9.52E-02	3.53E+00	4.14E+01
	RWMA-Sasobit	5.25E-02	6.21E-03	3.89E-05	9.51E-02	3.54E+00	4.14E+01
	RWMA-Rediset	6.17E-02	6.55E-03	3.97E-05	9.68E-02	3.72E+00	4.14E+01
	RWMA-Astec	5.25E-02	6.21E-03	3.89E-05	9.51E-02	3.54E+00	4.14E+01
	RWMA-Gencor	5.25E-02	6.21E-03	3.89E-05	9.51E-02	3.54E+00	4.14E+01
Group C (Additives- Lower Temperature)	RWMA-Advera	5.09E-02	6.17E-03	3.80E-05	9.50E-02	3.50E+00	4.14E+01
	RWMA-Evotherm	5.01E-02	6.17E-03	3.73E-05	9.53E-02	3.50E+00	4.14E+01
	RWMA-SonneWarmix	5.14E-02	6.19E-03	3.82E-05	9.54E-02	3.54E+00	4.14E+01
	RWMA-CECABASE	4.98E-02	6.15E-03	3.75E-05	9.52E-02	3.49E+00	4.14E+01
	RWMA-Sasobit	5.12E-02	6.18E-03	3.83E-05	9.51E-02	3.51E+00	4.14E+01
	RWMA-Rediset	5.98E-02	6.50E-03	3.86E-05	9.68E-02	3.69E+00	4.14E+01
	RWMA-Astec	5.09E-02	6.17E-03	3.81E-05	9.51E-02	3.51E+00	4.14E+01
	RWMA-Gencor	5.05E-02	6.16E-03	3.79E-05	9.51E-02	3.50E+00	4.14E+01

2.3.4. Interpretation

The LCIA results reveal that the combination of WMA mixing temperature, the chemical components of the WMA technologies, and the dosage of additives in the mix are the three main factors influencing the final environmental emissions. Figure 2-32 shows the comparison of GWP, as a global impact category, for 1 kg of non-rubberized asphalt concrete mix types considered in this study. As expected, group C has a lower GWP compared to group B (almost 3%) due to the reduced temperatures and natural gas consumption during the production of the WMA. This figure also shows the WMA with Rediset as the most impactful WMA technology, while the CECABASE has the lowest GWP compared to the other additives. The temperature used in the mixture of WMA with Rediset is not the highest temperature among the other WMA technologies. Therefore, the chemical components used in Rediset, including hexamethylenediamine (HMDA), as well as the dosage of Rediset in the mix (0.13%), are the reasons for this high amount of GWP. HMDA is a colorless, low-melting solid with an important industrial use that produces toxic oxides of nitrogen during combustion. It is the starting material for manufacturing nylon 6-6, which is a polyamide used widely in textiles and plastics. HMDA is also used in the production of polymers (Smiley, 2000).

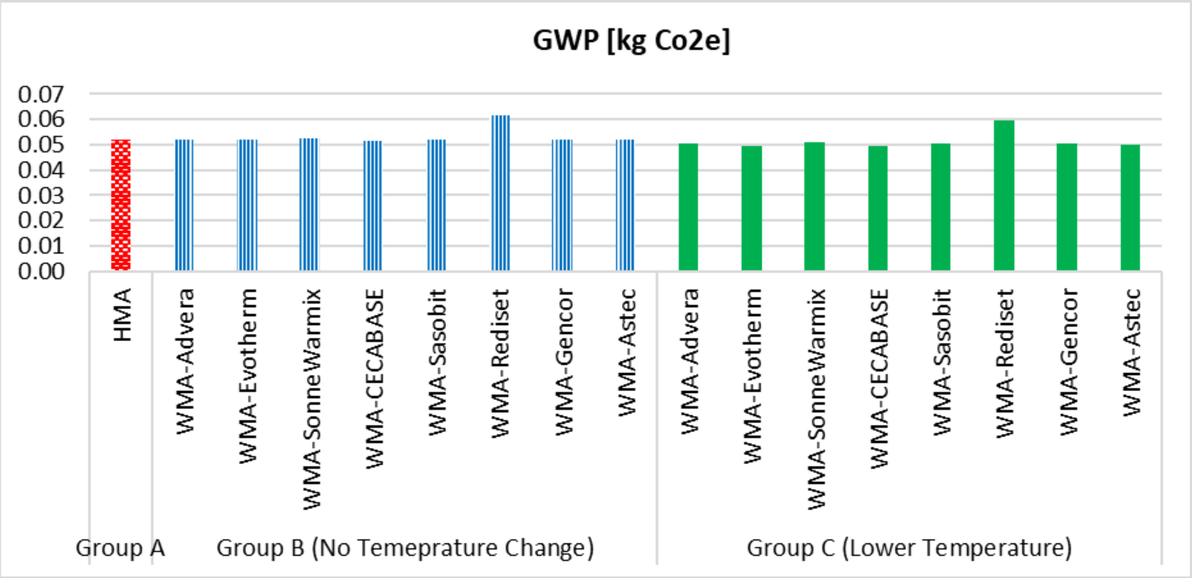


Figure 2-32. Global Warming Potential results for 1 kg of Non-Rubberized Warm Mix Asphalt

Figure 2-33 through Figure 2-36 show the regional environmental impacts and energy consumption for 1 kg of non-rubberized WMA in California. As can be observed from these Figures, WMA-Rediset has the highest smog formation potential, human health particulate effects, as well as renewable energy and non-renewable energy consumption, while WMA-CECABASE and WMA-Advera have the lowest impacts in PM2.5 and PED-NR, and in smog formation and PED-R, respectively.

WMA-CECABASE’s mixing temperature is lower than most of the WMAs, which presents the importance of mixing temperature in WMA-CECABASE’s low environmental impacts. The lower dosage of WMA-CECABASE in the mix, compared to other additives, is another important factor that results in WMA-CECABASE’s low environmental impacts. WMA-Advera’s mixing temperature (295˚F) is higher than WMA-Rediset’s mixing temperature (285˚F). However, WMA-Rediset has the highest environmental impacts. It reveals that the role of chemical components and the dosage of additives used in these WMA technologies are more significant than mixing temperature in influencing environmental impacts.

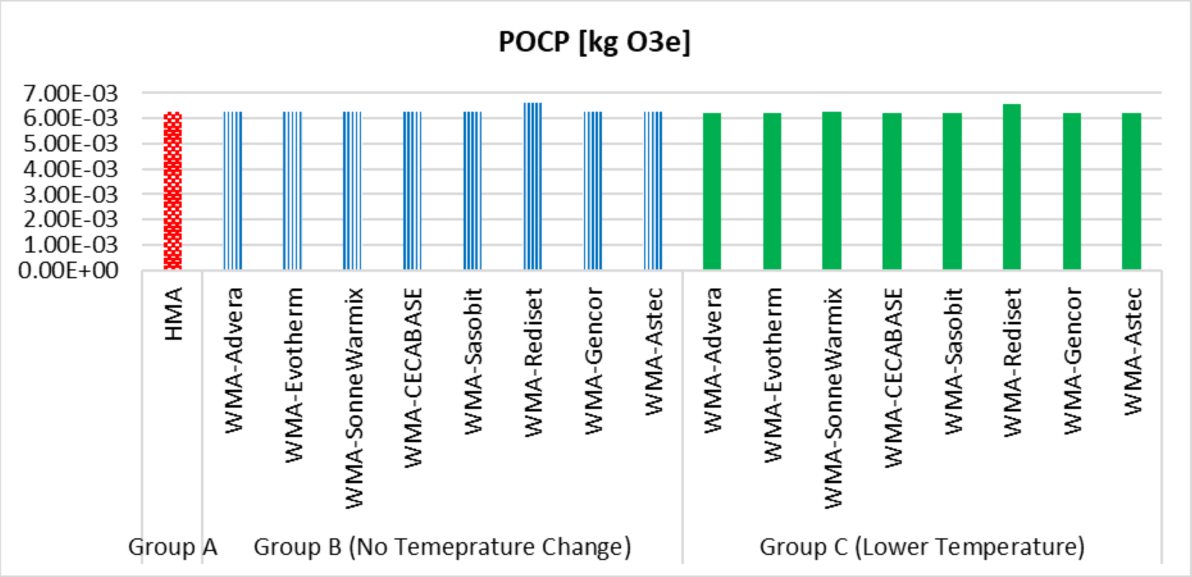


Figure 2-33. Smog Formation Potential results for 1 kg of Non-Rubberized Warm Mix Asphalt

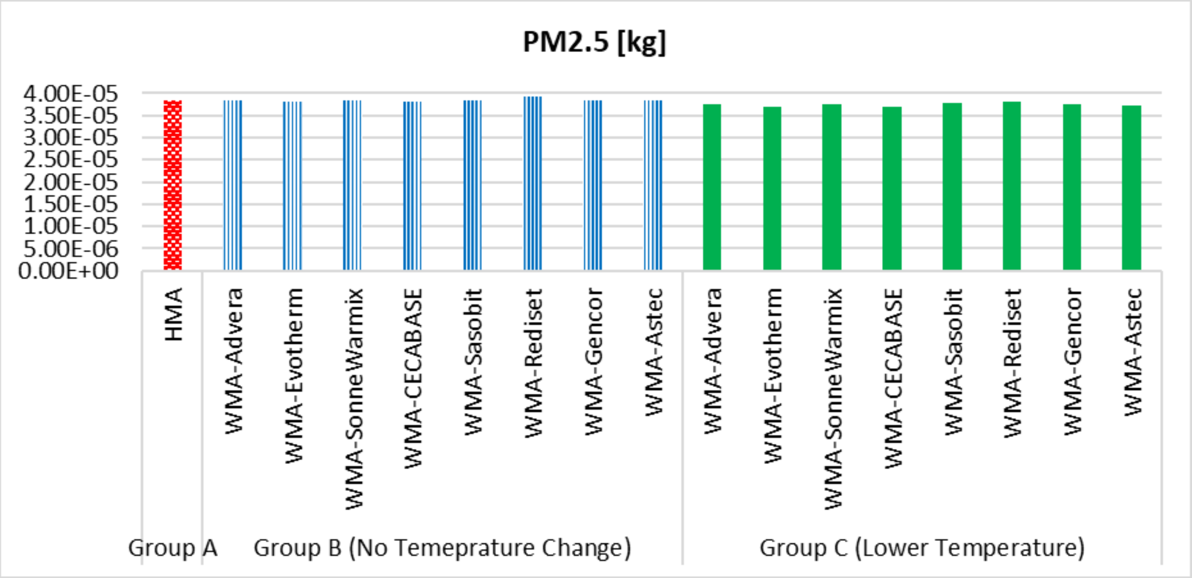


Figure 2-34. Human Health Particulate Effects results for 1 kg of Non-Rubberized Warm Mix Asphalt

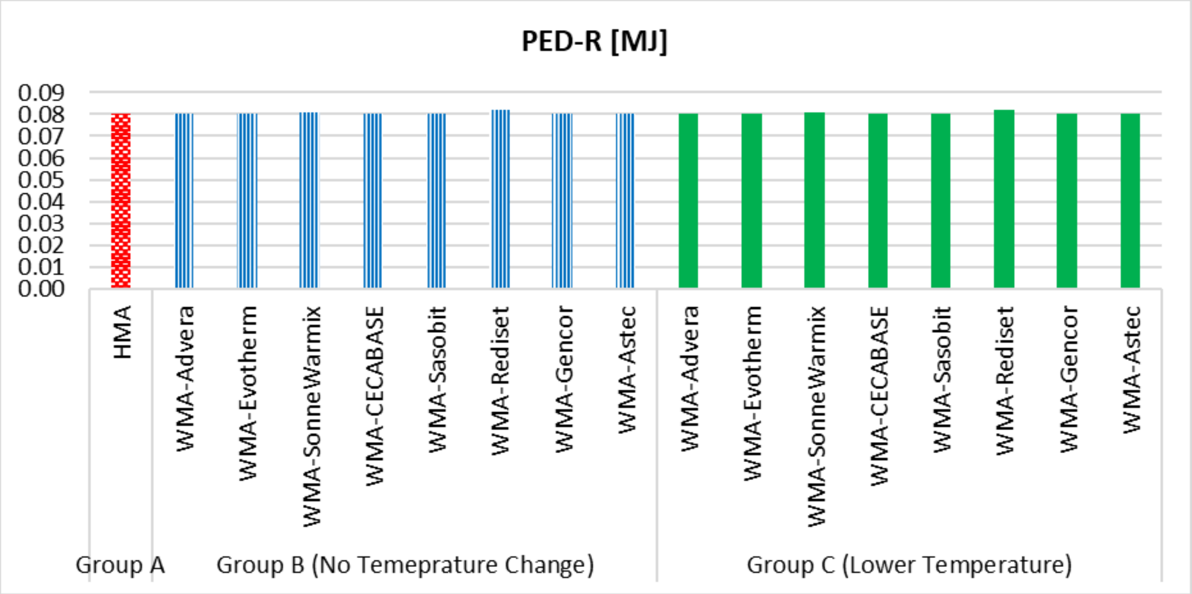


Figure 2-35. Renewable Energy results for 1 kg of Non-Rubberized Warm Mix Asphalt

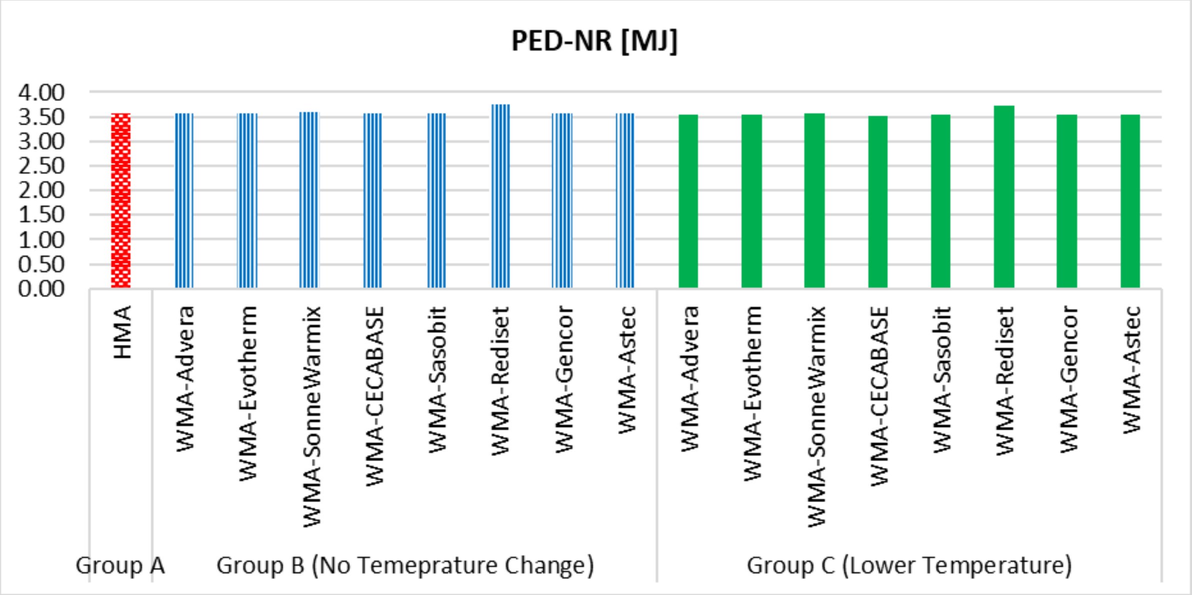


Figure 2-36. Non-Renewable Energy results for 1 kg of Non-Rubberized Warm Mix Asphalt

Figure 2-37 through Figure 2-41 compare the environmental impacts of three mix asphalt groups for different WMA technologies. As expected, group C has lower GWP compared to group B, due to the reduced temperatures and natural gas consumption during the production of the WMA.

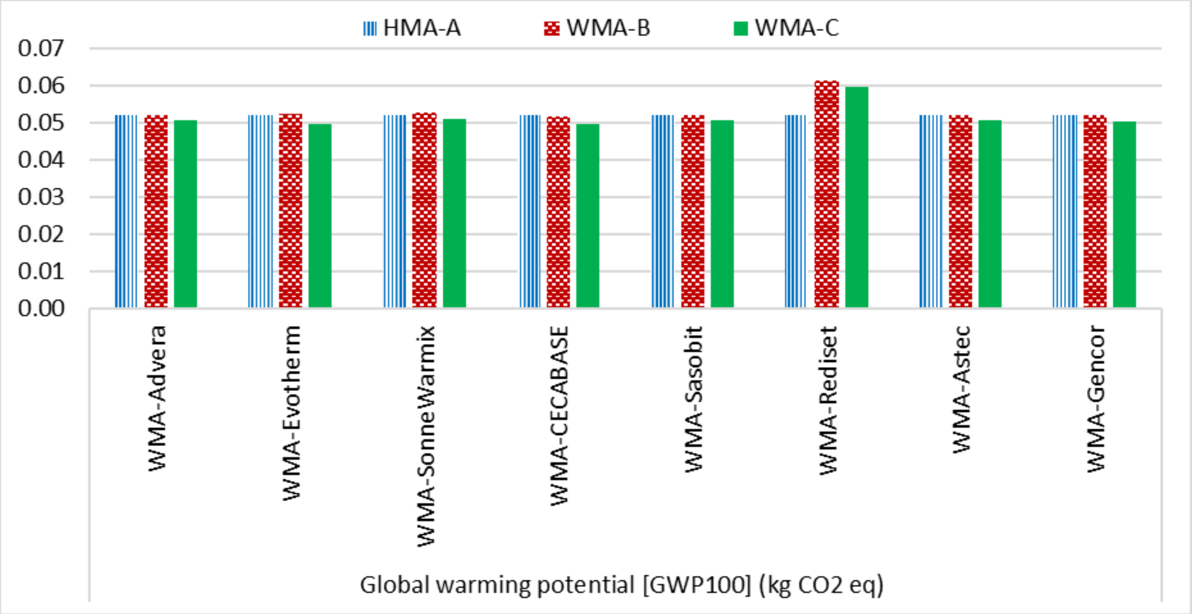


Figure 2-37. Global Warming Potential results for 1 kg of Non-Rubberized Warm Mix Asphalt for different WMA groups

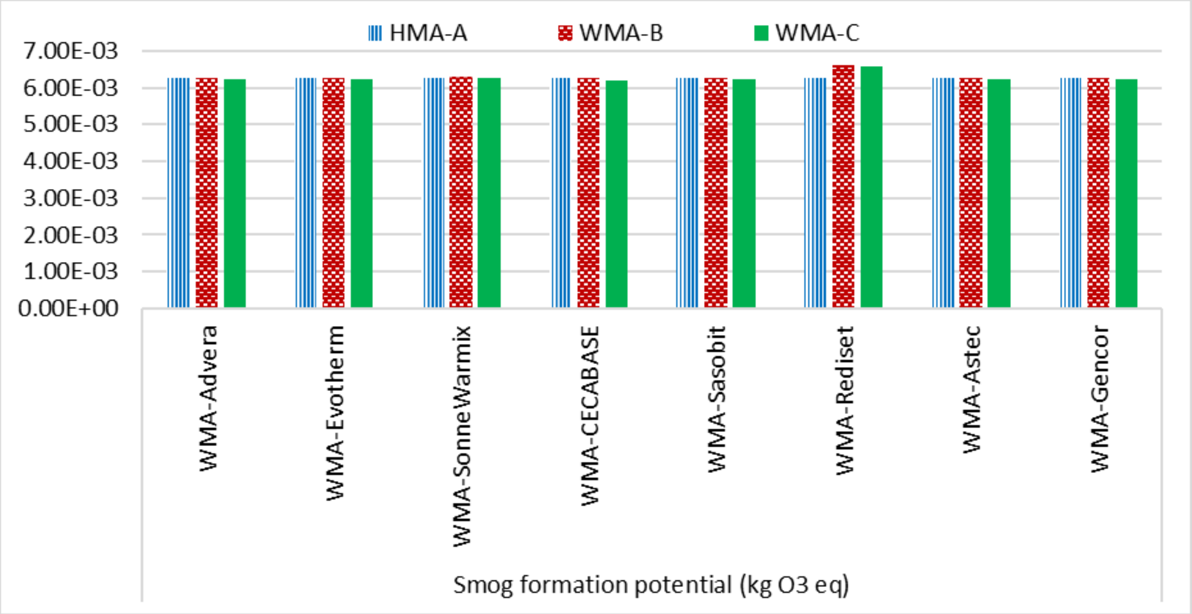


Figure 2-38. Smog Formation results for 1 kg of Non-Rubberized Warm Mix Asphalt for different WMA groups

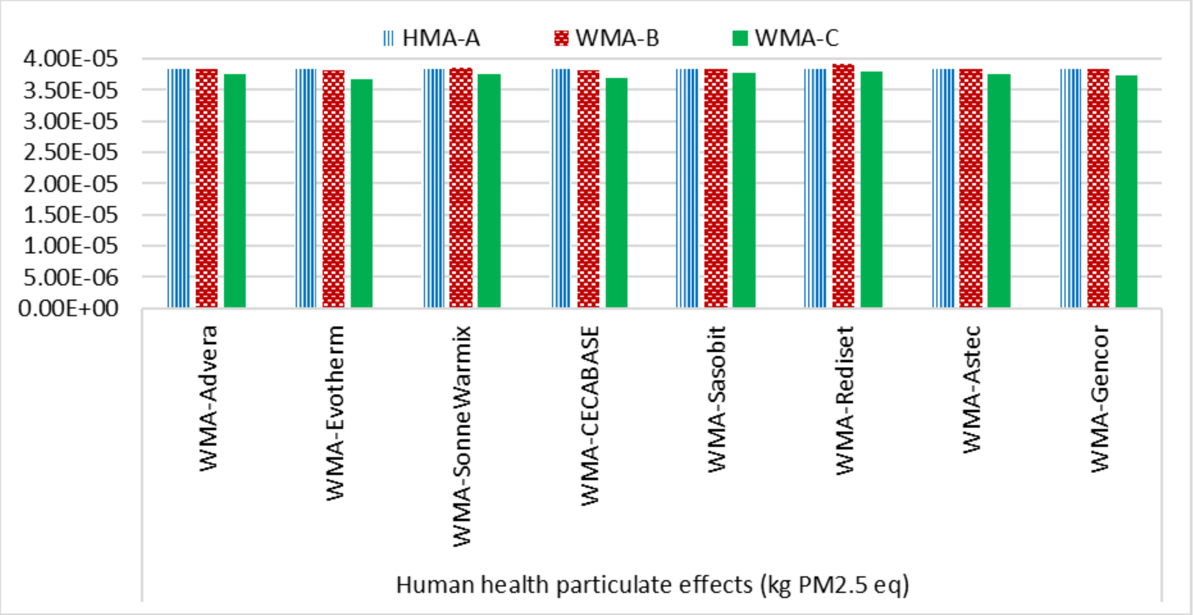


Figure 2-39. Human Health Participate Effect results for 1 kg of Non-Rubberized Warm Mix Asphalt for different WMA groups

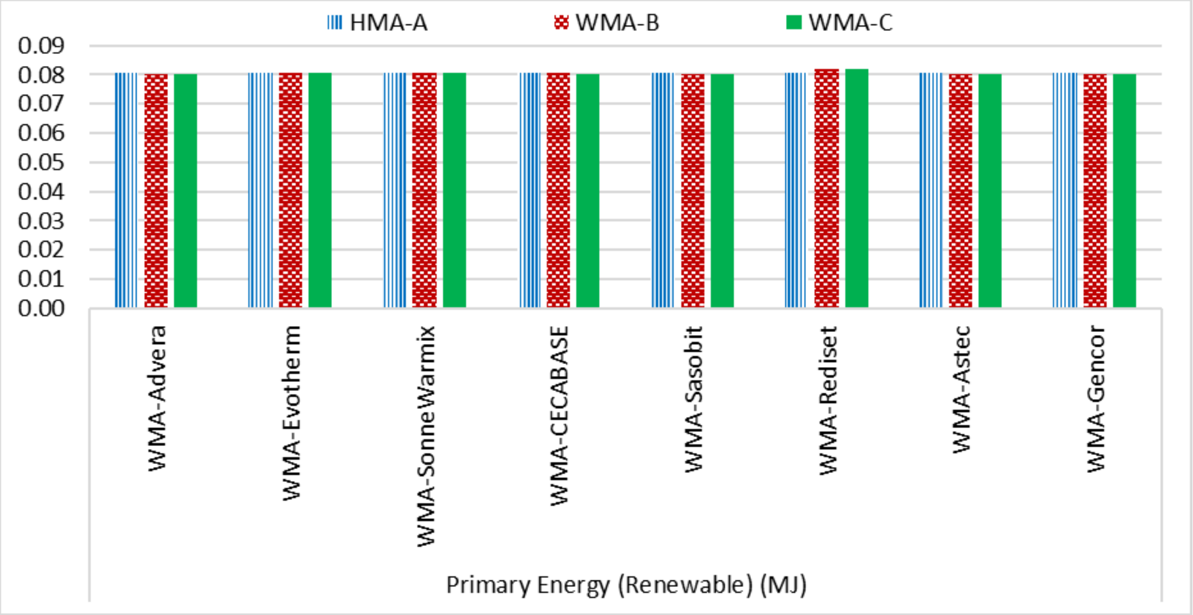


Figure 2-40. Renewable Energy results for 1 kg of Non-Rubberized Warm Mix Asphalt for different WMA groups

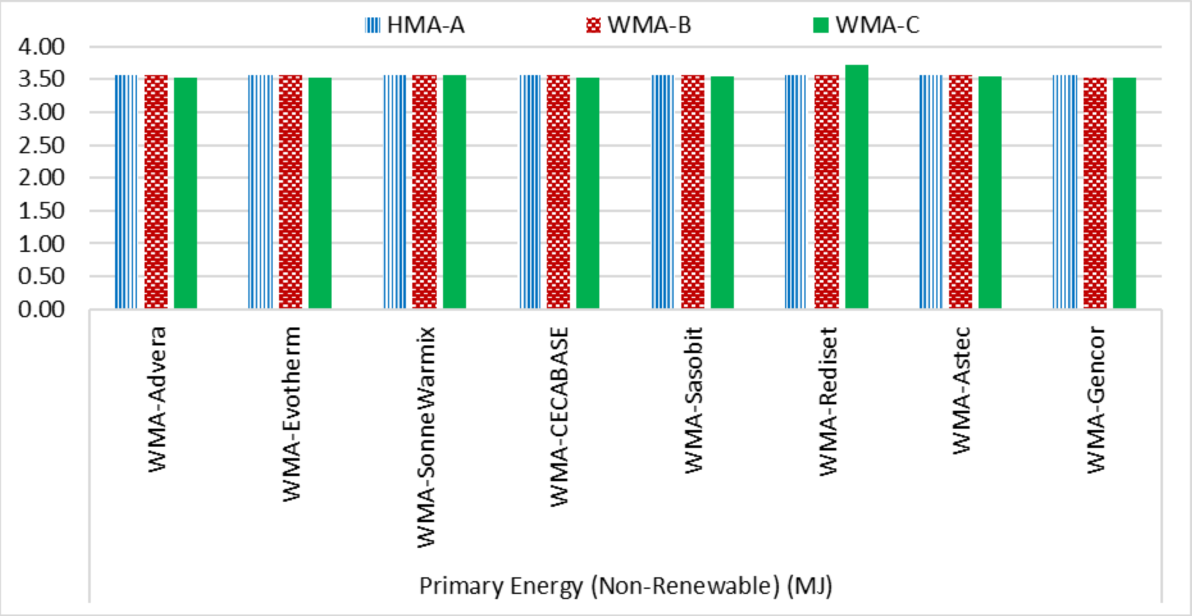


Figure 2-41. Non-Renewable Energy results for 1 kg of Non-Rubberized Warm Mix Asphalt for different WMA groups

Figure 2-42 through Figure 2-46 show environmental impacts and energy consumption for 1 kg of rubberized WMA. The LCIA results reveal that the combination of WMA mixing temperature, the chemical components of the WMA technologies, and the dosage of additives in the mix are the three main factors influencing the final environmental emissions.

As can be observed from these Figures, WMA-Rediset has the highest environmental impacts and energy consumption in all impact categories. As also observed in non-rubberized WMA, the temperature used in the mixture of WMA with Rediset is not the highest temperature among the other WMA technologies. Therefore, the chemical components used in Rediset, including HMDA, and the dosage of Rediset in the mix (0.13%), are the reasons for this high impact.

WMA-CECABASE has the lowest impacts in most categories, in both groups B and C. WMA-CECABASE's mixing temperature is lower than most of the WMAs', which presents the important role of mixing temperature in WMA-CECABASE's environmental impacts. The lower dosage of WMA-CECABASE in the mix, compared to other additives, is another important factor that results in WMA-CECABASE's low environmental impacts.

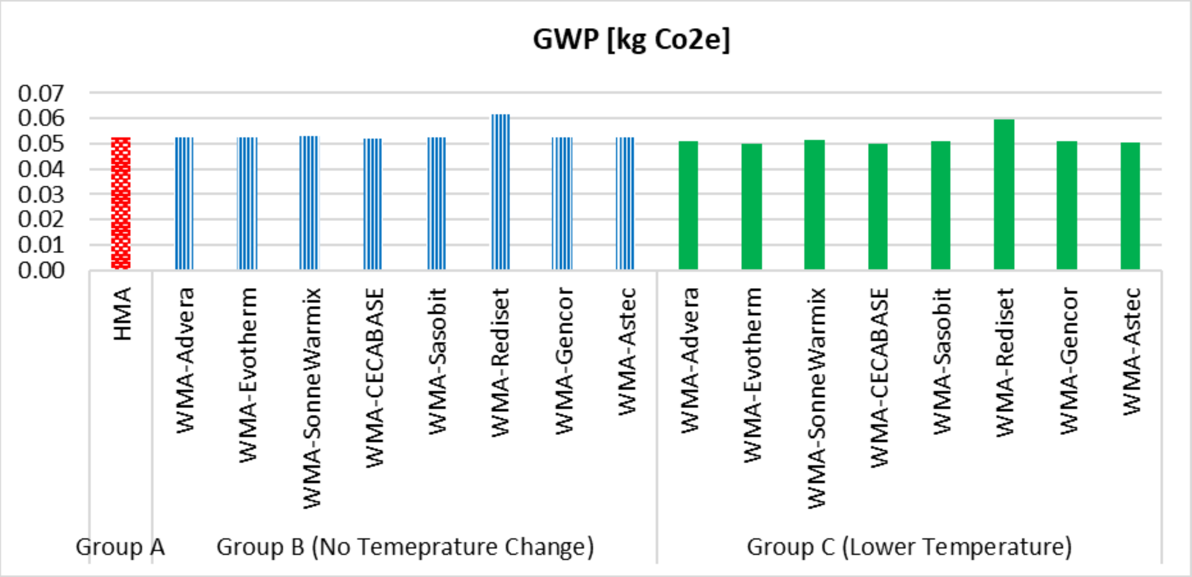


Figure 2-42. Global Warming Potential results for 1 kg of Rubberized Warm Mix Asphalt

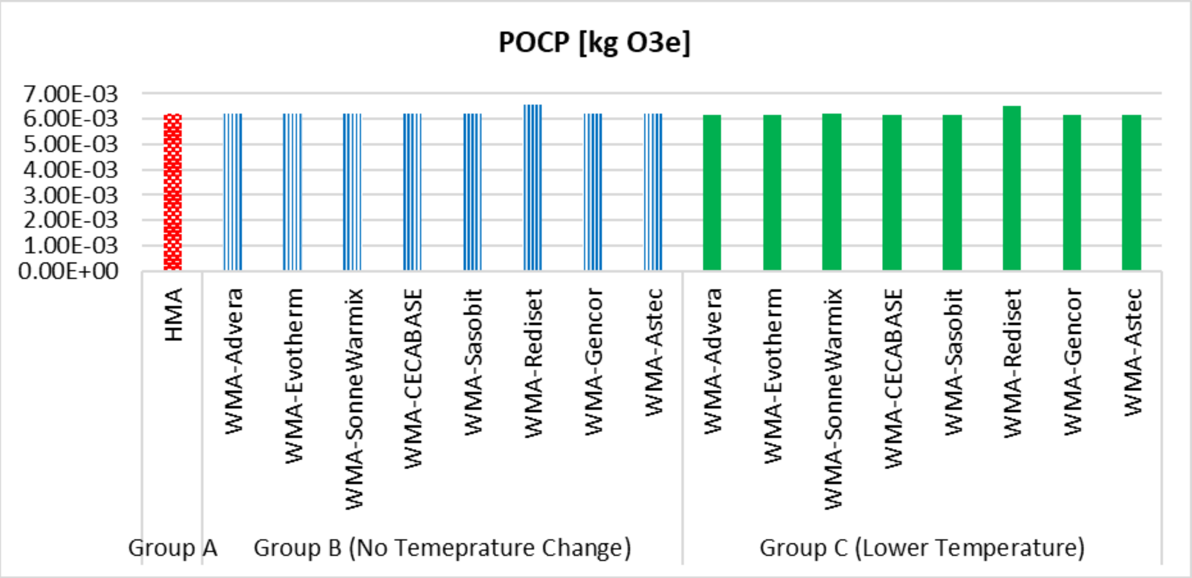


Figure 2-43. Smog Formation Potential results for 1 kg of Rubberized Warm Mix Asphalt

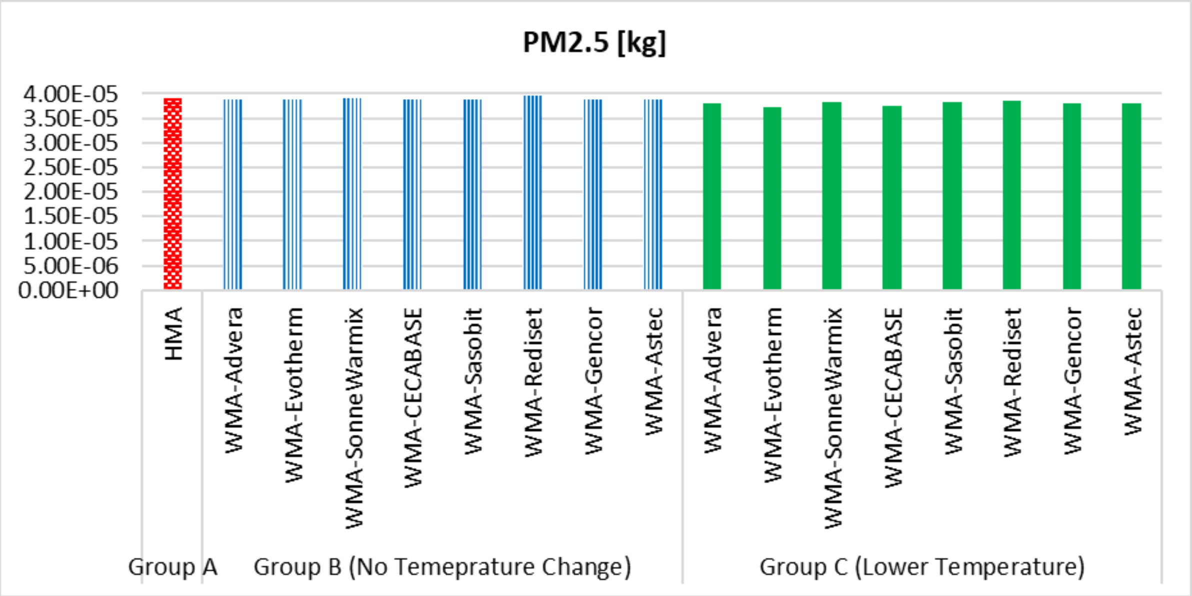


Figure 2-44. Human Health Particulate Effects results for 1 kg of Non-Rubberized Warm Mix Asphalt

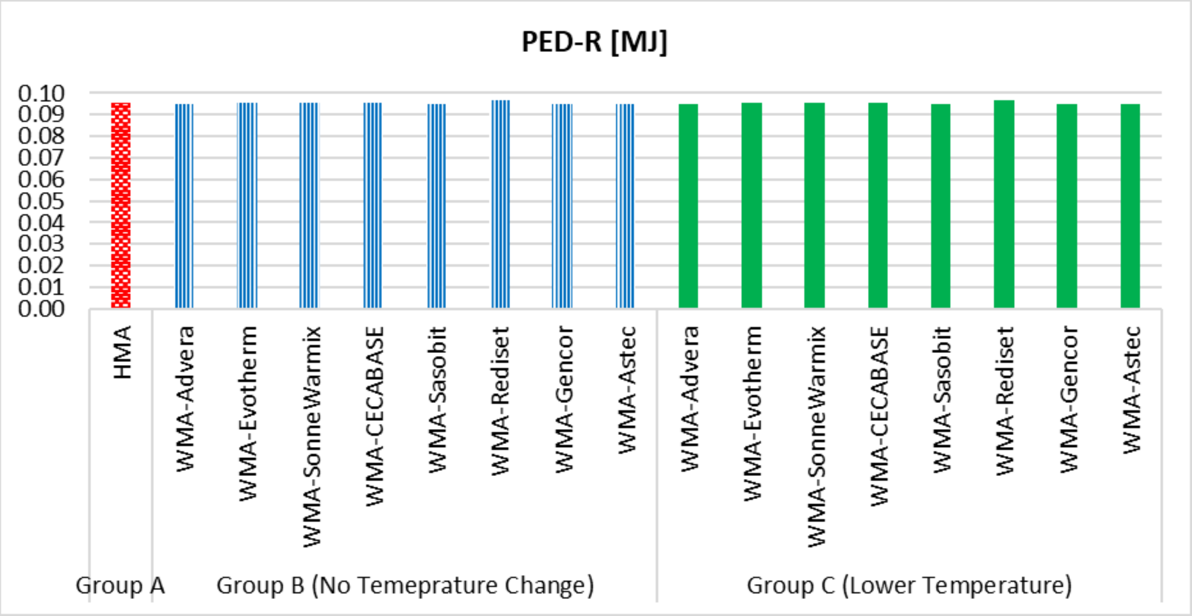


Figure 2-45. Renewable Energy results for 1 kg of Rubberized Warm Mix Asphalt

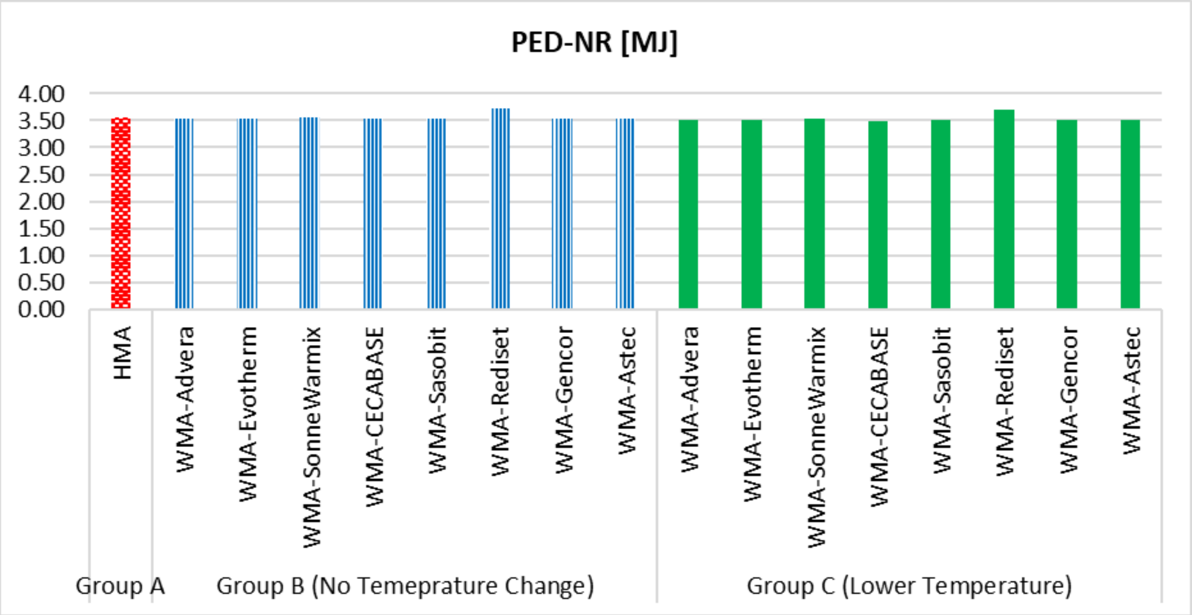


Figure 2-46. Non-Renewable Energy results for 1 kg of Non-Rubberized Warm Mix Asphalt

Figure 2-47 through Figure 2-51 compare the environmental impacts of group A, group B, and group C for different WMA technologies. As expected, group C has lower GWP compared to group B, due to the reduced temperatures and natural gas consumption during the production of the WMA.

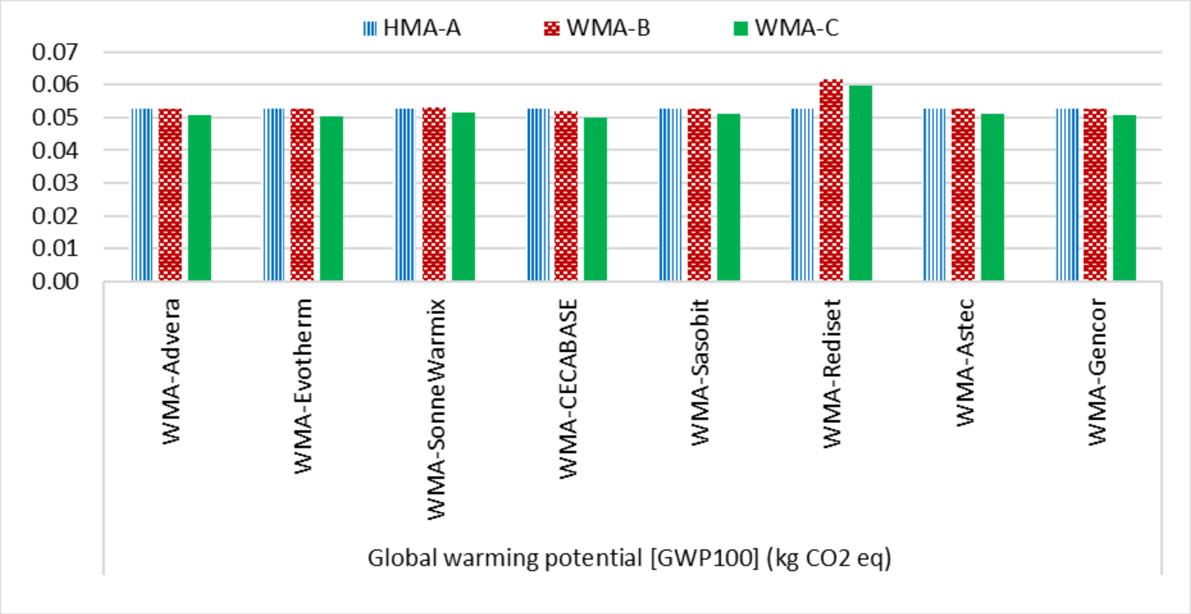


Figure 2-47. Global Warming Potential results for 1 kg of Rubberized Warm Mix Asphalt for different WMA groups (groups A, B, and C)

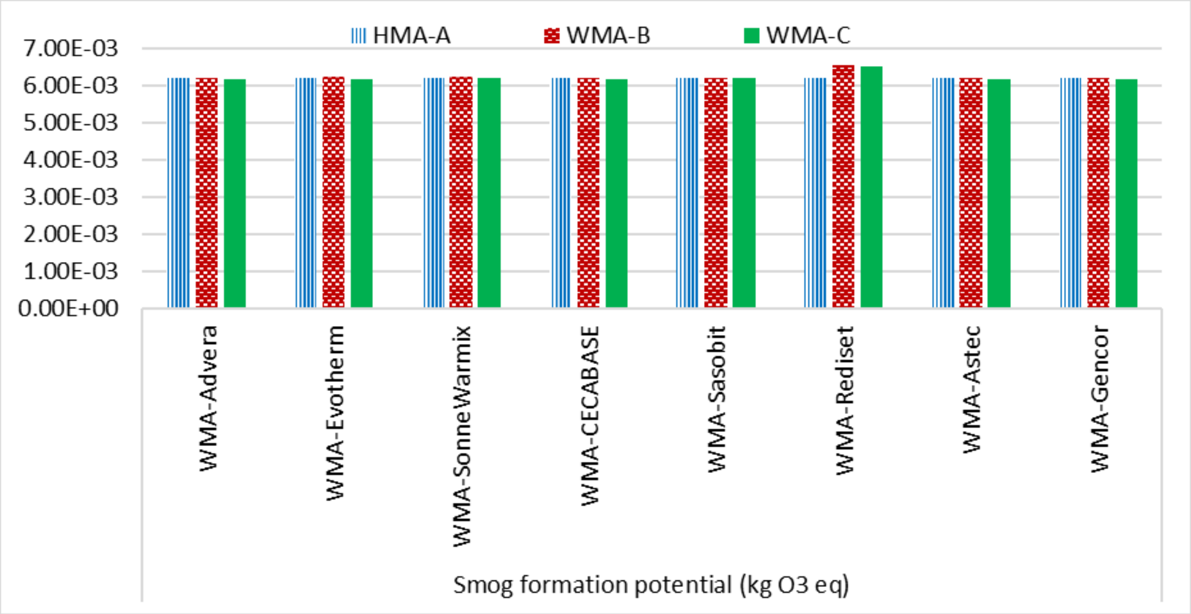


Figure 2-48. Smog Formation results for 1 kg of Rubberized Warm Mix Asphalt for different WMA groups (groups A, B, and C)

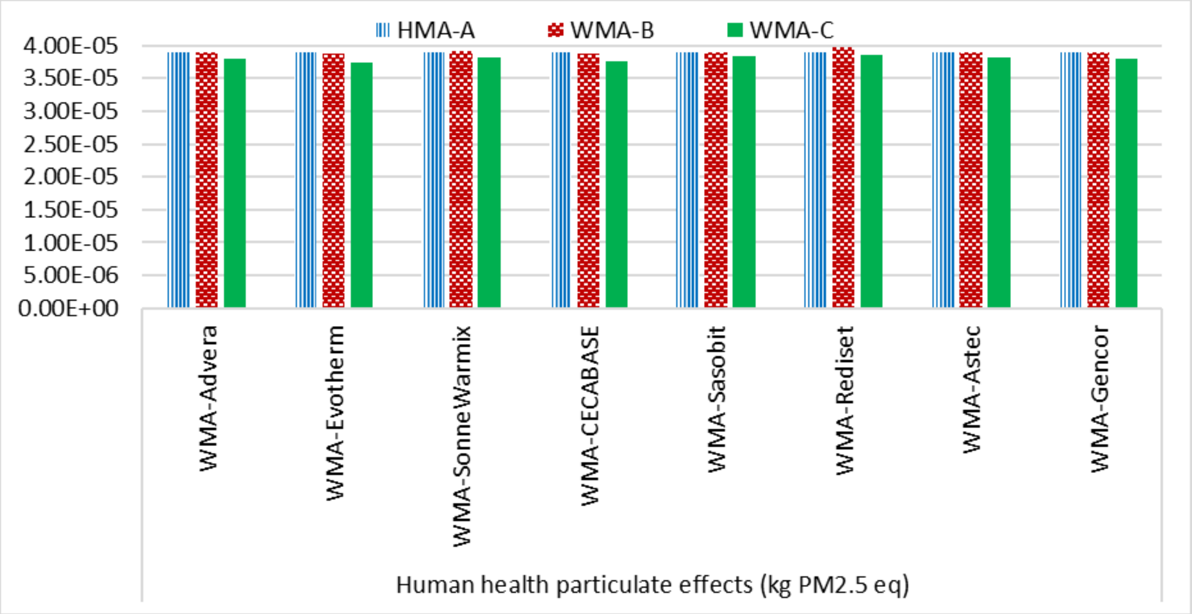


Figure 2-49. Human Health Particulate Effect results for 1 kg of Rubberized Warm Mix Asphalt for different WMA groups (groups A, B, and C)

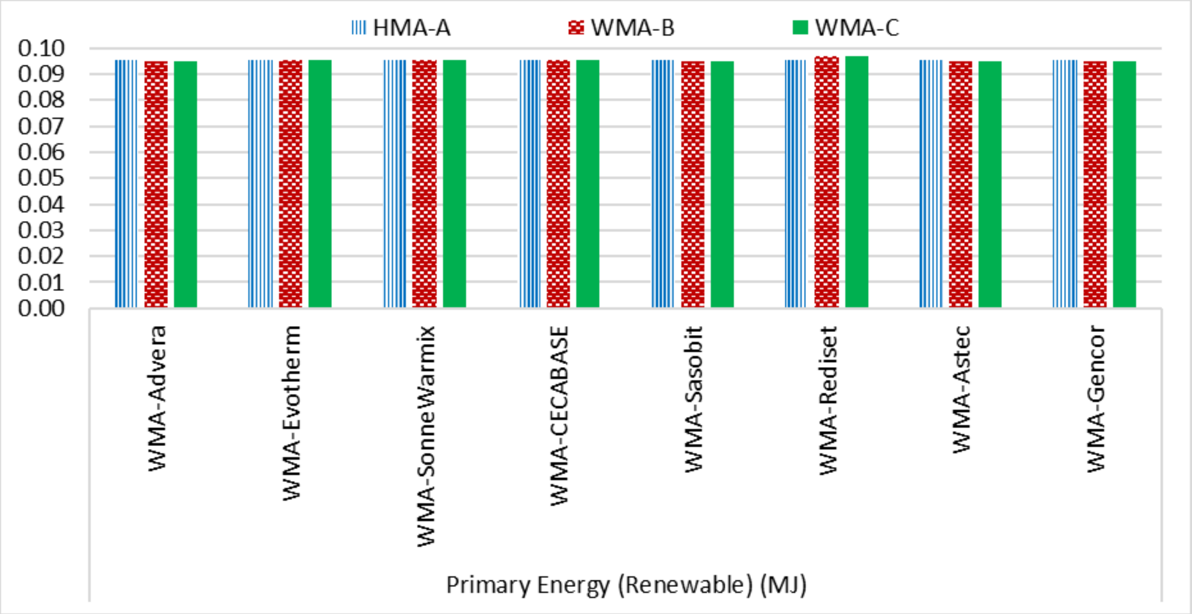


Figure 2-50. Renewable Energy results for 1 kg of Rubberized Warm Mix Asphalt for different WMA groups (groups A, B, and C)

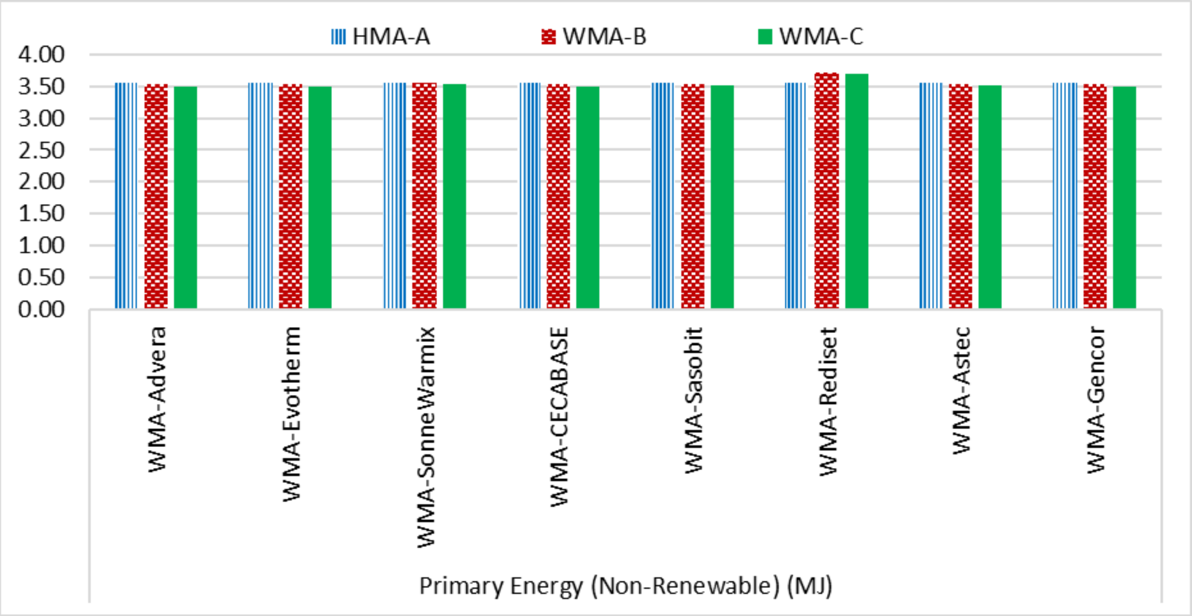


Figure 2-51. Non-Renewable results for 1 kg of Rubberized Warm Mix Asphalt for different WMA groups (groups A, B, and C)

Changes in each impact category in the WMA group compared to conventional HMA can be seen in Table 2-34 and Table 2-35.

Table 2-34. Changes in each impact category in the Non-Rubberized WMA group compared to conventional HMA

Group	WMA Groups	GWP [kg Co2e]	POCP [kg O3e]	PM2.5 [kg]	PED-R [MJ]	PED-NR [MJ]	PED-FS [MJ]
Group A	HMA	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Group B (No Temperature Change)	WMA-Advera	-0.09%	-0.10%	-0.21%	-0.25%	-0.26%	0.00%
	WMA-Evotherm	0.20%	0.10%	-0.52%	0.00%	0.00%	0.00%
	WMA-SonneWarmix	0.98%	0.27%	0.27%	0.25%	0.56%	0.00%
	WMA-CECABASE	-0.95%	-0.22%	-0.52%	-0.07%	-0.28%	0.00%
	WMA-Sasobit	-0.16%	-0.03%	0.02%	-0.12%	-0.27%	0.00%
	WMA-Rediset	17.87%	5.51%	1.89%	2.00%	5.04%	0.00%
	WMA-Astec	-0.16%	-0.03%	0.02%	-0.12%	-0.27%	0.00%

	WMA-Gencor	-0.16%	-0.03%	0.02%	-0.12%	-0.27%	0.00%
Group C (Lower Temperature)	WMA-Advera	-3.16%	-0.74%	-2.30%	-0.25%	-1.10%	0.00%
	WMA-Evotherm	-4.79%	-0.86%	-4.16%	0.00%	-1.12%	0.00%
	WMA-SonneWarmix	-2.09%	-0.21%	-2.08%	0.25%	0.00%	0.00%
	WMA-CECABASE	-5.17%	-1.02%	-3.90%	-0.12%	-1.40%	0.00%
	WMA-Sasobit	-2.65%	-0.51%	-1.81%	-0.12%	-0.83%	0.00%
	WMA-Rediset	14.08%	4.76%	-0.90%	2.00%	4.21%	0.00%
	WMA-Astec	-3.03%	-0.67%	-2.33%	-0.13%	-0.88%	0.00%
	WMA-Gencor	-3.80%	-0.67%	-2.85%	-0.13%	-1.11%	0.00%

Table 2-35. Changes in each impact category in the Rubberized WMA group compared to conventional HMA

Group	WMA Groups	GWP [kg Co2e]	POCP [kg O3e]	PM2.5 [kg]	PED-R [MJ]	PED-NR [MJ]	PED-FS [MJ]
Group A	HMA	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Group B (No Temperature Change)	WMA-Advera	-0.05%	-0.19%	-0.15%	-0.23%	-0.82%	0.00%
	WMA-Evotherm	0.42%	0.16%	-0.45%	0.08%	-0.56%	0.00%
	WMA-SonneWarmix	1.00%	0.34%	0.32%	0.19%	0.00%	0.00%
	WMA-CECABASE	-0.91%	-0.16%	-0.70%	-0.02%	-0.84%	0.00%
	WMA-Sasobit	0.07%	0.04%	-0.18%	-0.13%	-0.55%	0.00%
	WMA-Rediset	17.61%	5.53%	1.88%	1.66%	4.50%	0.00%
	WMA-Astec	0.07%	0.04%	-0.18%	-0.13%	-0.55%	0.00%
	WMA-Gencor	0.07%	0.04%	-0.18%	-0.13%	-0.55%	0.00%
Group C (Lower Temperature)	WMA-Advera	-3.10%	-0.68%	-2.46%	-0.23%	-1.66%	0.00%
	WMA-Evotherm	-4.53%	-0.64%	-4.30%	0.08%	-1.68%	0.00%
	WMA-SonneWarmix	-2.05%	-0.31%	-1.98%	0.19%	-0.56%	0.00%

	WMA-CECABASE	-5.10%	-0.96%	-3.78%	-0.02%	-1.96%	0.00%
	WMA-Sasobit	-2.41%	-0.45%	-1.72%	-0.13%	-1.40%	0.00%
	WMA-Rediset	13.99%	4.72%	-0.95%	1.66%	3.66%	0.00%
	WMA-Astec	-2.98%	-0.61%	-2.23%	-0.13%	-1.40%	0.00%
	WMA-Gencor	-3.74%	-0.77%	-2.75%	-0.13%	-1.68%	0.00%

2.3.4.1. Sensitivity Analysisjs

As explained in section 2.3.1.1, the current study used the specific heat (c) of asphalt and the mix temperature of each WMA technology for calculating the natural gas used in WMA production. In addition, natural gas calculated from Athena's study results (Athena Institute, 2005), D'Angelo's study results (D'Angelo et al., 2008), and Mukherjee's study results (Mukherjee, 2016) were compared with the current study results.

Athena's study considered energy use information on a total of seven hot-mix asphalt plants. According to Athena's study, higher heating values (HHV) for fuel physical quantity conversions to MJ of natural gas equals 38.03 MJ/m^3 (Athena Institute, 2005). Therefore, the average natural gas use per tonne of hot-mix asphalt production in Athena's study was considered to be 177.21 MJ per tonne of hot-mix asphalt. However, Athena's report, written in 2005 did not consider different mixing temperatures and only considered HMA mixing temperatures. Mukherjee in 2016 does not separate out mixing energy used from other processes, although natural gas energy for mixing is probably the main point of consumption for natural gas (Mukherjee, 2016). Makherjee's study considered four different mixes (Table 2-36), and the range of these mixes, which are significantly higher than other studies, is shown in Table 2-37.

D'Angelo's study considers eight European WMA additives, including four wax additives and four foaming technologies, which are different additives than the WMAAs evaluated in the current study (D’Angelo et al., 2008). Figure 2-52 presents D’Angelo’s chart that shows the fuel consumption (Liters /Tonne) of cold to hot mix asphalt at different production temperatures.

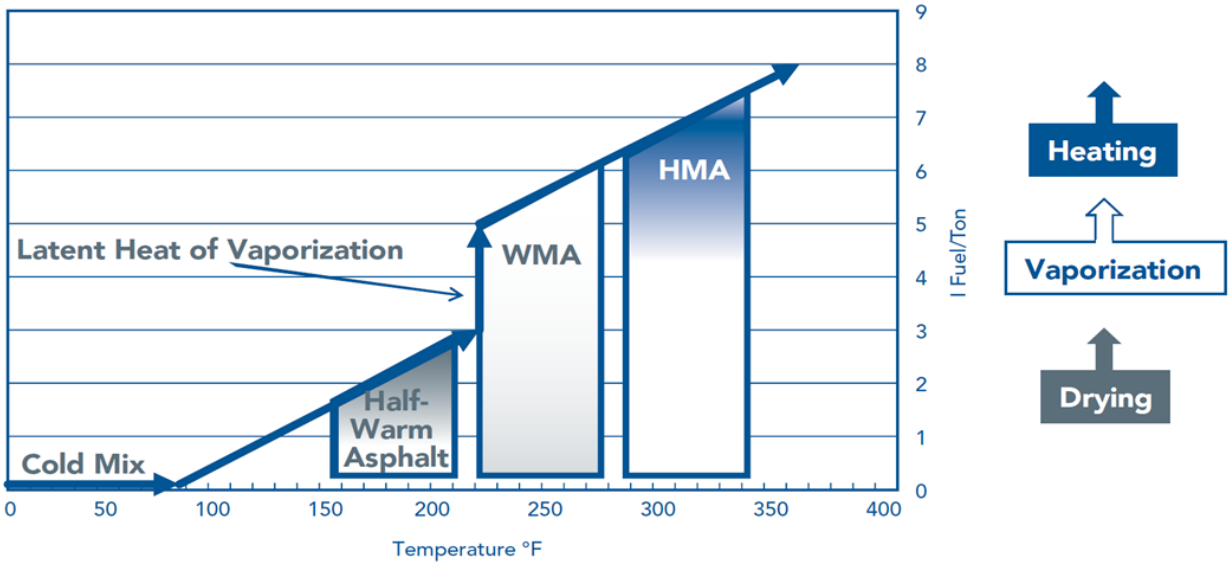


Figure 2-52. Classification of various application temperatures and diesel fuel use for different mix types. (D’Angelo et al., 2008, p.14)

Table 2-36. Mukherjee’s Study results showing natural gas for mixing per 1 kg of asphalt mix

Mix No.	**Input Table**	***Mcf/ton**	**ft^3/lb**	**m^3/kg**
Mix 1	Natural gas, combusted in industrial boiler	0.3640	0.182000	0.011362
Mix 2	Natural gas, combusted in industrial boiler	0.2330	0.116500	0.007273
Mix 3	Natural gas, combusted in industrial boiler	0.2230	0.111500	0.006961
Mix 4	Natural gas, combusted in industrial boiler	1.0000	0.500000	0.031214

**1Mcf/ton   0.5 ft^3/lb*

Table 2-37 and Figure 2-53 compare the volume of natural gas per 1 kg of WMA and HMA in the mentioned studies. It should be mentioned that D'Angelo's study NG’s column in Table 2-37 is calculated based on the interpolation using Figure 2-52.The results show that the minimum amount of natural gas used are very similar for De’Angelo’s, Mukherjee’s, and current study. Athena's study, which considered only one mixing temperature, used the lowest natural gas while Mukherjee's study shows the highest used natural gas amount for its four mixes compared to other studies. The difference between these studies are due to the difference in types of additives and date of studies.

Table 2-37. Comparison of D'Angelo's, Athena's, and the current study's results to calculate natural gas for mixing per 1 kg of asphalt mix

Mix Asphalt Natural Gas [(m^3)/ kg] ([(ft^3)/ lb])	D'Angelo's study NG* [(m^3)/ kg] ([(ft^3)/ lb])	Athena's study NG [(m^3)/ kg] ([(ft^3)/ lb])	Mukherjee's Study NG [(m^3)/ kg] ([(ft^3)/ lb])	The current study NG [(m^3)/ kg] ([(ft^3)/ lb])
Range	0.00646 *(0.10348)* - 0.00732 *(0.11726)*	0.00466 *(0.07465)*	0.00696 *(0.11150)* - 0.03121 *(0.5000)*	0.00666 *(0.10664)* - 0.00793 *(0.12704)*

* *NG is calculated based on the interpolation using Figure* 2-52

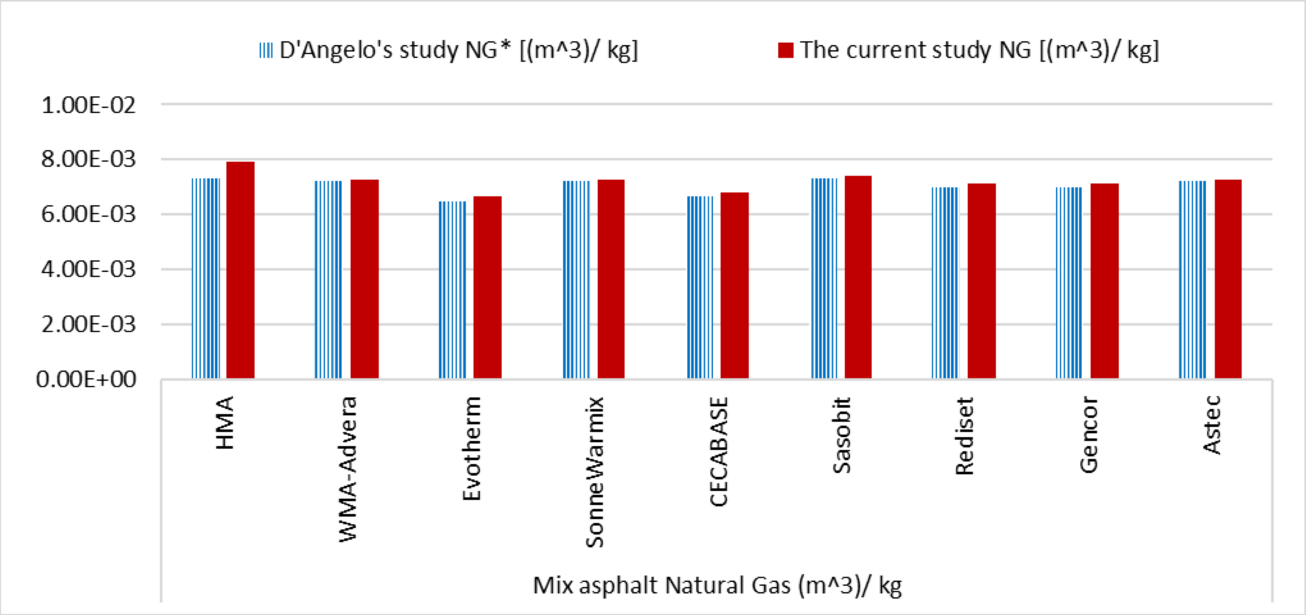


Figure 2-53. Comparison of D'Angelo's, and the current study's results to calculate natural gas per 1 kg of mix asphalt

2.4. LCA of Bonded Concrete Overlay on Asphalt, and Case study

2.4.1. Background

Bonded concrete overlay on asphalt (BCOA) is a rehabilitation alternative that consists of placing a hydraulic cement concrete overlay on an existing asphalt pavement (Mukherjee, 2016). This study is mainly focused on thin BCOA, where the overlay is 100 to 175 mm (4 to 7 in) thick. BCOA with an overlay thickness of 50 to 100 mm (2 to 4 in), typically referred to as ultrathin, is primarily used in urban areas with light traffic. While the technology for thin BCOA has been used on highways and conventional roads in several US states as well as in other countries for at least 20 years, the use of thin BCOA has been very limited in California. BCOA has been evaluated under accelerated trafficking conducted with the Heavy Vehicle Simulator (HVS) by UCPRC for Caltrans with positive results (Mateos et al., 2019). Caltrans decided to move forward and built a pilot thin BCOA project on state Route 113 (SR 113) in Woodland, California (Mateos et al., 2021). The experimental data presented in this study come from the Woodland thin BCOA construction project.

BCOA construction typically includes milling the existing asphalt layer to remove surface distresses and/or because of geometry constraints (e.g., to maintain road surface elevation, change cross-slope). Asphalt surface pre-overlay repairs like localized patching and crack sealing may be included as well. Sweeping multiple times, air blasting the asphalt surface to remove dust and debris, and wetting the surface are the other pre-paving activities of BCOA construction.

BCOA construction includes placing the concrete overlay and sawing joints to form 5’×5’ to 8’×8’ slabs. In the areas where the asphalt surface reflects excess deterioration, as an alternative, a thin gap-graded rubberized hot mix asphalt (RHMA-G) overlay is placed before the placement of the concrete overlay. This approach has shown good bonding between the concrete overlay and the underlying layers during the HVS testing but has not been validated elsewhere. Thin BCOA joints are not always sealed because of the high cost (Mateos et al., 2019). All these activities were considered in modeling the construction stage except for sawing.

The UCPRC study on the thin BCOA for Caltrans (Mateos et al., 2019) recently concluded that a well-designed, well-built 6’×6’ thin bonded concrete overlay placed on top of an asphalt base that is in fair to good condition could potentially provide 20 years of good serviceability on most of California’s non-interstate roadways. LCCA and LCA studies, on the other hand, are required for such rehabilitation alternatives to understand the economic and environmental benefits and dis-benefits. This study is expected to help bridge this gap by presenting a methodology that can be applied to conduct the LCA of thin BCOA construction.

This study presents the development of the LCIs and some initial impact analysis of the BCOA technology as it has been piloted in California. As a sensitivity analysis, this study compares several alternative BCOA cross-sections with the pilot project BCOA design and the concrete mix used in the pilot project with alternative mixes for faster and slower strength gain. The study does not include comparisons with other technologies because any comparison will be highly context-driven and cannot be comprehensively evaluated yet. Instead, the intent is to place these new inventories in the environmental LCA of pavements (eLCAP) software programeLCAP which will allow users to evaluate their own scenarios (Ostovar, 2020; Harvey et al., 2020).

2.4.2. Goal and Scope

The goal of this study is to quantify the potential environmental impacts due to the material and construction stages of thin BCOA. The scope of the study is from cradle-to-laid, which includes the material and construction stages along with the transportation of the materials. The use and end-of-life stages were not included in the study's scope. The functional unit defined for this study is the construction of a 1 lane-km of the pavement surface. A standalone LCA approach has been adopted in this study which focuses on a thin BCOA pilot project built in Woodland, California, in 2018-2019. The two considered BCOA layers include a 0.5 ft (150 mm) thick portland cement concrete (PCC) overlay on top of a new RHMA pavement and a 0.5 ft (150 mm) thick PCC overlay on top of a milled old asphalt (Figure 2-54). These configurations are referred to as 2B and 2A, respectively, in Table 2-38. Figure 2-54 shows the cross-section of the pavement designed and laid in the Woodland pilot project.

Table 2-38. Different BCOA considered in this study

Case	Material	Concrete Thickness mm (inch)	RHMA Thickness mm (inch)
1-A	HVS PCC Type III (4-hr OT)+ Tie Bar	150 (6)	30 (1.18)
1-B	HVS PCC Type III (4-hr OT)+ Tie Bar+ RHMA	150 (6)	30 (1.18)
2-A	Woodland PCC Type II (24-hr OT)+ Tie Bar	150 (6)	30 (1.18)
2-B	Woodland PCC Type II (24-hr OT)+ Tie Bar+ RHMA	150 (6)	30 (1.18)
3-A	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar	150 (6)	30 (1.18)
3-B	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar+ RHMA	150 (6)	30 (1.18)
4-A	HVS PCC Type III (4-hr OT)+ Tie Bar	125 (5)	30 (1.18)
4-B	HVS PCC Type III (4-hr OT)+ Tie Bar+ RHMA	125 (5)	30 (1.18)
5-A	Woodland PCC Type II (24-hr OT)+ Tie Bar	125 (5)	30 (1.18)
5-B	Woodland PCC Type II (24-hr OT)+ Tie Bar+ RHMA	125 (5)	30 (1.18)
6-A	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar	125 (5)	30 (1.18)

6-B	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar+ RHMA	125 (5)	30 (1.18)

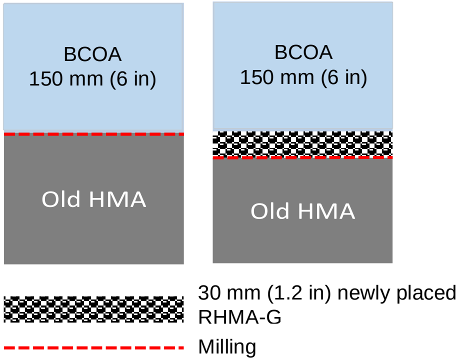


Figure 2-54 Thin BCOA Pavement Cross-Section of the Woodland Pilot Project

The material stage includes the extraction of raw materials from the ground, transportation to the processing plants, and plant operations. Transportation of the materials from the plant to the site was also included. The intended audience of the study includes local governments, pavement researchers and practitioners, and pavement designers.

Additionally, a sensitivity analysis has also been performed in order to evaluate a few other BCOA design alternatives. This analysis is scoped at cradle-to-gate and is performed by comparing ten different BCOA design alternatives in addition to the two Woodland pilot project alternatives described above (2A and 2B). Table 2-38 shows all the twelve different BCOA design alternatives that are compared in the sensitivity analysis. Each design alternative consists of a PCC overlay on top of either a new RHMA overlay or the milled asphalt pavement. Three concrete mix designs that are used in the BCOA alternatives include (1) a rapid strength concrete, 4-hour opening time (OT), made with PC Type III (1A and 1B in Table 2-38), (2) PCC Type II/V designed to be open to traffic in 24 hours constructed in Woodland (2A and 2B in Table 2-38), and (3) a normal strength concrete, 10-day design OT, made with PC Type II/V (3A and 3B in Table 2-38). The first one [(1)] was used to build one of the sections that were tested with the HVS for a former research project on thin BCOA (Mateos et al., 2019). The third mix [(3)] presents the typical concrete mix used in Caltrans standard jointed plain concrete pavements. For each of the three BCOA design alternatives, additional three designs with a thickness of 0.4 ft (125mm) are also considered in the sensitivity analysis (4A to 6B in Table 2-38).

Table 2-39. PCC and RHMA Mix Designs and Number of Tie bars in BCOA layers

HVS PCC Mix Design Type III (4-hour OT)			Woodland PCC Type II/V Mix Design (24-hour OT)			Normal Strength PCC Type II/V Mix design (10-day OT)			RHMA Mix Design	
Material	Mass per Volume (lb/yd3)	% by mass	Material	Mass per Volume (lb/yd3)	% by mass	Material	Mass per Volume (lb/yd3)	Percentage by mass	Material	% by mass
Accelerator	37. 436	0.89	Accelerator	0.00	0.00	Accelerator	76	1.62	Crushed	92.50
Flyash	0.00	0.00	Flyash	101	2.55	Flyash	704.153	15.00	Natural	0
Crushed Aggregate	1787	31.86	Crushed Aggregate	1200	30.34	Crushed Aggregate	1350	28.76	Bitumen	6.00
Natural Aggregate	1348	42.23	Natural Aggregate	1787	45.18	Natural Aggregate	1875	39.94	Extender oil	0.15
Type III Portland Cement	799	18.88	Type II/V Portland Cement	574	14.51	Type II/V Portland Cement	429	9.14	Crumb Rubber Modifier (CRM)	1.35
Retarder	4	0.095	Retarder	0.897	0.023	Retarder	0.2	0.004	Polymer	0
Water Reducing Admixture	6.25	0.15	Water Reducing Admixture	1.614	0.041	Water Reducing Admixture	2	0.040	RAP	0
Water	250	5.91	Water	291	7.36	Water	258	5.50		
Number of Tie bars										
Number of tie bars per slab (slabs are 6 ft long)						2				
Number of tie bars per 1 km						1094				

2.4.3. Life Cycle Inventory and Life Cycle Impact Assessment

UCPRC has developed LCA models for different life cycle stages of the pavement, determined and collected California-specific data, and produced an LCI database (Saboori et al., 2022) for Caltrans (which is being used in the eLCAP software for Caltrans (Harvey et al., 2020)). This database is mainly used to develop LCIs and LCIAs of BCOA pavements (Harvey et al., 2020).

All the PCC mix designs, including PCC Type III used for the HVS test sections with 4 hours OT, PCC Type II/V used for the Woodland project with 24 hours OT, and the normal strength PCC Type II/V used by Caltrans with the 10 days OT, as well as RHMA mix design used in the pavement layers of the project can be seen in Table 2-39. The PCC with 4 hours and 24 hours OT were designed to provide 450 psi (3 MPa) flexural strength (Caltrans requirement for opening the lane to traffic) after 24 hours, while the PCC with days OT was designed to provide 650 psi (4.5 MPa) flexural strength at 10 days.

The 2017 electricity grid mix for California that was used to calculate the impacts of materials and construction for this case study is shown in Table 2-40 (Saboori et al., 2022).

Table 2-40. Energy Input for 1 kg of PCC and RHMA

Energy	PCC	RHMA
Electricity	0.00618 MJ	0.0076319 MJ
Natural Gas	0.000122 m^3	0.0103261 m^3
Diesel	2.54E-007 m^3	

2.4.3.1. LCI Data and Results

2.4.3.1.a. Material Production Stage

PCC and RHMA mix designs and the number of tie bars in BCOA layers are shown in

Table 2-41 and Table 2-42 show the environmental impacts of BCOA during the material stage.

2.4.3.1.b. Transportation and Construction Stages

Table 2-43 shows the transportation impacts for a functional unit of 1,000 kg-km of materials being transported. Table 4-7 and Table 2-45 present the transportation information and the impacts from the transportation of materials, respectively, for PCC Type II/V with 24-hour OT used in the Woodland project.

Table 2-41. Material Stage Impacts for the Functional Unit of 1 kg of Materials.

Material	Unit	GWP (kg CO2e)	POCP (kg O_3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
HVS PCC Type III (4-hr OT)	1kg	1.78E-01	1.50E-02	9.72E-05	2.08E-01	1.08E+00	0.000E+00
Woodland PCC Type II/V (24-hr OT)	1kg	1.296E-01	1.120E-02	8.502E-05	1.418E-01	8.652E-01	0.000E+00
Caltrans Normal Strength PCC Type II/V (10-d OT)	1kg	1.169E-01	8.228E-03	1.183E-04	1.076E-01	8.150E-01	0.000E+00
RHMA	1kg	5.628E-02	5.977E-03	4.036E-05	9.329E-02	3.408E+00	6.487E+00
Tie Bar	Each	3.343E+00	1.667E-01	1.616E-03	1.443E+00	4.147E+01	0.000E+00

Table 2-42. Material Stage Impacts for different BCOA Alternatives for 1 ln-km.

Case	Material	Concrete Thickness mm (inch)	RHMA Thickness mm (inch)	GWP (kg CO_2e)	POCP (kg O_3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
1-A	HVS PCC Type III (4-hr OT)+ Tie Bar	150 (6)	30 (1.18)	2.41E+05	2.02E+04	1.31E+02	2.79E+05	1.48E+06	0.00E+00
1-B	HVS PCC Type III (4-hr OT)+ Tie Bar+ RHMA	150 (6)	30 (1.18)	2.56E+05	2.18E+04	1.42E+02	3.03E+05	2.39E+06	1.73E+06
2-A	Woodland PCC Type II (24-hr OT)+ Tie Bar	150 (6)	30 (1.18)	1.763E+05	1.510E+04	1.150E+02	1.904E+05	1.198E+06	0.00E+00
2-B	Woodland PCC Type II (24-hr OT)+ Tie Bar+ RHMA	150 (6)	30 (1.18)	1.913E+05	1.669E+04	1.258E+02	2.153E+05	2.106E+06	1.73E+06
3-A	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar	150 (6)	30 (1.18)	1.594E+05	1.114E+04	1.593E+02	1.449E+05	1.131E+06	0.00E+00
3-B	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar+ RHMA	150 (6)	30 (1.18)	1.744E+05	1.273E+04	1.701E+02	1.697E+05	2.039E+06	1.73E+06
4-A	HVS PCC Type III (4-hr OT)+ Tie Bar	125 (5)	30 (1.18)	2.01E+05	1.68E+04	1.10E+02	2.32E+05	1.24E+06	0.00E+00
4-B	HVS PCC Type III (4-hr OT)+ Tie Bar+ RHMA	125 (5)	30 (1.18)	2.16E+05	1.84E+04	1.20E+02	2.57E+05	2.15E+06	1.73E+06
5-A	Woodland PCC Type II (24-hr OT)+ Tie Bar	125 (5)	30 (1.18)	1.475E+05	1.261E+04	9.614E+01	1.590E+05	1.006E+06	0.00E+00
5-B	Woodland PCC Type II (24-hr OT)+ Tie Bar+ RHMA	125 (5)	30 (1.18)	1.625E+05	1.420E+04	1.069E+02	1.838E+05	1.914E+06	1.73E+06
6-A	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar	125 (5)	30 (1.18)	1.334E+05	9.316E+03	1.331E+02	1.210E+05	9.500E+05	0.00E+00
6-B	Caltrans Normal Strength PCC Type II (10-d OT)+ Tie Bar+ RHMA	125 (5)	30 (1.18)	1.484E+05	1.091E+04	1.438E+02	1.458E+05	1.858E+06	1.73E+06

Table 2-43. Transportation Impacts for a Functional Unit of 1,000 kg-km of Materials

Heavy Truck	Functional Unit	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
	1000 kg-km	7.798E-02	1.243E-02	2.492E-05	0.000E+00	1.116E+00	0.000E+00

Table 2-44. Transportation Information Assumptions

Material	Transportation	Material in 1lane-km (kg)	No. of trips	1000 kg-km (1 Lane-km)
PCC Type II	1-way 40 km (25 mile) from plan to the construction field	1,332,000	56	53,280
Cement	1-way 692km (430 mile) from cement plant to the mixing plant	193,292	9	133,78
RHMA	1-way 56km (35 mile) from plan to the construction field	266,400	12	14,918
Bitumen	1-way 435km (270 mile) from refinery to the plant	15,974	1	6,949
Crushed Agg.	1-way 40 km (25 mile) from quarry to the plant	246,420	11	9,857

Table 2-45. Transport Impact

Material	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
Woodland PCC Type II	4.354E+04	6.941E+03	1.391E+01	0.000E+00	6.231E+05	0.000E+00
RHMA	7.385E+03	1.177E+03	2.360E+00	0.000E+00	1.057E+05	0.000E+00
Total Transport. Impact	5.092E+04	8.119E+03	1.627E+01	0.000E+00	7.288E+05	0.000E+00

Table 2-46 shows the fuel LCIAs and PEDs that were used to prepare impact assessments for the material and construction stages. The impact of construction activities for each pavement layer is calculated by estimating total fuel consumption for 1 ln-km of the road by considering the equipment used, engine horsepower and fuel efficiency, and the number of passes needed. The construction information can be seen in Table 2-47. Table 2-48 shows the impact results due to the construction stage for PCC Type II/V with 24-hour OT used in the Woodland project.

Table 2-46. Impacts of Non-Electricity Energy Source

Diesel Burned (1 gallon)	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
	1.194E+01	5.273E+00	9.369E-03	0.000E+00	1.645E+02	0.000E+00

Table 2-47. Construction Information

Layer	Equipment/ Activity	Engine Power Kw (hp)	Hourly Fuel Use m3/hr(gal/hr)	Speed km/h(ft/min)	Time for 1Pass over 1lane-km (hr)	No. of Passes	Fuel Used m3(gal)	Total Fuel Used for 1lane-km m3 (gal)
Woodland PCC Type II	Milling for 25 mm (1 in)	522 (700)	0.076 (20)	0.183 (10)	5.47	1	0.41 (109.36)	0.49 (129.05)
	Sweeping (multiple times)	59.66 (80)	0.008 (2)	1.83 (100)	0.55	2	0.01 (2.19)	
	Wetting	59.66 (80)	0.008 (2)	1.83 (100)	0.55	1	0.004 (1.09)	
	Concrete Placement	67.11 (90)	0.011 (3)	0.183 (10)	5.47	1	0.06 (16.40)	
RHMA	Prime coat application	260.1(350)	0.027 (7.2)	0.457 (25)	2.19	1	0.06 (16.40)	0.54 (143.15)
	RHMA placement	186.43(250)	0.040 (10.6)	0.274 (15)	3.65	1	0.15 (39.62)	
	Rolling (vibratory)	111.86(150)	0.031 (8.1)	0.457 (25)	2.19	2	0.13 (34.34)	
	Rolling (static)	111.86(150)	0.031 (8.1)	0.457 (25)	2.19	3	0.2 (52.83)	

Table 2-48. Construction Impacts

Material	Activity	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
Woodland PCC Type II	Milling for 25mm (1in)	1.306E+03	8.304E+01	1.475E-01	0.000E+00	2.591E+03	0.000E+00
	Sweeping(multiple-times)	2.612E+01	1.153E+01	2.049E-02	0.000E+00	3.599E+02	0.000E+00
	Wetting	1.306E+01	5.767E+00	1.025E-02	0.000E+00	1.799E+02	0.000E+00
	Concrete placement	1.959E+02	8.650E+01	1.537E-01	0.000E+00	2.699E+03	0.000E+00
	Total	1.541E+03	1.868E+02	3.320E-01	0.000E+00	5.830E+03	0.000E+00
RHMA	Prime coat application	1.883E+02	8.315E+01	1.477E-01	0.000E+00	2.594E+03	0.000E+00
	RHMA placement	4.620E+02	2.040E+02	3.625E-01	0.000E+00	6.366E+03	0.000E+00
	Rolling (vibratory)	4.236E+02	1.871E+02	3.324E-01	0.000E+00	5.838E+03	0.000E+00
	Rolling (static)	6.355E+02	2.806E+02	4.986E-01	0.000E+00	8.756E+03	0.000E+00
	Total	1.709E+03	7.549E+02	1.341E+00	0.000E+00	2.355E+04	0.000E+00
Total Construction Impact		3.250E+03	9.417E+02	1.673E+00	0.000E+00	2.938E+04	0.000E+00

2.4.4. Interpretation

In this analysis, Figure 4-2 through Figure 4-5 depict the impacts of the different stages of the life cycle for the Woodland PCC Type II/V with 0.5 ft (150 mm) thickness and 24 hours OT, RHMA layer, and the whole BCOA.

The material stage can be considered the hot spot due to high environmental impacts and high energy consumption compared to the transportation and construction stages (Table 2-49). Improvement of the material production techniques will likely result in the most significant improvement in environmental impacts and energy use.

The transportation stage is of secondary importance to the materials meaning that methods of shortening the haul distance for aggregate or reusing aggregate sources would be an approach to reduce the transportation impacts. The assumed distances between the stone quarries to the asphalt and concrete plants and other hauling distances are included in the analysis, with longer distances leading to higher environmental impacts.

Table 2-49. Final Impacts of BCOA in different stages (Woodland case study)

Layer	Life Cycle Stag	Percent of total					
		GWP	POCP	PM2.5	PED-R	PED-NR	PED-FS
Woodland PCC Type II (24-hr OT)	Materials	71.82%	58.64%	80.03%	88.45%	41.83%	0.00%
	Transportation	17.74%	26.95%	9.68%	0.00%	21.76%	0.00%
	Construction	0.63%	0.73%	0.23%	0.00%	0.20%	0.00%
	Total	90.19%	0.00%	0.00%	0.00%	0.00%	0.00%
RHMA	Materials	6.11%	6.18%	7.48%	11.55%	31.70%	100.00%
	Transportation	3.01%	4.57%	1.64%	0.00%	3.69%	0.00%
	Construction	0.70%	2.93%	0.93%	0.00%	0.82%	0.00%
	Total	9.81%	0.00%	0.00%	0.00%	0.00%	0.00%
BCOA (PCC+ RHMA)	Materials	77.93%	64.82%	87.51%	100.00%	73.53%	100.10%
	Transportation	20.74%	31.53%	11.32%	0.00%	25.45%	0.00%
	Construction	1.32%	3.66%	1.16%	0.00%	1.03%	0.00%
TOTAL for the Functional Unit		2.45E+05	2.58E+04	1.44E+02	2.15E+05	2.86E+06	1.73E+06
		[kg CO_2e]	[kg O_3e]	[kg]	[MJ]	[MJ]	[MJ]

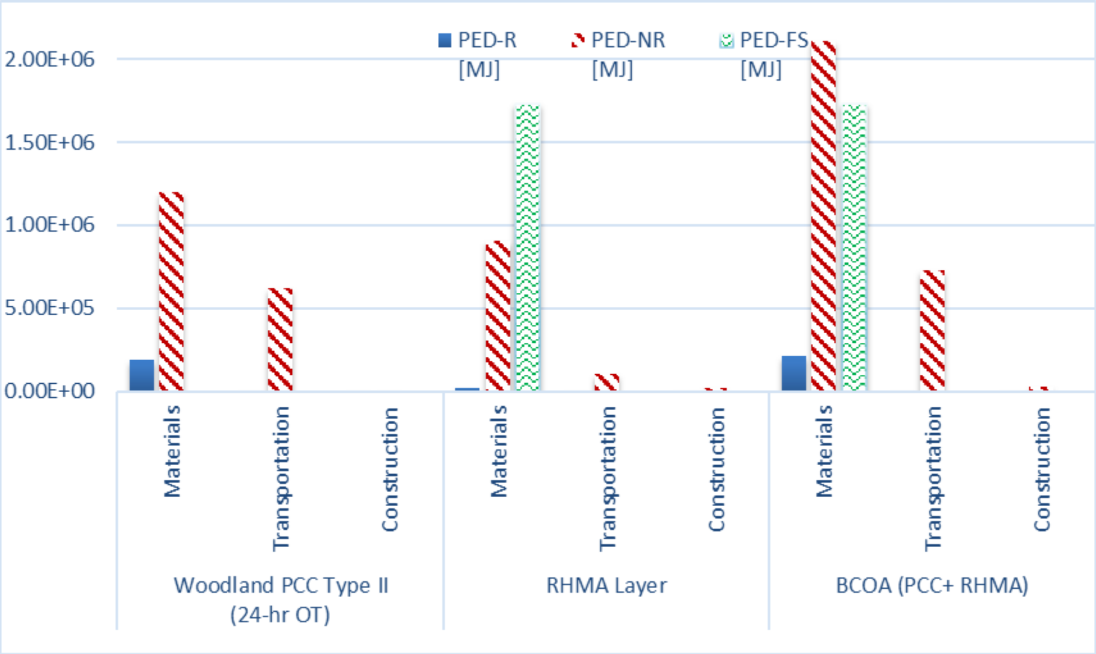


Figure 2-55. Consumed Energy per life cycle stage per pavement layer (Woodland case study)

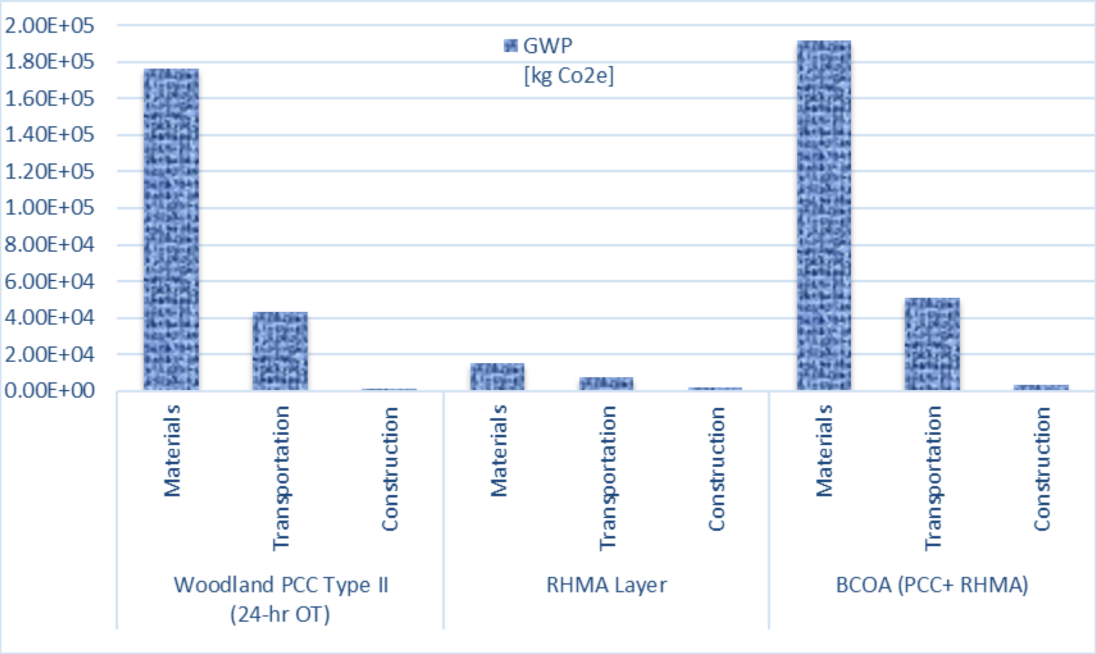


Figure 2-56. Global Warming Potential results per life cycle stage per pavement layer (Woodland case study)

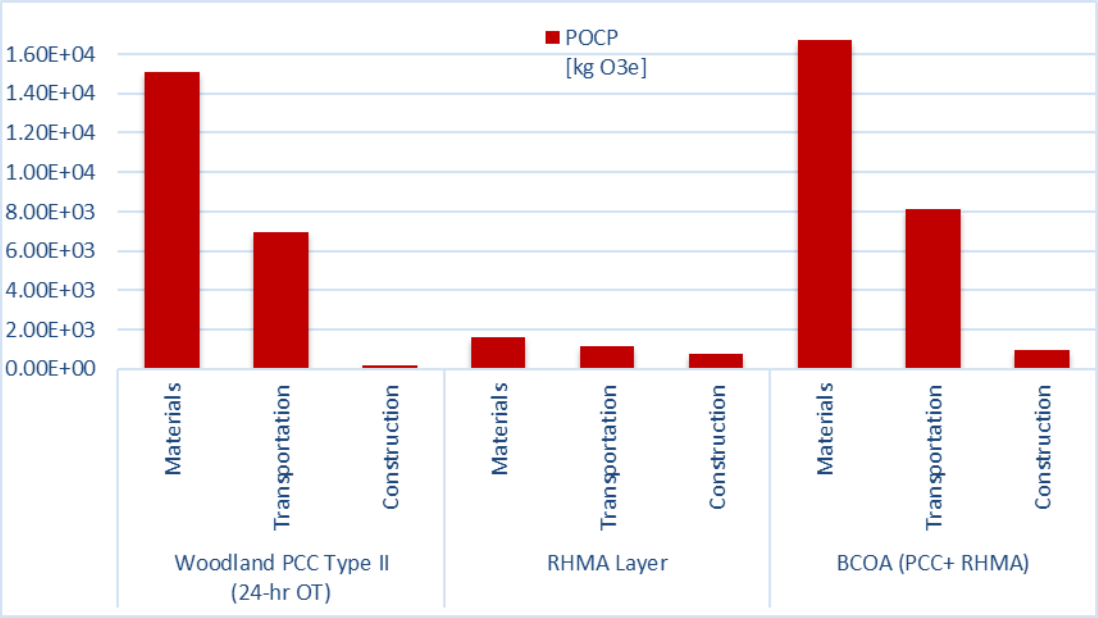


Figure 2-57. Smog Formation Potential results per life cycle stage per pavement layer (Woodland case study)

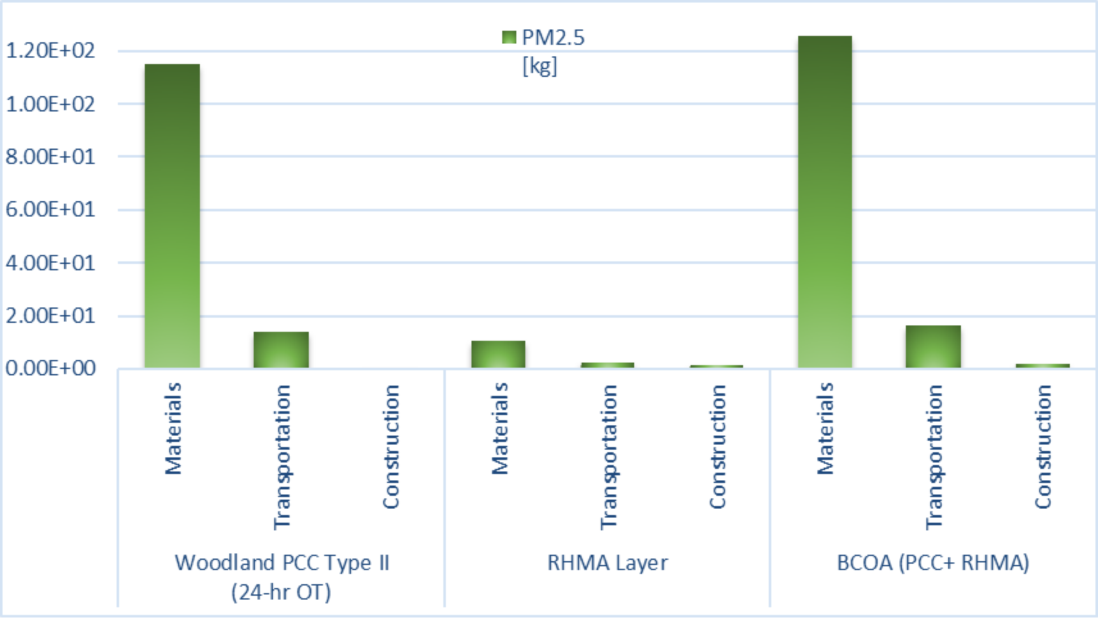


Figure 2-58. Human Health Particulate Effect results per life cycle stage per pavement layer (Woodland case study)

2.4.4.1. Sensitivity Analysis

As can be seen in Figure 4-6 through Figure 4-9, the thickness of the surface layer is an important factor affecting environmental impacts and energy consumption in the material stage. The second influential criterion is the additional RHMA layer under the surface rigid layer, resulting in a significant increase in the environmental impacts and primary energy demand. The results show an increase of 8 to 13% in GWP, POCP, $PM_{2.5}$, and PED-R. The sharp rise in PED-NR (75 percent) can also be seen in Figure 4-9 because of the feedstock energy in the asphalt mix and the tire rubber.

The difference in the concrete mix designs is another notable factor that causes emissions and energy consumption changes. HVS PCC Type III mix with 4 hours OT has the highest environmental impacts and energy consumption, followed by PCC Type II/V mix designs. It should be mentioned that the finer grinding of Type III PC and the higher amount of cement compared to Type II/V PC lead to higher environmental impacts.

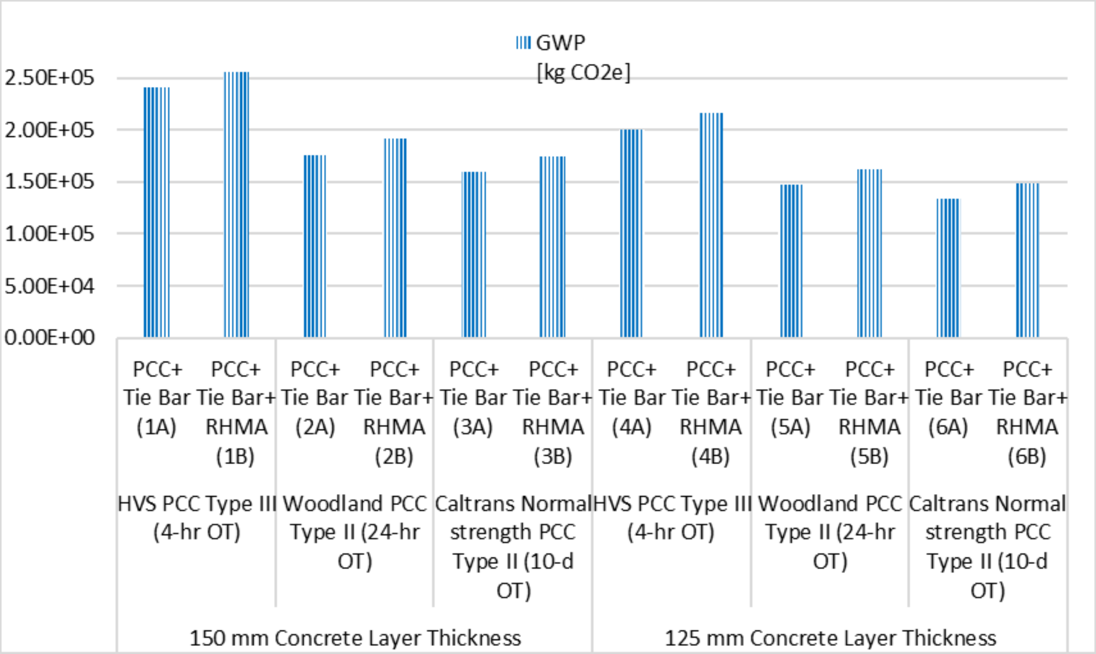


Figure 2-59. Global Warming Potential results in material stage for different alternatives

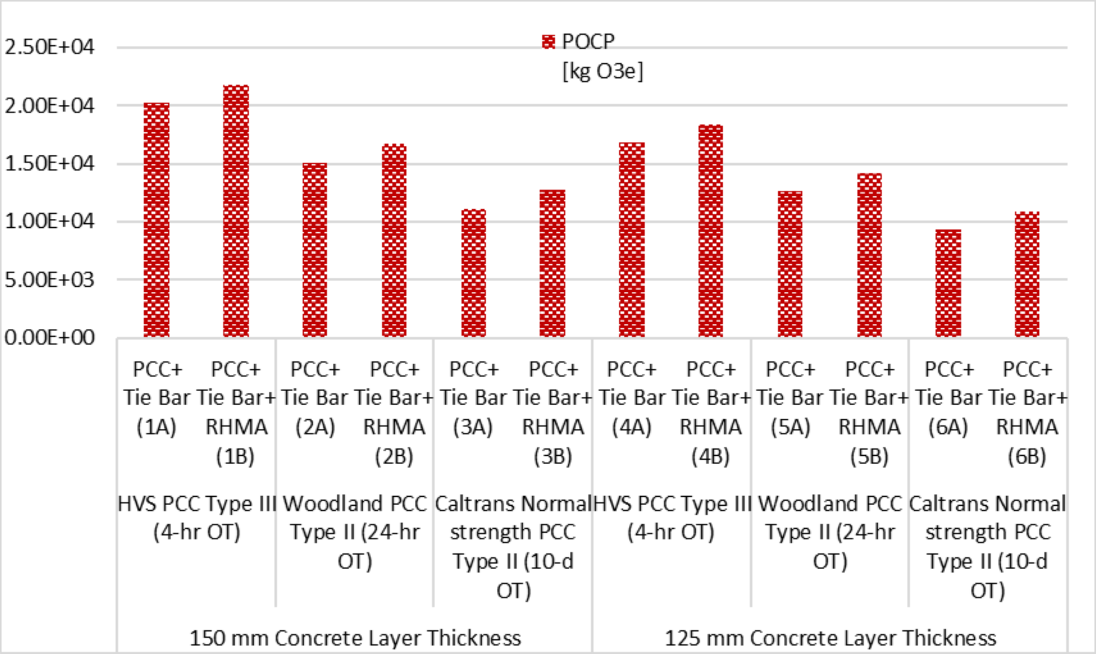


Figure 2-60. Smog Formation Potential results in material stage for different alternatives

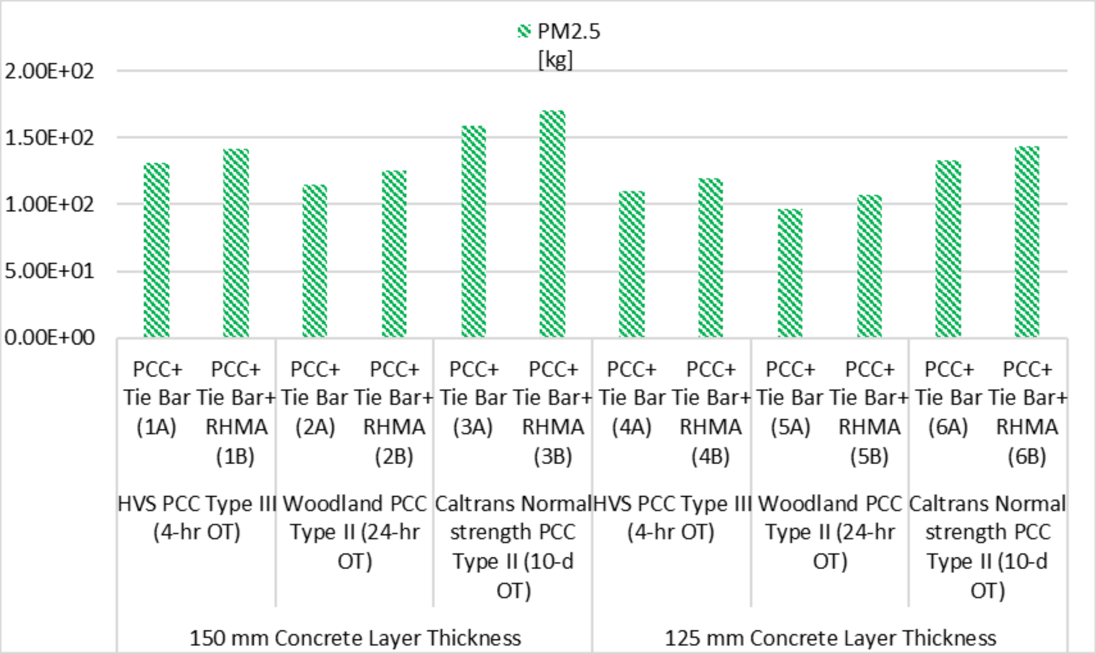


Figure 2-61. Human Health Particulate Effect results in material stage for different alternatives

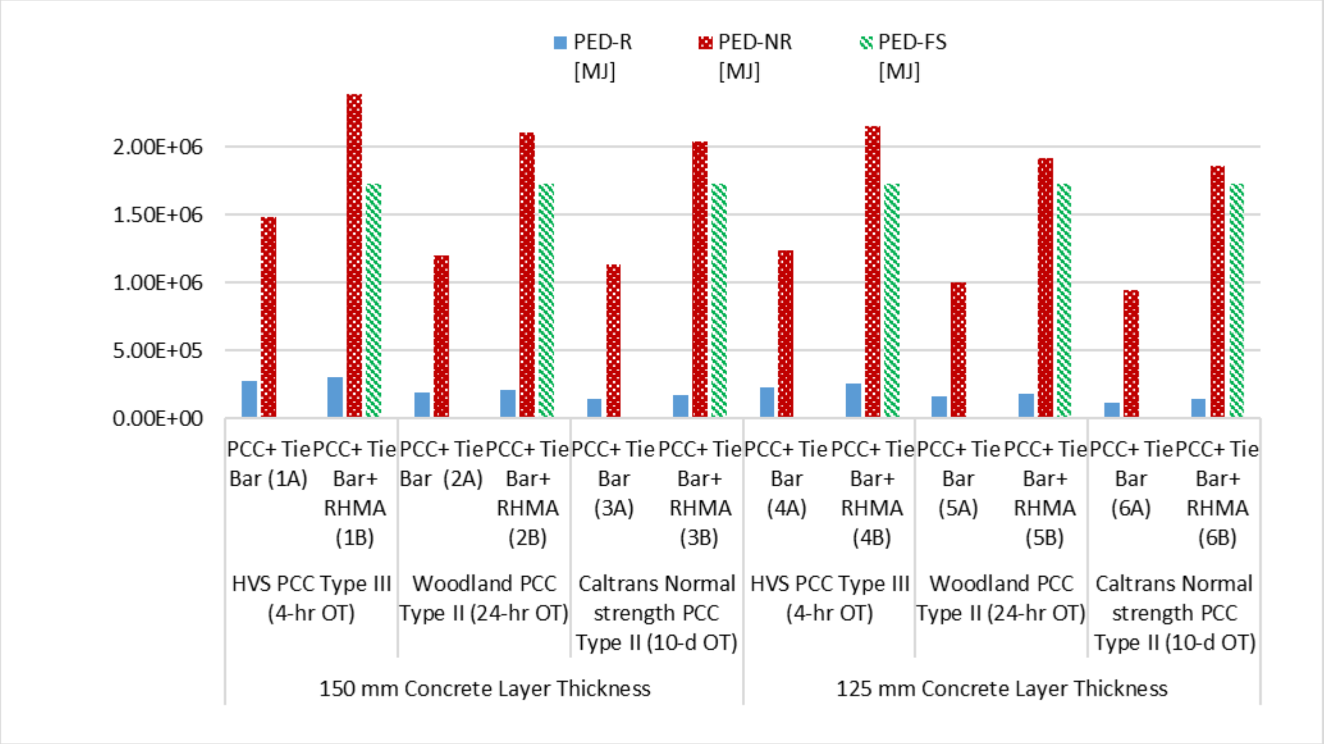


Figure 2-62. Energy consumptions result in the material stage for different alternatives

Caltrans normal strength PCC Type II/V with 10-day OT has a higher percentage of cement compared to Woodland PCC Type II/V with 24 hours OT (14 percent vs. 9 percent, respectively). According to Figure 2-59 through Figure 2-62 , Caltrans normal strength mix has a slightly lower impact in terms of GWP, POCP, and energy consumption compared to the Woodland mix. This study demonstrates the use of LCA to quantify and evaluate the environmental impacts of alternative materials, construction, and designs for a pavement structure. This analysis should consider the relative performance of the different designs if it is expected to be different.

CHAPTER 3. COMPLETE STREETS, SOCIO-ECONOMIC PERFORMANCE MEASURES, AND SOCIAL LIFE CYCLE ASSESSMENT FRAMEWORK

This chapter describes complete streets as a modern design philosophy for urban streets aiming to reach social and environmental benefits, defines socio-economic performance measures for complete streets, and develops social life cycle assessment framework for complete streets.

As funding for complete streets increases and the use of complete streets is encouraged to improve desirable social outcomes, appropriate indicators and performance measures are needed for decision-makers to prioritize funding between different complete streets projects and to select features to design into individual projects. Transportation is also moving to a time, through both federal legislation such as MAP-21 and various state and local policy frameworks, when performance outcomes are expected to be predicted for transportation investments and then measured afterward. The social indicators proposed by this study are intended for use in evaluating a project, and for comparing projects.

Complete streets are often proposed as an infrastructure-oriented intervention to improve social, economic, and environmental conditions of a neighborhood or corridor. However, there is still a lack of consensus regarding qualitative and quantitative approaches to evaluate or anticipate the effects of complete street interventions.

LCA has been adopted by the pavement field to systematically and objectively assess the environmental performance of pavement systems. Performance measures help stakeholders and decision makers assess the usefulness of investment decisions and their impact on users of the transportation system. Because complete streets are envisioned to provide environmental and socio-economic benefits, defining performance measures in terms of socio-economic and environmental impacts is an important step towards understanding the efficacy of complete streets to achieve desired outcomes.

Concurrent with the adoption of LCA in the pavement field, researchers have struggled to address the lack of social indicators available to LCA practitioners. If the ultimate goal of understanding environmental impacts is to improve the well-being of people and their environments, the lack of social indicators that assess the well-being of people to complement environmental indicators is clearly a critical gap that needs to be filled. There is currently a significant effort to develop appropriate social indicators under the auspices of Social LCA (S-LCA). There have been a number of studies and proposed performance parameters for evaluating complete streets projects, which were evaluated for inclusion in the proposed complete streets framework developed in this dissertation study and are discussed in this chapter.

3.1. Complete streets

3.1.1. Background

The complete street concept is a set of design concepts for streets and intersections (mainly urban) intended to improve the ability of active transportation users (primarily bicyclists and pedestrians), by making them safer, more comfortable and inviting compared with conventional modern streets, while also accommodating motorized transportation and parking. Complete streets are typically developed by transforming existing streets, which were built to facilitate motorized vehicle movement and parking, following complete streets design concepts. These design concepts have emerged and evolved over several decades (Appleyard 1980; Trancik 1986; Alexander 1987; Smith et al. 2010; NACTO 2013; Wendell 2015; Harvey et al., 2018; Harvey et al., 2020).

By making streets safer and more inviting it is expected that they will lead to mode choice changes away from motorized transportation and towards active transportation. A stated assumption in most complete streets literature is that complete streets will also lead to increased economic development by making an area a more attractive destination for shopping and social activities, and by becoming more welcoming to potentially vulnerable segments of the population such as children, senior citizens and people with physical mobility limitations (Harvey et al., 2018; NACTO 2013; Caltrans 2014).

Placemaking is another concept that has been put forward as a desired outcome from complete streets. The placemaking process helps build a community asset which is attractive, fun and safe, and promotes health and well-being (Wanat et al. 2016; Fritz 2017; Cosgrove et al. 2017). Another complementary concept to complete streets is context sensitive solutions (CSS). CSS is a process that aims to design a road project to into a given environmental and societal context (LaPlante and McCann 2011). The Toronto Center states that CSS is a project-oriented approach whereas creation of a complete street is a process-oriented approach; however, they may be complementary when applied together (Harvey et al., 2018, Toronto Center 2017).

Streets are shared public spaces whose functionality should safely accommodate motorized traffic, active transportation (bicycling and walking), and transit travel (NACTO, 2015). Additionally, complete streets designs should create economic benefits, and provide cultural and social spaces. Complete streets can fulfill different movement, environmental, and place functions, dependent on the street's type classification and the priorities for its functionality (Ostovar et al., 2021 and Hui et al., 2018). Complete Streets policies guide planning in communities by making the transportation system accommodating to all users, including vehicle drivers, pedestrians, and bicyclists, as well as those using public transportation. Complete streets policies are also strategies for building healthy and safe community environments that support active living (Moreland-Russell, 2013). The benefits of complete streets as identified as increased transportation choices, economic revitalization, improved return on infrastructure investments, livable communities, improved safety, more walking and bicycling to improve public health, greenhouse gas (GHG) reduction, and improved air quality (Pucher et al., 2010; SGA&NCSC, 2017, 2018, 2019; Caltrans, 2019). Movement of freight and emergency vehicles, and the required functionality of a street for specific types of these vehicles, should also be considered as important functions during multimodal commercial street planning and design, however these operators are often overlooked or viewed (NYSERDA, 2018).

Streets built prior to automobilization had multi-functionality, including space for businesses, vehicles, carts, and pedestrians (Project for Public Spaces, 2017). Many types of streets were public spaces, meant to be shared by all users; however, modern street designs are largely oriented towards efficiency and safety of automobile travel defined in terms of vehicle collisions and travel time (Smith et al. 2010; PPS, 2017).

The idea of "complete streets" is to restore the safe multi-functionality of streets so that the benefits that have been lost in the pursuit of motorized transportation travel time can be restored. Complete Streets America states that complete streets "are designed and operated to enable safe access for all users, including pedestrians, bicyclists, motorists and transit riders of all ages and abilities" (Smart Growth America a, 2018). A multitude of goals have been stated for complete streets in addition to improving the safety of non-motorized transportation, including reduced costs and environmental burdens, and creation of more livable communities, or in other words, the creation of livable, sustainable, and economically vibrant communities. According to Smart Growth America (2018a), "there is no singular design prescription for complete streets; each one is unique and responds to its community context”. To create a complete street and complete street design requires responding to community needs considering both the neighborhood and interconnectivity of neighborhoods, which then leads to selection of locations for complete streets and the features that are included in them (Harvey et al., 2018, Caltrans 2017 and Complete Streets Design Manual, 2010).

As funding to create complete streets is increasing in many parts of the U.S, the processes by which complete streets are located and funded has become more important. Issues that have come to the forefront include the “equity” of the investments in transportation infrastructure, including complete streets. Some of these issues exist in the processes that decide where complete streets projects get built, what goals they are designed to achieve, and whether they are beneficial or disruptive, including contributing to displacement of existing residents, particularly in disadvantaged communities. Disadvantaged communities are usually defined as low-income communities which are often communities of color. Examples of policy goals for transportation investment and design to address these issues include: 1) to counter displacement of core transit riders and other low-income people of color; 2) to preserve and grow local small business and other community institutions; 3) to produce and preserve housing for low-income households; 4) to create quality job opportunities for disadvantaged workers; 5) to eliminate criminalization of our communities; and 6) ensure quality, affordable, accessible multi-modal transportation options (Harvey et al., 2018 and ACT LA, 2018).

3.1.2. Best Practices for Neighborhood Planning

Without sufficient guidance on how to move from policy to practice, both agencies and neighborhoods are vulnerable to reliance on community engagement as a proxy for sound urban planning (Hernandez, 2021). The development and the testing of a framework of quantitative outcome-based environmental and social performance measures for complete streets project evaluation combined with neighborhood vulnerability and exposure information (such as is provided in this study by CalEnviroScreen) is intended to support the two concepts of best practices recommended by Hernandez (2021): location and sustainability. Following guidance from Hernandez early in its development, the unit of interest for the calculation of the performance measures (i.e., the location) is the neighborhood rather than the individual or the region. The framework considers sustainability to include both social and environmental performance indicators, which matches the best practices recommended by Hernandez (2021).

The interpretation of the social performance indicators is intended to identify the final values for the indicators for the complete street project and the amount of improvement or reduction in the indicator values (Ostovar et al., 2022; Harvey et al., 2022; Harvey et al., 2018). Access to the social determinants means access to opportunity (Hernandez, 2021), and transportation is the service that provides access to destinations that provide opportunity. The performance indicator calculation results are also intended to provide data for identifying investments in neighborhood transportation infrastructure and complete streets that are needed to improve indicator values. In particular, investments in transit access and use of complete streets to connect transit to opportunity destinations in the neighborhood and adjacent neighborhoods can improve many of the indicators.

3.1.3. Complete Street Design Guidelines and Policies

The complete street design guidelines typically discuss street typologies (different types of streets) followed by design elements for complete street components such as intersections, curbsides, sidewalks, roadways, bicycle paths, landscaping, and parking among other features. Guidelines tend to emphasize that complete street design is context-specific; and the design guidelines differ in some of their details and there are differences between guidelines intended for national use and those developed by states and local governments (Ostovar et al., 2022; Harvey et al., 2021; Harvey et al., 2018).

Several national, state, and local government complete street design guides were published in the last decade. Some examples of popular complete streets design guides include the National Association of City Transportation Officials (NACTO), North Carolina Department of Transportation (DOT), Florida DOT, New York City, Chicago, Boston, Philadelphia, City of Los Angeles and several others (Harvey et al., 2018). A list of complete streets policies and guides at different levels (i.e., state, regional, county, and city levels) was also published by the American Association of Retired Persons (AARP, 2019).

"The elements of a complete streets policy" developed by the National Complete Streets Coalition (NCSC) is a guidance document that identifies ten elements of a comprehensive complete street policy (SGA and NCSC, 2018). The guidance lists ten elements of an ideal complete street policy: (i) vision and intent, (ii) diverse users, (iii) commitment in all projects and phases, (iv) clear, accountable expectations, (v) jurisdiction, (vi) design, (vii) land use and context-sensitivity, (viii) performance measures, (ix) project selection criteria, and (x) implementation steps. The guidance states that considering these elements leads communities to implement policies efficiently, balance different modes' needs, and support economies, natural environments, and cultures. These elements are considered a best-practices national model that can be applied to all levels of governance in most types of CS policy (SGA and NCSC, 2018; SGA and NCSC, 2019).

The model developed in this dissertation study combining the use of social performance measures and socio-economic data regarding the neighborhood the complete street intended to support, provides an example of how socio-economic data can be integrated into the SLCA model using available tools. CalEnviroScreen data was used for these case studies since it appears to be a data source that is annually updated, contains a good array of data that provides indicators of local social and economic stability, and can be easily used because it has data for the case study corridors. The model addresses the following elements of the guidance: (ii) identification of the expected users and their social and economic conditions; (vii) performance measures including social performance measures. These two elements can be used to support (iv) clear, accountable expectations and (ix) project selection.

3.1.4. Performance Measures Considered in Complete Street Case Studies

More quantitative approaches are needed to evaluate the environmental, social and economic advantages and disadvantages of complete streets for cities and local authorities to select between alternative complete street designs, and to prioritize funding between alternative projects. To achieve these goals, performance measures and indicators are needed to support the decision-making process (Lenker et al., 2016).

In the last decades, many successful complete street projects in different states and cities of the U.S. have been performed (Gregg and Hess, 2019). Ranahan et al (2014) interviewed representatives from several municipalities with active complete street programs and found that none of them had gathered measurable data to calculate the impacts of their complete street projects. Ranahan et al.'s report provided a list of performance measures to demonstrate the impact of municipalities' complete street initiatives. The indicators evaluated seven areas of impact in their study: bicycle/pedestrian, citizen feedback, economic, environmental, health, multi-modal level of service, and safety. The resources used in their study included agency reports, existing complete street policies, journal articles, and scholarly books identified through electronic database searches (including google scholar, academic search complete, masterFILE Premier, EBSCOhost, MEDLINE), and phone interviews. They used McCann and Rynne's (2010) framework to classify and evaluate five complete street projects in terms of "outputs" and "outcomes".

Outputs were defined as the main features to classify the complete street projects (e.g., number of crosswalk enhancements, miles of on-street bicycle routes, etc.). Outcomes of complete street projects (i.e., bicycle/pedestrian, citizen input, economic, environmental, health, multi-modal level of service, and safety) were defined in terms of the impacts experienced by citizens, businesses, and the environment. Ranahan et al (2014) in their study used a measurement tool for each category that was developed considering potential importance, frequency of use, availability, cost, and strategies for measurement.

Lenker et al. (2016) evaluated the impacts of complete street projects in Buffalo, New York, and explored the feasibility of the data collection methods. Eight street corridors were selected due to their socio-economic diversity, a mix of commercial and residential uses, and a range of complete street features. Some residents, merchants, and streetscape users who lived near the complete streets or used them were surveyed. Surveys covered completed and planned (future) complete street projects.

To obtain a diversity of impacts in their study, the following data collection tools were used, including (i) streetscape quality (functional and aesthetic items in pedestrian spaces that provide amenity and utility to pedestrians and other street users); (ii) street usability and satisfaction for drivers, bicyclists, and pedestrians; (iii) traffic volume for vehicles, pedestrians, and bicyclists; (iv) accidents and injuries; (v) economic vitality; and (vi) health impact. It was determined in the study that after the complete street was built, 73.5% of residents, 58.4% of merchants, and 75.7% of streetscape users presented that they were “much more satisfied” or “somewhat more satisfied” with the street (Lenker et al., 2016). Considering available pre-implemented and post-implemented data points, the study results revealed that complete street corridors were safer in terms of crashes and injuries and absorbed higher volumes of pedestrians, bicyclists, and vehicles than the conventional street before conversion (or planned conversion).

Sukumana et al (2019) emphasized the needs of bike lanes in conventional streets and analyzed the design of bicycle lanes based on the complete streets concept for a road segment in Indonesia with high demand for both vehicle and bicycle transportation. The authors used a non-experimental descriptive research approach along with qualitative and quantitative approaches for their study. Data collection consisted of nonrandom on-site participant interviews and questionnaires regarding bicycle user's perceptions of security concepts and comfort using a bicycle lane in a complete street concept. The answers to the survey results indicated a large preference for a 1.5 m bicycle lane in particular sub-segments of the roadway to provide safety based on vehicle traffic levels, with higher traffic segments having a higher preference for the bicycle lane.

Of these studies considering performance measures for complete street projects (Lenker et al., 2016; Gregg and Hess, 2019; Ranahan et al., 2014; Sukmana et al., 2019), none of them evaluated the socio-economic and environmental impacts of the projects using the LCA approach.

3.2. Social life cycle assessment framework for complete streets

3.2.1. Background

Life cycle assessment (LCA) is a holistic approach in which the environmental sustainability of a product, project, process, or system can be assessed and quantified. Environmental LCAs quantify the energy, resource use, and emissions to air, water, and land for a product or a system. Social LCAs quantify the social and sociological aspects that are related to a system. The advantage of using an LCA methodology is that it is a systems approach, with system boundaries depending on the goal of the assessment study, and because it considers the life cycle to account for long-term impacts rather than only initial outcomes. One gap that has been identified in current LCA impact indicators is the lack of socio-economic indicators to complement the existing environmental indicators (Evans et al., 2008; Rosenbaum, 2014). Social life cycle assessment (S-LCA) can also help understand the processes that decide where complete street projects get built, what goals they are designed to achieve, whether they are beneficial, and determine who receives such benefits.

Previous studies, including Harvey et al., 2018 (Harvey et al., 2018) seek to develop a scientific method for evaluating the potential benefits or disadvantages of a complete streets project. Impacting the development of any method to evaluate publicly funded transportation improvements are Title VI of the Civil Rights Act of 1964 and Executive Order 12898, known as Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations, issued by President Clinton in 1984.

According to the US EPA, the purpose of these policies is to focus federal attention on the environmental and human health effects of federal actions on minority and low-income populations with the goal of achieving environmental protection for all communities. More specifically, the executive order is intended to promote nondiscrimination in Federal programs substantially affecting human health and the environment. Transportation projects, such as publicly funded complete streets projects, fall under the umbrella of Executive Order 12898 as well as Title VI. State, regional, and local government agencies are required to identify and address the disproportionately high and adverse human health or environmental effects of their actions on minority and low-income populations. Such prevention activities can help ensure that all communities and persons live in a safe and healthful environment by identifying and correcting adverse conditions, especially in low-income communities from being subject to disproportionately high and adverse environmental effects.

Although, Federal, State, and local funding agencies overseeing public infrastructure investment pay close attention to the provisions of Title VI and Executive Order 12898, little to no information is provided on how to meet these requirements. This Complete Streets SLCA model is an attempt to add to our knowledge of how complete streets projects can assist transportation planners in moving towards achieving environmental protection for minority and low-income populations. The model incorporates a number of indicators on social well-being using data sources on local socioeconomic conditions. Through this process, the Complete Streets SLCA demonstrates how a more rigorous analysis can inform environmental justice concerns in minority and low-income neighborhoods by helping us respond to three basic questions:

- Does the project cause harm – in particular to a legislatively designated disadvantaged area/priority investment area?
- Does the project benefit a legislatively designated disadvantaged area/priority investment area?

- Does the project improve access to the social determinants of health and/or community destinations that help manage social determinants?

LCA is proposed by this series of studies and some work by others as an appropriate tool to quantify environmental and social impacts of urban streets. However, most of this work has focused on environmental impacts of materials (such as Gamez Garcia et al., 2019; Hoxha et al., 2021) without considering the use stage and rethinking approaches to environmental LCA of transportation projects in general (Saxe et al., 2021), as does the environmental part of the framework considered in this study (Saboori et al., 2020). No study on LCA for complete streets that considered the combined environmental effects of construction and maintenance and their effects on the use stage was found in the literature except the one that was performed by Harvey et al. in 2018 including the author of this dissertation (Harvey et al., 2018).

A lack of socio-economic impact indicators and their corresponding quantification methods/models has been observed in LCA for some time (Rosenbaum 2014). Social life cycle assessment (SLCA) is still at the early stages of development (Haaster et al., 2017, Kuhnen and Hahn, 2017, Martinez-Blanco et al., 2015, and Benoit et al., 2010), unlike well-established methodologies such as environmental LCA (eLCA) and life cycle cost analysis (LCCA). UNEP and SETAC (Benoit et al., 2013) published “The Methodological Sheets for Subcategories in Social Life Cycle Assessment” to complement the SLCA Guidelines published in 2009 by the United Nations Environment Programme (UNEP) and support the development of SLCA case studies. The purpose of the UNEP sheets was to clarify the concepts of subcategories, recommended data sources, and existing policies for the SLCA (Benoit et al., 2013). The proposed framework by UNEP adopted the four LCA phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. According to this framework, SLCA can be applied as a standalone tool or combined with LCA to complement LCA with social and socio-economic indicators (Benoit et al., 2013; Du et al., 2014). Although UNEP developed a framework guideline for SLCA (Benoit et al., 2013), there is still a need for a framework for SLCA to measure the social impacts during the supply chain and product life cycle due to a lack of general standardized indicators (Kuhnen and Hahn, 2017; Corona et al., 2017; Arcese et al., 2018; Kroeger and Weber, 2015).

Kuhnen and Hahn (2017) argued that there is a need to standardize social indicators that provide uniform rules to avoid unnecessary variation and incomparable assessments. Their review paper entitled "Indicators in Social Life Cycle Assessment, A Review of Frameworks, Theories, and Empirical Experience", used five main guidelines, including Global Reporting Initiative (GRI) sustainability reporting guidelines, UNEP and SETAC SLCA guidelines and methodological sheets, UN millennium and sustainable development goals, Social Accountability International (SAI) SA 8000, and ISO 26000. Inconsistencies, gaps, and trends in SLCA research indicators across industry sectors were provided in these guidelines. In addition, the authors reviewed 141 scholarly articles that considered how to incorporate a life cycle or supply-chain perspective. Their reviews showed that the focus of most of the studies was on worker-related and health-related indicators which they argued missed other important indicators. They also found that many of the studies remain conceptual rather providing empirical data; 37% of the reviewed literature included non-empirical (conceptual) articles, and 63% empirical studies, including 50% qualitative and 50% quantitative approaches.

According to the UNEP guidelines (Andrews et al., 2009), the social life cycle impact assessment (SLCIA) phase includes three steps to define social and socio-economic impacts via social and socio-economic mechanisms as can be seen in Figure 3-1.

1. Selecting impact categories, characterization methods, and models.
2. Linking inventory data to specific SLCIA sub-categories and impact categories

3. Determining and calculating sub-category indicator results

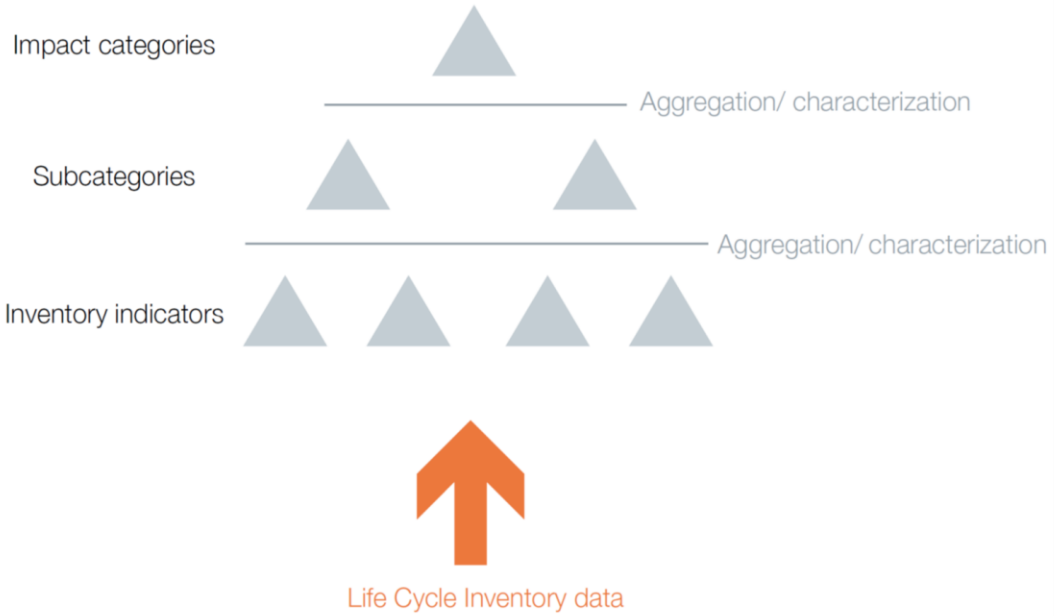


Figure 3-1. Concept of Subcategory (Andrews et al., 2009, Page 70)

According to the UNEP guidelines (Andrews et al., 2009, Benoit et al., 2013), two types of SLCIA methods or characterization methods are identified: Type 1) performance reference points, and Type 2) the causal-effect relations between indicators and social impacts. In Type 2 impact categories, as in eLCA, quantitative data and cause-effect chain modeling is required to aggregate indicators in characterization models. On the other hand, Type 1 impact categories do not make use of causal-effect chains. They use ordinal scales describing the risk, performance, degree of management or comparing the results to the context. The semi-quantitative form of Type 1 impact category models uses weighting systems called performance reference points for aggregation.

Qualitative and semi-quantitative indicators such as surveys and interviews are usually used in SLCA because of the nature of social impacts. Data collection is one of the most challenging parts of SLCA (Andrews et al., 2009; Du et al., 2014; Benoit et al., 2013; Haaster, 2017; Corona, 2017). Because the evaluation of qualitative indicators is subjective, categorizing such indicators into a scale or scoring system helps to convert the data to a form suitable for quantitative analysis (Andrews et al., 2009).

Most of the work on SLCA to date has been looking at relatively large-scale systems, such as countries, companies, or commonly available products. There has not been much work on SLCA for projects at the typical scales of a complete streets project: the neighborhood scale where the project is built, and the network-scale for the network that the project contributes to.

3.2.2. Approach for considering equity

There are a number of approaches that can be considered for social indicators for active transportation projects. The Federal Highway Administration (Semler et al. 2016) noted that "[r]ecognizing the disparate costs and impacts of transportation decisions on populations of different income levels, agencies are beginning to calculate equity factors. Households without access to vehicles may not be well-served by auto-oriented transportation solutions and require walking, bicycling, and transit infrastructure. One component of equity is ensuring that pedestrian facilities along public rights-of-way are accessible so they do not discriminate against people with disabilities and serve people of all ages and abilities." Caltrans (2017) in a report on performance measures for the state bicycle and pedestrian plan includes accessibility and equity together. This performance measure should "[e]valuate a system's overall accessibility, including its ability to accommodate residents with unique circumstances, such as people with disabilities and traditionally underserved populations" (Caltrans 2017). In a report on active transportation measures, Fehr & Peers (2015) state that "[e]quity performance measures evaluate the fair distribution of active transportation improvements and funding. They can be measured by the geographic diversity of the areas covered by a project, relative investment in Communities of Concern, or a project's compliance with ADA requirements."

A white paper on transportation equity, Karner et al. (2016) extended these recommendations to also consider the burdens of transportation projects, stating that "[a]n equitable transportation system would ensure that the benefits and burdens created by transportation projects, policies, and plans are shared fairly such that no groups would be unduly burdened by a lack of access to adequate transportation nor by the negative effects of proximity to transportation infrastructure. Such a system would also ensure that public participation in the transportation decision making process is meaningful and effective and that participants would have a reasonable expectation that their voices would be heard and decisions changed in response." Karner et al. also note that "[r]egional equity advocates often focus on the underlying causes of spatial differences in opportunity that arise from differential tax bases, school quality, and job opportunities across a metropolitan area." They observe from the literature and case studies that those differences in opportunity are commonly evaluated with respect to race, ethnicity and income level, and they are also evaluated with respect to rural, transit-dependent, and elderly populations.

The concept of equity was used in this study to test in three ways each potential performance indicator reviewed and selected later in this chapter for the complete streets LCA framework.

First, the interpretation of an indicator is important from an equity point of view. A performance measure may have a built-in bias towards putting a proposed project in an advantaged neighborhood versus a disadvantaged neighborhood depending on how it is written. As shown in Figure 3-2, if the performance measure is written to identify which proposed project will produce the best value for the indicator (in this case the highest value) then the project in the advantaged neighborhood on the left in the figure would get the highest priority. Alternatively, if the performance measure is written to select the project that creates the largest improvement (change) in the indicator rather than the highest final value, then the disadvantaged project on the right side of the figure would have a higher priority. Based on the definition of equity, the project shown on the right in Figure 3-2 in the disadvantaged neighborhood would produce a more equitable result because it would move the disadvantaged neighborhood towards a state of transportation opportunities more similar to those of the advantaged neighborhood. This interpretation of the performance measure will also permit comparison between projects in terms of benefit (change of performance) to cost, which can also be applied for identifying for the most cost-effective features included within a project.

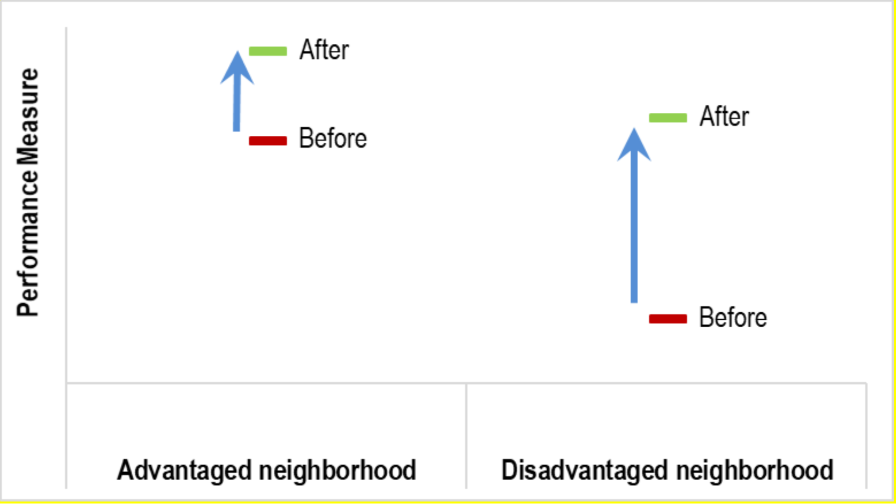
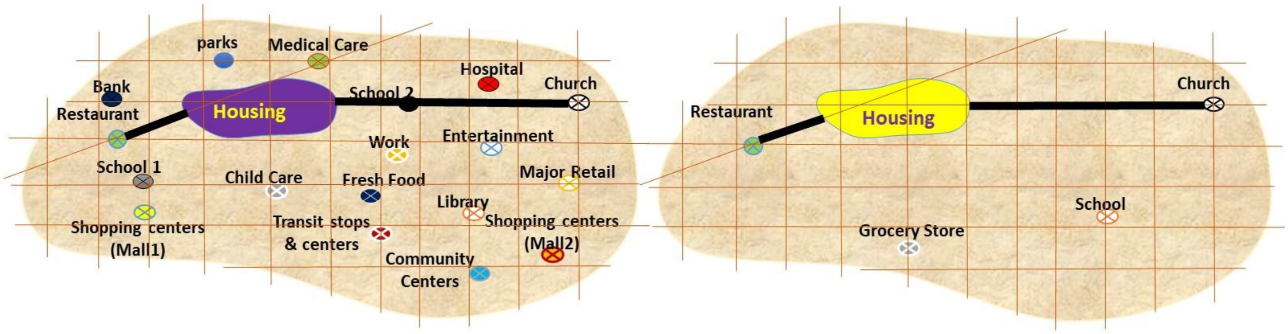


Figure 3-2. Evaluation of a Performance Measure for an Advantaged versus a Disadvantaged Neighborhood.

Second, many performance indicators for transportation projects calculate accessibility in terms of the number of connections or improvement of connections to opportunity destinations that a project will produce. What is missing from these performance indicators is the consideration of the number of opportunity destinations that are in the neighborhood. For example, Figure 3-3 shows similar complete streets projects on similar street grids in two neighborhoods, with an opportunity-rich neighborhood on the left and one that is disadvantaged in that regard on the right. Any performance measure that calculates the increase in access to opportunity destinations would result in a higher, better value for putting the project in the advantaged neighborhood on the left compared with putting the same project in the neighborhood on the right, simply because the neighborhood on the left has more locations to connect.



**Opportunity Destination-
Rich Neighborhood**

**Opportunity Destination-
Poor Neighborhood**

Figure 3-3. Consideration of Opportunity Destination Density in Two Neighborhoods when Considering Accessibility Measures.

A first step towards using a social indicator for active transportation access to opportunity destinations is to do a neighborhood assessment of the density of those destinations in the neighborhood, many of which are built by direct public investment in infrastructure or are encouraged or leveraged by public planning and investment. This process could consist of:

- Mapping opportunity destinations and supporting infrastructure of different types identified in the neighborhood
- Identifying past investment in opportunity destinations in the neighborhood. This should be identified on both a per-capita and per-area basis.

- The calculations should be repeated considering public dollars invested in opportunity destinations, since a common reason for low numbers is historical low public investment in opportunity destinations. These calculations should include both capital and maintenance funding, and it is best if they are shown separately.

If the first step shows inequities in opportunity destinations, and particularly if there is inequity in public investment in opportunity destinations and their maintenance, then public investment in access is not the primary issue, but instead investment in creating and maintaining more destinations and including active transportation access as a part of the creation of those opportunity destinations is needed. In other words, creation of destinations and active transportation options to reach them need to be bundled together.

A third consideration when identifying accessibility and connectivity performance measures is connectivity between neighborhoods by active transportation and/or active transportation combined with transit between adjacent neighborhoods, as shown in Figure 3-4. This type of connectivity facilitates people coming into the neighborhood to create more economic opportunity for its businesses and facilitates people in the neighborhood being able to access opportunity destinations in adjacent neighborhoods. The existing patterns of inter-neighborhood connections in many urban areas are often the result of historical transportation and housing planning decisions that resulted in segregation and limited connectivity between neighborhoods defined by race, ethnicity and/or income level. These were routinely created and enforced by race/ethnic/religious exclusions that were written into housing development covenants, sometimes by mortgage lending practices, sometimes by violence or the threat of it, and sometimes by elimination of connections by not building easy-to-use transportation connections or by placement of difficult-to-cross transportation facilities.

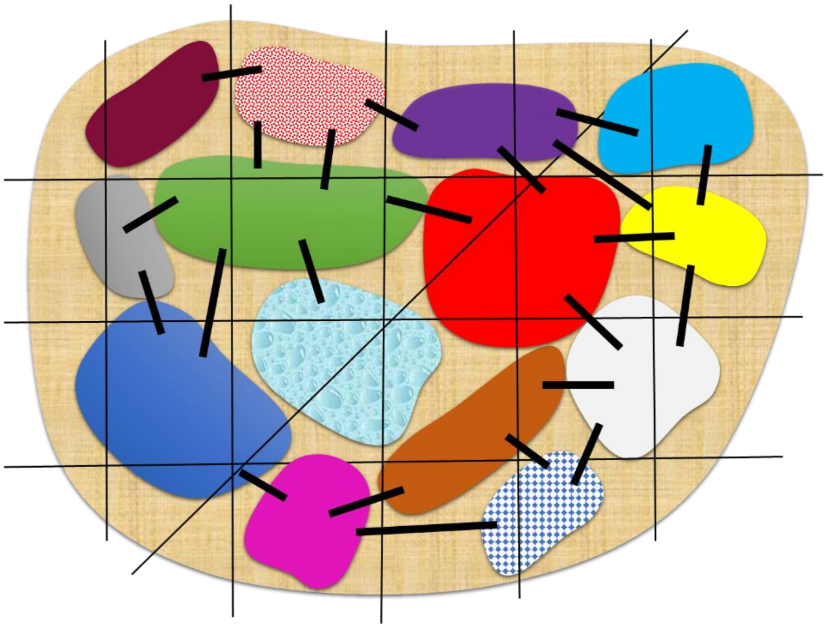


Figure 3-4. Consideration of Active Transportation and Transit-Active Transportation Connectivity between Neighborhoods.

An important consideration for social indicators and performance measures is that they consider projects that facilitate travel that uses mixed active transportation and transit modes, and not just active transportation. Transit is an important extender of the range and effectiveness of active transportation features such as complete streets to reach both within-neighborhood destinations and those in other neighborhoods, as shown in Figure 3-5. Calculation of travel times, connectivity and access for performance measures needs to include mixed mode trips and the opportunity destination mapping as a part of the consideration of equity should include the richness of transit stop connections that active transportation can connect to. Mixed mode trips are also an important part of consideration of equity, since the portion of the population that cannot afford car ownership and is dependent on transit for part of their trip is generally much greater in disadvantaged neighborhoods.

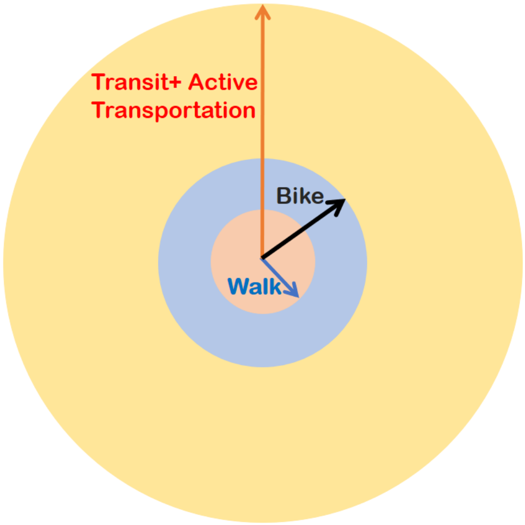


Figure 3-5. The Ability of Mixed Mode Travel Including Transit and Active Transportation to Improve Travel.

Another consideration is that environmental and social indicators and performance measures should be applicable to three functional units: 1) a functional unit of a neighborhood for performance of the project; 2) performance of the future built-out complete street network in the neighborhood if the project is a part of that planned network; and 3) on a regional basis for performance of the complete street network if the project is a part of the plan for connectivity between neighborhoods.

The purpose of the social indicators proposed by this study is to help bring quantitative analysis of complete streets projects into decision-making. The indicators are not intended to quantify the additional benefits of complete streets on neighborhoods in terms of “placemaking” or “location making” and other less tangible outcomes which may be of importance to decision-makers and neighborhoods, and for which non-quantitative assessment is likely most appropriate. However, the effects of placemaking will likely have some influence on some of the social indicators associated with economic/jobs outcomes if the placemaking leads to more economic activity.

3.2.3. Selection of Performance Measures for Complete Streets

At this point in the development of S-LCA, the term “social indicators” or “socio-economic indicators” is a generic term for all indicators that are not measures of environmental flows (resource inputs and emissions outputs) that affect natural systems or human health. From a sociologist’s point of view, the term social indicators can mean the characteristics of people or the outcomes of decisions that affect people in terms of quality of life. For the purposes of this study, and S-LCA, the term social indicators refer to measures of outcomes from decisions that affect quality of life. The first definition of social indicator, characterizing the people affected, is still applicable in planning and design of complete streets projects when considering who is affected by the positive, negative or indifferent outcomes of a decision. A comprehensive set of social indicators is identified that can be used as performance measures for complete street projects. Use of the full set of indicators or the selection of an appropriate sub-set of indicators to best evaluate a complete street project or its contribution to a complete street network with regard to the goals for changes in quality of life for the neighborhood resident is left to the planner and designer (Ostovar et al., 2022 and Harvey et al., 2018).

Indicator development and selection in this study focuses mostly on outcomes for all people affected by the project; however, some indicators consider the social demographic indicators of the people affected by outcomes. For example, the social indicators for connectivity of active transportation routes or mixed-mode transportation accessibility to important services may be considered to be more important for those who have fewer alternatives to motorized vehicles such as children, seniors or lower-income families or who live in places lacking in public transit investment and local amenities. The proposed indicators are also intended to contribute to equity assessment of projects (Ostovar et al., 2022 and Harvey et al., 2018).

3.2.3.1. Goal and Approach

The goal of this section is to select a set of social performance indicators appropriate for a complete streets LCA framework. Specifically, the desired characteristics for the S-LCA performance indicators are that they:

- Be applicable to comparisons between complete streets projects, and the travel networks they reside in, and between alternative transportation projects that involve other transportation modes or are multi-modal.
- Be comprehensive with regard to covering the range of desired values and outcomes for transportation projects across stakeholders.
- Have at least several important indicators in each subject area or "category" of goals/values identified in the literature, and
- Be practical with regard to the ability of stakeholders and the general public to understand them, and be practical, meaning easy to calculate or at least feasible to estimate with available data and other information.
- Select indicators in each category that have as little redundancy as possible in terms of what they assess.

There are a large number of potential indicators that can be considered in S-LCA, even after narrowing the scope to only consider those likely to be applicable and useful for complete streets projects. After a review of the literature, these two primary sources were used to produce a list of potential social performance measures: the FHWA Guidebook for developing performance measures for pedestrian and bicycle travel (Semler et al., 2016), and a Caltrans technical report regarding development of active transportation programs (Caltrans 2017). The selection of categories for social performance measures was taken as the first step towards development of S-LCA performance measures to ensure that the final selected set of measures is appropriately comprehensive. The proposed categories were selected based on those in the FHWA and Caltrans documents and feedback from the interviews and meetings described in chapter 3 of Harvey et al.'s study (Harvey et. al., 2018). Table 3-1 illustrates the categories of LCA performance measures proposed by this study, and the corresponding categories in the FHWA and Caltrans (Semler et al., 2016, Caltrans 2017)

The performance measures for transportation projects can be divided into two main categories, social and environmental. The environmental indicators are shown in Table 3-1 and some of those indicators overlap with social performance measures, particularly in the area of public health. Note that the FHWA Guidebook and Caltrans technical report, also included in Table 3-1, did not consider specific environmental indicators, but instead considered broad categories (e.g., environmental, sustainability).

As shown in Table 3-1, the proposed complete streets framework, which brings together LCA and S-LCA, has environmental performance measures in several distinct categories. The full set of environmental performance measures recommended in the FHWA pavement LCA framework (Semler et al., 2016) was too complex for use in most complete streets studies and a reduced set that covers what are thought to be the most important categories was selected. This same set was also used for a recently completely analysis of urban heat island effects of changing pavement albedo (CARB 2017).

Table 3-1. Summary of FHWA, Caltrans and proposed categories for social performance measures (Harvey et al., 2016; Semler et al., 2016; Caltrans 2017)

FHWA Goal Categories	Caltrans Goal Categories	Proposed Categories in this Study
Equity	Accessibility	Accessibility
Economic	Economy	Jobs
Connectivity	Mobility/connectivity	Connectivity/mobility
Health	Safety/public health	Safety/public health
Livability	Preservation	Livability
Safety	Recognition	

An additional reason for mapping social performance measure categories between the Caltrans and FHWA documents is that in the absence of completely standardized language for social performance measures, different terms are used for approximately the same measure, as can be seen in Table 3-1. For the same reason, and again to check that a comprehensive set of measures is proposed in each impact category, Table 3-2 shows the performance measures proposed by Caltrans and FHWA, and in cases where the terminology differed, Table 3-2 shows the selected terminology initially adopted in this study. These terms are indicated in bold type in the table. The table can be used to cross-reference the selected measures with the Caltrans indicators. The FHWA terminology was later changed for some indicators after additional review for equity and to improve the clarity and comprehensives of the indicators.

Table 3-2. Caltrans Performance Measures compared to FHWA Performance Measures and Terminology Initially Adopted in this Study (bold type indicates initially adopted terminology)

Caltrans Performance Measures	FHWA Performance Measures
Access to community destinations	**Access to community destinations**
Adherence to accessibility laws	Adherence to accessibility laws
Crossing opportunities	Crossing opportunities
Density of destinations	Density of destinations
Network completeness	Network completeness
Population served by walk/bike/transit	Population served by walk/bike/transit
Transportation-disadvantaged population served	Transportation-disadvantaged population served
Access to jobs	**Access to jobs**
Job creation	**Job creation**
Land value	Land value
Retail impacts	Retail impacts
Average travel time	**Average travel time**
Average trip length	**Average trip length**
Connectivity index	**Connectivity index**
Delay	**Bike/pedestrian delay**
Level of service	**Level of service**
Mode split	Mode split
Person throughput	Person throughput
Route directness	Route directness
Volume	Volume
Miles of pedestrian/bicycle facilities	Miles of pedestrian/bicycle facilities
Presence, width, and condition of bicycle and pedestrian facilities	
Adherence to traffic laws	Adherence to traffic laws
Bicycle miles traveled	**Vehicle miles traveled (VMT) impacts**
Bicyclist or pedestrian collisions per mile traveled (or other exposure measure)	**Crashes**

Caltrans Performance Measures	FHWA Performance Measures
Number of bicycle/pedestrian fatalities	**Crashes**
Number of bicycle/pedestrian serious injuries	**Crashes**
Pedestrian miles traveled	**Vehicle miles traveled (VMT) impacts**
Perceived safety of walking /bicycling	User perceptions of comfort and safety
Bicycle level of service / Bicycle compatibility index	**Level of service**
Bicycle level of stress	**Level of service**
Land consumption	**Land consumption**
Street trees	**Street trees**
Utilization of walking for short trips and biking for short trips (% of all trips)	N/A
Vehicle miles traveled (VMT) and GHG Impacts	**Vehicle miles traveled (VMT) impacts**
Bicycle friendly communities	N/A
Bicycle friendly state ranking	N/A
Walk friendly communities	N/A

Note: Proposed indicators included in the framework are shown in bold type

The final selected performance measures used in the framework of this study are shown in Table 3-3, organized by the selected goal/value category. As noted by FHWA (Semler et al., 2016), there are multiple measures that can be used within each category, and since they often address similar attributes, inclusion of all of the possible measures in a category is not desirable because of the extra work needed to complete a study and the work on the part of the reader to understand multiple measures that can have various levels of redundancy. Measures selected within each category therefore needed to be screened for clarity, overlap and simplicity of calculation or estimation. Table 3-3 shows the recommended performance measures based on whether they reflect to the goals of the complete street approach, and whether data are available to calculate the measure. In the next sections of this study, a brief description of each performance measure, the data resources required, calculation methods derived from FHWA guidance, and example studies are provided.

Table 3-3. Social Performance Measures Selected for Use in the Proposed Framework

Selected Category	Selected Performance Measures
Accessibility	Access to Community Destinations
	Access to Schools
Jobs	Access to Jobs
	Job Creation
Mobility/Connectivity	Active Transportation to Local and Regional Transit Connectivity Index*
	Connectivity Index
	Bike/Pedestrian Delay
	Level of Service (Auto)
Safety/Public Health	Level of Service (Bicycle Level of Service)
	Level of Service (Pedestrian level of Service)
	Level of Service (Bicycle Level of Stress)
	Crashes
	Physical Activity and Health
	Vehicle Miles Traveled (VMT) Impacts
	Pedestrian Miles Traveled (PMT)*
	Bicycle Miles Traveled (BMT) *
Livability	Green Space*
	Street Trees

** Not in the FHWA guidance*

Details of the performance measures selected for the framework after reviewing expected practicality and internal review for equity are shown in Section 3.3, including discussions regarding how some performance measures were redefined for this project. These performance measures are reviewed by stakeholders as part of the case studies (CHAPTER 4).

3.2.4. Proposed Socio-economic performance measures for complete streets

As mentioned in the previous section, two primary sources used to develop a list of potential performance indicators in the complete streets LCA framework considered in this study were the FHWA Guidebook for developing performance measures for pedestrian and bicycle travel (Semler et al., 2016) and a Caltrans technical report regarding the development of active transportation programs (Caltrans, 2017a). Table 3-3 shows the list of social performance measures that were included in the complete street LCA framework based on adaption of guidance from these two sources. The indicators and methods of calculation for the indicators are primarily taken or adapted from the FHWA Guidebook, except as noted in the table. Definitions and calculation methods for these indicators are described in detail in Section 3.3.

The set of indicators evaluated in this study is based on work done by FHWA and some recommendations from Caltrans that are more than 6 years old. There has been considerable work on level of service indicators for bicycle and pedestrian travel since then. While a complete update of the indicators was not part of the proposal for this project, a limited review of updates to the level of service indicators was completed.

A conference reviewing pedestrian and bicycle safety research conducted at university transportation centers was held in December 2016 and the proceedings were published by the Transportation Research Board (TRB, 2016). Results of breakout sessions at the conference regarding bicycle travel and infrastructure identified a need to bridge "the gap between perceptions of safety and actual safety outcomes". The groups called for more effective quantification of the "performance of the infrastructure and using the correct surrogate safety measures that translate into meaningful safety outcomes and reductions in crashes and serious injuries." This points out that BLOS is a measurement of perception of risk and safety, while the Crashes performance indicator is measurement of the most dangerous of safety outcomes.

A pedestrian and bicyclist road safety audit guide produced by Goughner et al (2020) for the Federal Highway Administration lists the factors influencing a pedestrian's decision to walk or not as including (only those affected by the infrastructure shown):

- Distance and access to desired destinations
- Accessibility and space, where space includes conforming to Americans with Disabilities Act (ADA) specifications for dimensions
- Intersection safety

- Safety and comfort

Regarding safety and comfort, the FHWA guide notes that factors affecting the pedestrian's perception of safety and comfort by the pedestrian "include high-speed traffic, lack of separation from vehicles, inadequate crossing facilities, lighting conditions, and poor quality of the walking experience."

Principles affecting a bicyclist's decision to use their bicycle identified in the FHWA guide, also limited here to those connected to infrastructure, include:

- Space, with specific dimensions recommended for the width of the bicycle lane or path
- Vertical gradients affecting ability to pedal, and accelerate and decelerate at intersections
- Network connectiveness, including directness of routes, and continuity and connectivity of bicycle facilities
- Comfort

Factors listed as affecting perceived bicycle risk and comfort "include degree of separation from vehicular traffic, lighting, roadway condition, and a rider's confidence in ability." The guide notes that other studies "found that bicyclists rated facilities having a higher degree of separation from drivers more positively, with protected/separated bike lanes and multi-use paths being the best. The study also showed that parking was a clear deterrent for comfort, perceived safety, and willingness to bicycle."

A study by Mensomore et al (2020) found that "a key tool in designing low-stress networks is the use of separated or protected bicycle lanes, and intersections are the critical links." The study was based on analysis of the perceived level of comfort of current and potential bicyclists from 277 survey respondents who rated 26 first-person video clips of a bicyclist riding through mixing zones, lateral shifts, bend-in, bend-out, and protected intersection designs. A total of 7,166 ratings were obtained from surveys conducted at urban and suburban location in four states. The results showed that designs that minimize interactions with motor vehicles, such as fully separated signal phases and protected intersections, are rated as most comfortable. Mean comfort drops off significantly for other designs and interactions with turning vehicles result in lower comfort ratings though there are differences for each design. Comfort decreases as the exposure distance increases, measured as the distance a person on a bicycle is exposed to traffic.

A review of bicycle level of service (BLOS) research over the last three decades completed in 2020 by Kazemzadeh et al., focused on user perceptions of comfort to provide guidance for decision-makers and planners. Separated bicycle facilities were noted to consistently rank as most important features. The review found that "despite general agreement among existing BLOS variables and the adopted indices, several important research gaps remain to be filled." Those mentioned included attention to trip-end facilities such as bicycle parking facilities (also noted in the FHWA guide), the challenges associated with separated bicycle facilities (e.g., the presence of electric bikes and electric scooters)". Other considerations covered regarding infrastructure included utilities in the path such as access covers, pavement macrotexture and roughness, and the presence of speed bumps use for vehicle traffic calming.

Fitch et al (2022) reported results from a similar study to Mensomore et al.'s using video from a variety of urban and semi-rural roads around the San Francisco Bay Area where bicycling rates vary. The results indicated considerable effects of socio-demographics and attitudes on absolute video ratings, but relative universal agreement about which videos are most comfortable and uncomfortable. The presence of bike infrastructure and low speed roads are especially important in generating higher comfort ratings, but may still not convince everyone to use a bicycle.

The results provide guidance for improving roads with on-street bike facilities where protected or separated facilities may not be suitable.

3.3. Performance Measures Description

This section of this chapter presents a summary description of the indicators. Methodology and data collection are discussed completely in a study developed by Harvey et al. (Harvey et al., 2018) and are discussed in CHAPTER 4 for each case study, separately.

3.3.1. Access to Community Destinations

Access to community destinations reflects the proximity of pedestrian, bicycle, and transit infrastructure and services to origins and destinations. Community destinations include (Ostovar et al., 2022; Harvey et al., 2018; adapted from Semler et al., 2016):

- Parks
- Grocery stores
- Medical centers
- Senior day care centers
- Businesses with a certain number of employees
- High-density residential locations
- Community centers
- Community colleges
- Community services
- Government offices
- Major tourist destinations
- Major retail and entertainment locations
- Office buildings
- Places of worship

- Public libraries
- Retirement homes
- Transit centers
- Universities and colleges.

Transportation agencies should define specific destinations which are to be included in the scope of the case study analysis. It is important to mention that access to school is treated as a special separate performance measure which is discussed in a later section.

The assessment consists of counting the community destinations within a reasonable travel time or distance (active transportation or combination of active and transit transportation) of a complete street project. The density of community destinations in a neighborhood should be considered when interpreting the results from this indicator for a given neighborhood and comparing projects in different neighborhoods . This indicator should not be used to compare projects unless they have a similar number of destinations within some pre-determined range. Comparison of neighborhoods that do not have similar numbers of community destinations (potentially broken down by types) within a reasonable travel time or distance may be more of an indication that a community needs more community destinations than an indicator of the value of the complete street project to connect to destinations.

Use of this indicator to prioritize funding for complete streets without this consideration will lead to the selection of projects in areas that are already advantaged in terms of the richness of destinations. If the preliminary analysis indicates that there are few community destinations, this will indicate that investment to increase the number of destinations would be the first step towards improving more equality of quality of life and equity between the neighborhoods, and complete streets and transit can be included in those destination development projects to provide active transportation access (Ostovar et al., 2022 and Harvey et al.,2018).

The required data for this performance measure is the number of destinations (depending on the category) and the number of people (employees/customers) who typically visit that destination, sorted by proximity to the complete street. Three values were calculated for this indicator: the access to community destinations before the construction (or proposed construction) of the complete street, the access to community destinations after the complete street, and the change in access to community destinations by means of the complete street. For this and the other two case studies, there was no access by complete street prior to the case study complete street, therefore the starting point for the change in access by means of the complete streets is zero access. The access values before and after are controlled by the number of destinations, which may go up or down for any number of reasons in the short time between before and after complete street construction.

The cumulative method was selected as a measurement method. Accessibility was calculated for specific time thresholds, and the result was a simple count of reachable destinations within each threshold.

$$A_i = \sum O_i\, f(C_{ij})$$

A_i = accessibility for location i

O_j = number of opportunities at location j

C_{ij}= time cost of travel from I to j

$f(C_{ij})$ = weighting function

$$f(C_{ij}) = \begin{cases} 1 & \text{if } C_{ij} \le t \\ 0 & \text{if } C_{ij} > t \end{cases}$$

t = travel time threshold

Assumptions include:

- O: Number of students + employees,
- t= 20 min,
- f (C)= 1

According to the complete street LCA framework (Harvey et al., 2018) and FHWA guidelines (Semler et al., 2016), the following measures were proposed for evaluating access to community destinations. Operational measures of walking and cycling accessibility were reviewed to select the best method for each case study, or active transportation plus transit. Four situations were considered (see Figure 4-9) that include:

- Walking mode: A number of destinations can be accessed within half a mile along with a walking network from a given point on the network.
    - Three points on the complete street were selected that include two edge points and one point at the center of the street. A 0.5-mile radius circle is then drawn from each of the three points.
- Bicycling mode: A number of destinations can be accessed within two miles along with a bicycling network from a given point on the network.
    - Three points on the complete street were selected, which include two edge points and one point at the center of the street. A 2-mile radius circle is then drawn from each of the three points.

- Transit mode: A number of destinations can be accessed within three miles or 4.5-miles along with a transit network from a given point on the network.
    - Three points on the complete street were selected, which include two edge points and one point at the center of the street. A 3-mile and a 4.5-mile radius circle are then drawn from each of the three points.

For multimodal trips, transit schedules were studied for local buses, trains, and light rail. To calculate the average speed and travel times, the destination routes were mapped in Google Maps™ for different modes of transportation in a specific trip, which resulted in a multi-modal trip distance. Data collection is challenging for access to community destination performance measures since data needed (i.e., number of destinations in a specific area, number of employees, and number of customers) for this indicator's measurement were not collected by the cities from before or after construction (or design plans if not yet built). Therefore, historical satellite imagery of Google Earth™ was used for the data collection.

3.3.2. Access to Schools

3.3.2.1. Description and Methodologies

Access to school reflects the proximity of pedestrian, bicycle, and transit infrastructure and services to schools. Schools are separated from the access to community destinations indicator because of the vulnerability of the student population and the importance of helping to establish transportation mode choice impressions early in life for the full range of possibilities to be considered "acceptable" later in life (Harvey et al., 2018; Evenson et al., 2010).

The assessment should consider whether a school is accessible to the populations of students that are assigned to it if the complete street project is built and if the complete street project is part of a plan for an active transportation/transit network. If there are not enough schools, this would suggest that investment in neighborhood schools closer to student residences should be a first step towards equity and improving the density of school access between neighborhoods, and complete streets and transit can be included in those destination development projects to provide active transportation access. Having nearby schools is more important for disadvantaged neighborhoods because they tend to have fewer transportation alternatives to begin with (Ostovar et al., 2022 and Harvey et al.,2018).

The assessment should also look at the change in the number of students who can access the school with the building of the complete street/transit project. As with the other access indicators, three values were calculated for this indicator: the access to schools before the construction (or proposed construction) of the complete street, the access to schools after the complete street, and the change in access to schools by means of the complete street. Use of the change in the number of students who have access by complete street is provided instead of only counting the number of students who have access since more advantaged neighborhoods may already have existing complete streets (Harvey et al.,2018).

According to the complete street LCA framework (Harvey et al.,2018), and FHWA guideline (Semler et al., 2016), the following measures are used for evaluating access to school.

- Number of schools can be accessed within a ½ mile along with a walking network functional for students from a given point on the network.
- Number of schools within 2 miles along with a bicycling network from a given point on the network.
- Number of schools within combined bike or walk and transit trip of 20 minutes to specific schools (Semler et al., 2016; Harvey et al., 2018 and Ostovar et al., 2022).

Another suggestion for an additional measure of this indicator was to send a survey/questionnaire to school principals near the complete street to provide better information regarding students' and employees' travel behaviors to and from their school. As shown in Figure 3-6, there is a possibility that students who live further away from the complete street do not necessarily need to use the complete street in their travel to school. Possible reasons include:

- Example A – The student may not be using the complete street as both the school and student's home are located on one side of the complete street.
- Example B – The student may only be crossing the complete street and may not be using it if both the school and student's home are not located on the same side of the complete street.

Figure 3-6. Possible Students' and Schools' locations

3.3.2.2. Questionnaire

Surveys were developed for school principals who could provide better information about how students travel to the school, and students' and parents' perceptions. The survey instruments for elementary, middle, and high schools are provided in APPENDIX C. The survey/questionnaire was designed to aid the understanding about how children get to school and parent perceptions of safety and convenience including transit services and active transportation now available or that may be available after the construction of the complete street. Two of the major interests of this study were to:

- Estimate the mode choice between students' homes and schools, and
- Learn effects of complete streets on student travel to and from school.

The aim of the surveys was quantification of the benefits to students from the conversion of streets into complete streets. No personal data of schools, school representatives, parents or students were collected. Participation in research was completely voluntary. The survey instrument and methodology were submitted and approved by the UC Davis Institutional Review Board (IRB) for research involving human subjects.

3.3.3. Access to Jobs

Access to jobs illustrates the ability of pedestrian, bicycle, and transit infrastructure and services to provide access to places of employment. Transportation investment can impact communities since it offers people accessibility to a greater number and a greater variety of employment opportunities (Ostovar et al., 2022, Harvey et al., 2018 and Semler et al., 2016).

Access to jobs is particularly important for disadvantaged neighborhoods with low car ownership or the ability to pay for car use and car ownership. ownership or ability to pay for car use. To evaluate the equity of using this indicator for active transportation, first, a neighborhood assessment of the density of places of employment in the neighborhood should be done. Access to jobs is calculated by counting places of employment and estimating the number of jobs at each employment location. Places of employment are identified by sources such as Google Maps and Apple Maps. The evaluation identifies the number of places of employment within 20 minutes of a complete street/transit project. Comparison of projects in different neighborhoods should consider whether a similar number of places of employment exist within the pre-determined range. Using this indicator will lead to the selection of the project in the advantaged neighborhood in terms of the richness of employment destinations. Therefore, the first step towards more equity between the neighborhoods and complete streets/ and transit would be private and public investment to increase the number of places of employment included and include in that investment projects to provide active transportation/transit access. Another consideration to evaluate the equity of the access to jobs indicator is connectivity between neighborhoods by active transportation and/or active-transportation combined with transit between a neighborhood and adjacent neighborhoods where there are employment opportunities.

As with the other access indicators, three values were calculated for this indicator: the access to jobs before the construction (or proposed construction) of the complete street, the access to jobs after the complete street, and the change in access to jobs by means of the complete street. If there was no complete street access before the case study complete street project, then the initial value for change of access by a complete street was zero.

If there are few job locations within a neighborhood, then the indicator may suggest that private and public investment is needed to increase the number of places of employment in the neighborhood and include in that investment projects to provide active transportation/transit access. Interpretation of this indicator should also look at the change in the number of jobs that become accessible by complete street with the building of the complete street/transit project and the complete street network it is a part of, rather than the number of jobs that become accessible.

Comparisons of the change of accessibility within the neighborhood for different projects can potentially provide a more useful result instead of the number of jobs made accessible (Ostovar et al., 2022 and Harvey et al.,2018). As with the other access indicators, the number of jobs may increase, decrease or remain static over the short period between before and after construction of the complete street. That change may be influenced by the complete street, or have nothing to do with it.

In addition to within neighborhood accessibility, an important consideration is the connectivity between neighborhoods by active transportation and/or active transportation combined with transit between a neighborhood and adjacent neighborhoods where there are employment opportunities. Connectivity between neighborhoods happens as complete streets within neighborhoods become connected to those in other neighborhoods. This can be assessed by looking at whether the complete street makes such connections or is part of a planned network of complete streets.

3.3.4. Job Creation

Job creation estimates the number of jobs expected to change in the neighborhood or region in which the complete street/transit project is built related to the modifications in infrastructure and pedestrian and bicycle travel policies. Transportation investment can influence local employment with both temporary construction jobs and permanent jobs. Permanent jobs are defined as jobs that exist after completing construction (Ostovar et al., 2022 and Harvey et al.,2018).

Most of the guidance available on job creation consists of “top-down” measures based on results from other projects. In other words, job creation resulting from previous projects is used to develop local impact indicators for use in future projects. The alternative, not discussed in the available guidance, is a “bottom-up” estimate for a complete streets/transit project and the effect of that project on the projected future built-out complete streets network if the project is a part of that network. (Harvey et al., 2018)

In a neighborhood where jobs are currently being lost, job retention may be a part of job creation. Evaluation of recent trends in jobs (increasing, static, or declining) is part of the pre-complete street comparison of different projects. Examples of job creation include construction and construction-related jobs, which would be of a more temporary nature, as well as longer-term job creation in areas such as manufacturing, food processing, wholesale trade businesses, transport by truck, employment services, food services, and drinking places, services to buildings and dwellings, management of companies and enterprises, real estate establishments, maintenance and repair construction of non-residential structures, accounting, tax preparation, bookkeeping, and payroll services (Ostovar et al., 2022 and Harvey et al., 2018).

There are strong arguments that job retention and retention of talent in disadvantaged neighborhoods by making them more attractive to stay in for local residents should be a focus of investment (Brancaccio and Conlon, 2022, as an example).

For a given project, a bottom-up estimate can be made using economic projections typical in local planning techniques to estimate future job creation, preferably broken down by temporary construction jobs and permanent jobs, required qualifications or job category type, and expected pay levels. Permanent job growth can take time after a complete street is installed, and a bottom-up approach requires counting places of employment several years or longer after completion of the street. That was outside the scope of these case studies.

Recent research shows that while pedestrian and bicycle infrastructure projects create 11–14 jobs per $1 million of expenditures, highway infrastructure projects create seven jobs per $1 million of spending (Harvey et al., 2018; Garrett-Peltier, 2011; SCAG, 2016).

The methods below are suggested to measure job creation by the 2016 FHWA guidebook (Ostovar et al., 2022, Harvey et al., 2018 adapted from Semler et al., 2016):

- “Number of jobs created by construction project – measure the direct number of temporary construction jobs.
- Retail sales tax findings – track new employers and the associated number of permanent jobs attracted to the project area.
- Employment data – review Census and BLS data to track the change in employment over time.”

However, since distinguishing between permanent and temporary jobs is not easy, this study uses job categories from Garrett-Peltier (2011), including direct, indirect, and induced jobs. According to the definition, direct jobs are created in the engineering and construction firms which are involved in infrastructure projects. In contrast, indirect jobs are created in the supply chain of industries such as cement manufacturing, sign manufacturing, and trucking. Moreover, workers in the direct and indirect sectors spend their earnings, leading to creating demand in industries such as food services and retail establishments, resulting in the induced effects and creating induced jobs (Garrett-Peltier, 2011).

3.3.5. Connectivity Index

3.3.5.1. Description and Methodologies

The number and directness of travel routes and options available to a user depict connectivity, while the number of specific measures used to assess walking and bicycling connectivity in a specific area present the connectivity index (Ostovar et al., 2022 and Harvey et al., 2018 adapted from Semler et al., 2016).

To use this indicator for active transportation/transit projects, first, the number of travel routes and options available to a user should be measured. The evaluation contains the number of intersections density and intersections per linear mile. These measures are defined by the number of intersections in a given land area (e.g., a square mile or acre); the number of intersections in a given land area divided by the linear network miles in the same given area; the number of linear miles of a street or other facility per given area (square mile); or the number of 3- or 4-way intersections divided by the number of intersections. To review this indicator for equity evaluation, the density of routes assessment between the neighborhoods and complete streets/ and transit should be assessed, and the indicator should look at the change in connectivity as opposed to the final value for connectivity. A neighborhood that is already well connected will have higher connectivity from a project, whereas a poorly connected neighborhood will likely have the greatest improvement in connectivity, although it may not have the final highest connectivity.

3.3.6. Active Transportation to Local and Regional Transit Connectivity Index

The number and connectivity of functional bicycle and walking travel routes to transit nodes that connect to within-neighborhood destinations, and the number and directness of functional bicycle and walking travel routes that connect to transit nodes that connect to out-of-neighborhood destinations are measures used to assess walking and bicycling connectivity to active transportation. The purpose of this indicator is to identify the ability to travel to and from a transit point by walking or bicycling, including considering the richness of within- and between-neighborhood transit points in a neighborhood (Ostovar et al., 2022 and Harvey et al., 2018).

The following measures can be used for calculating this indicator:

- Bicycle/ pedestrian facility density within 1 mile of a regionally significant transit or rail station: This measure, which is defined as the presence of several bicycle and/or pedestrian facilities within one mile of a regionally significant transit or rail station, depends on the location of significant transit stations, and bicycle and pedestrian facility data from local jurisdictions and transit operators. Aerial imagery or GIS can be used to calculate this measure by selecting all the bikeway/walking path segments within a 1-mile buffer of regionally significant transit stations (rail, ferry, bus rapid transit, or bus transfer stations). Then, the mileage of the total bikeway within the buffer should be divided by land area within the buffer (Harvey et al., 2018; Caltrans, 2017a).
- Number of distinct functional walking and bicycle routes with nodes at a regionally significant transit or rail station within 20 minutes of active transportation travel time. This measure relies on the location of significant transit stations, recently collected for the California State Rail Plan, and bicycle facility data from local jurisdictions and transit operators (Ostovar et al., 2022; Harvey et al., 2018; Caltrans, 2017a).

3.3.7. Pedestrian and Bicyclist Delay

This indicator, which is usually measured in time units (usually seconds), is related to biking and walking at specific locations such as a signalized intersection or across longer distances such as a corridor. This performance measure shows the amount of delay experienced by someone making a trip to or from a destination or transit stop through intersections or crossings. (Ostovar et al., 2022 and Harvey et al., 2018)

Dunn and Pretty's Method (Dunn and Pretty, 1984; FHWA, 1998) was used to calculate the delay. Following equations were determined to calculate pedestrian delay at signalized pedestrian crossings (FHWA, 1998).

Average delay per pedestrian for a narrow roadway (about 7.5 m or two lanes)

$$d = \frac{(g+15)^2}{2(g+20)}$$

Average delay per pedestrian for a wider roadway (about 15 m or four lanes)

$$d = \frac{(g+10)^2}{2(g+15)}$$

Where

d= average delay per pedestrian, s
g= vehicular green signal, s

Table 3-4 and Table 3-5 are used to calculate the green interval duration.

Table 3-4. Typical Minimum Green Interval Duration (NCHRP Report 812, 2015, Table 5-3)

Phase Type	**Facility Type**	**Minimum Green Needed to Satisfy Driver Expectancy (s)**
Through	Major Arterial (speed limit exceeds 40 mph)	10 to 15
	Major Arterial (speed limit 40 mph or less)	7 to 15
	Minor Arterial	4 to 10
	Collector, Local, Driveway	2 to 10
Left Turn	Any	2 to 5

Table 3-5. Typical Maximum Green Duration (NCHRP Report 812, 2015, Table 5-5)

Phase Type	**Facility Type**	**Minimum Green Needed to Satisfy Driver Expectancy (s)**
Through	Major Arterial (speed limit exceeds 40 mph)	50 to 70
	Major Arterial (speed limit 40 mph or less)	40 to 60
	Minor Arterial	30 to 50
	Collector, Local, Driveway	20 to 40
Left Turn	Any	15 to 30

3.3.8. Level of Service

The Level of Service (LOS) indicator measures how users might perceive a service condition (e.g., safety, travel time, delay, comfort, speed) by assigning a numerical or letter score to a street based on users' safety and comfort. Various methodologies exist that can be used to assess Bicyclist Level of Service (BLOS) and Pedestrian Level of Service (PLOS) depending on context and desired outcomes (Harvey et al., 2018 adapted from Semler et al., 2016). Some active transportation and transit factors that affect the perception of LOS are lighting, and sight distances on routes and in the vegetation on the sides of routes (hiding places), level of maintenance, litter, noise, and adjacent heavy traffic (Ostovar et al., 2022; Harvey et al., 2018; Cunningham and Michael, 2004; Humpel et. al, 2002; Owen et. al, 2004). The LOS indicators pass all three steps of the initial equity review applied to all indicators reviewed in this study because the indicator is not affected by low density of destinations of opportunity or lack of connectivity between different neighborhoods.

3.3.8.1. Pedestrian LOS

Pedestrian LOS is a rating system reflecting the quality of service that pedestrians perceive from pedestrian infrastructure on a street segment, ranging from A to F (A: best, and F: worst quality of service). Two methodologies were used in this case study, including:

- Highway Capacity Manual (HCM) Methodology (Huff and Liggett, 2014)
- National Cooperative Highway Research Panel (NCHRP) Methodology (NCHRP Report 616, 2008)

In the HCM methodology, Link PLOS, Segment PLOS, Pedestrian Space LOS, and Intersection PLOS are needed to calculate the Pedestrian LOS score or Facility PLOS, which is the final score for PLOS (Figure 3-7).

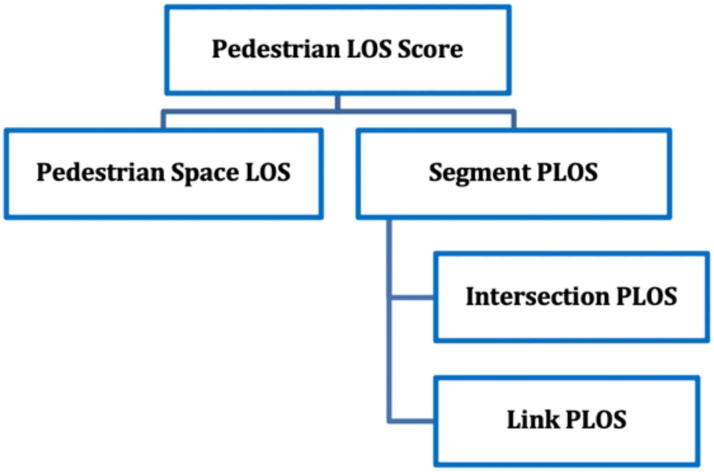


Figure 3-7. Pedestrian Highway Capacity Manual (HCM) Methodology (Huff and Liggett, 2014)

In the NCHRP methodology, according to the recommended set of equations (NCHRP Report 616, 2008: Chapter 7 and Chapter 8), PLOS is determined by the segment PLOS and Intersection PLOS scores, as well as the Roadway Crossing Difficulty Factor (RCDF).

The required data for calculating the PLOS, which are specified in the HCM (Huff and Liggett, 2014) and NCHRP 616 report (NCHRP Report 616, 2008), include traffic volume, speed data, roadway characteristic data (e.g., travel lane width, number of travel lanes, turn lanes, and driveway inventory), pedestrian facility characteristic data (e.g., sidewalk and buffer width, and street trees), traffic signal timing information, and land use and building data. Average pedestrian space is defined as a ratio of average space allocated to pedestrians compared to the number of pedestrians on the road. PLOS data was collected from Google Map™ and pedestrian counts using complete street planning reports and several traffic reports.

3.3.8.2. Bicycle LOS (BLOS)

Bicycle LOS (BLOS) is a rating system reflecting the quality of service that bicyclists perceive from a road segment, ranging from A to F (A: best, and F: worst quality of service). Two methodologies were used in this case study that includes (see Figure 3-8):

- Highway Capacity Manual (HCM) Methodology (Huff and Liggett, 2014)
- National Cooperative Highway Research Panel (NCHRP) Methodology (NCHRP Report 616, 2008)

HCM BLOS methodology requires two parameters to evaluate Facility BLOS, including Intersection BLOS and Link BLOS.

Figure 3-8. Bicycle Level of Service Methodologies

The methodology outlined in NCHRP Report 616 is used for a comprehensive BLOS analysis for the complete street. Intersection BLOS and Link BLOS should be calculated, both of which are feasible using the NCHRP methodology.

The required data for calculating the BLOS, which are specified in the HCM (Huff and Liggett, 2014) and NCHRP 616 report (NCHRP Report 616, 2008), includes traffic volume, speed data, roadway characteristic data (e.g., travel lane width, number of travel lanes, turn lanes, and driveway inventory), bicycle facility characteristic data (e.g., bicycle facility, sidewalk and buffer width, and street trees), traffic signal timing information, and land use and building data.

3.3.8.3. Urban Level of Service

Urban LOS is a rating system used to describe the quality of service that cars perceive on urban streets. Ratings vary from A (high travel speeds and slight delay) to F (severe congestion and low travel speeds). The required data for calculating the urban LOS are specified in the HCM (NCHRP Report 616, 2008). Street geometry data was collected from Google Maps™.

3.3.8.4. Transit Level of Service

Transit LOS is used to rate the quality of bus service, ranging from A to F; with the definition of:

> A: a road segment with many bus stops and frequent bus service would receive an A rating.
> F: a route with few bus stops, heavy delays, and infrequent service would receive an F rating.

The required data for calculating the Transit LOS are also specified in the HCM (NCHRP Report 616, 2008). Google Map™ and bus schedule maps were used to collect required data for the number of bus stops or bus frequency. A transit LOS calculator using the HCM equations was used to calculate transit LOS.

It should be mentioned that all of the LOS analyses should be done by segments. A segment begins after a controlled stop, such as an intersection or stop sign, and ends at the next controlled stop. There may be a new segment for every block in some cases, and in other cases, the segment may extend for many blocks.

3.3.8.5. Level of Traffic Stress (LTS)

Level of Traffic Stress (LTS) is a qualitative measure of the stress that bicyclists experience when biking near traffic. This semi-quantitative performance measure was not discussed in the framework of the complete street project (Ostovar et al., 2022 and Harvey et al., 2018); however, it was found useful to be included in the framework. In this performance measure, a corridor is assigned an LTS score depending on the speed limit, the geometry of the road, and the type of bike infrastructure available. Table 3-6 depicts the LTS scores based on the stress level the cyclists experience.

Table 3-6. Level of Traffic Stress (LTS) Score according to Cyclist Level of Service

Stress Level	LTS Score
None	0
Very Low	1
Low	2
Moderately Low	2.5
Moderately High	3
High	4
Very High	5

3.3.9. Crashes

This indicator is calculated by measuring the number of crashes or rate of crashes (crashes per volume of users) over a selected period (Ostovar et al., 2022 and Harvey et al., 2018 adapted from Semler et al., 2016). According to Semler et al., 2016, the measures shown below can be used to assess the safety of the transportation system for bicycle and walking:

- Number of bicycle-involved and/or pedestrian-involved crashes over five years.
- Number of fatal or severe injuries of bicyclists and/or pedestrians over five years.
- Crashes per volume of bicyclists and/or pedestrians over five years (crash rates).

The crashes indicator passes all three steps of the initial equity review applied to all indicators reviewed in this study because the indicator is not affected by a low density of destinations of opportunity or lack of connectivity between different neighborhoods

3.3.10. Physical Activity

Physical activity and health can be defined as a measure of the level of physical activity per capita or the portion of the population that is physically active (Harvey et al., 2018 and Semler et al., 2016). A review of definitions by relevant stakeholders (e.g. the Centers for Disease Control and Prevention and the American Heart Association) define physically active as "at least 30 minutes per day of moderate-intensity physical activity on most days of the week" (Brock et al. 2009).

Walking and bicycling are ways to incorporate physical activity into daily life and may lead "to improved health outcomes" (Harvey et al., 2018 and Semler et al., 2016). Many health conditions and diseases such as premature mortality, coronary heart disease, stroke, high blood pressure, Type 2 diabetes, osteoporosis, breast and colon cancer, falls, and depression can be controlled by appropriate physical activity (Harvey et al., 2018 and Semler et al., 2016).

The key to this type of indicator is to estimate the amount of additional physical activity that might be generated from a complete streets project which requires an estimate of mode choice change, or new trips with active transportation, that the project will cause in the neighborhood. This type of indicator can be somewhat difficult to estimate because the condition of active transportation infrastructure can be as important as its existence. The safety factors related to risk of obstacles and accidents in the safety discussion for Level of Service indicators are only considered in the LOS indicators are related to intersections and vehicle traffic. Cracked and uneven sidewalks, paths and bicycle paths that have obstacles such as power poles and dangerous stormwater grates, may create a perception of lack of safety that is not currently considered in LOS indicators and will reduce the use of active transportation for transportation and physical activity. Perception of danger due to crime is also not considered in current LOS indicators. Estimates of physical activity changes should include consideration of how a complete streets project will change these factors, which in turn will affect physical activity changes.

In disadvantaged neighborhoods, creating and using bike lanes and pedestrian lanes are not as helpful as in advantaged neighborhoods until the lack of connectivity and destinations, long distances between different destinations, lack of appropriate inter-connections in the disadvantaged area, and not enough connections between disadvantaged neighborhoods and advantaged neighborhoods are addressed. Creating bike lanes and pedestrian lanes by complete street design can be an important factor to make active transportation more viable in disadvantaged neighborhoods which can result in a huge improvement in physical activity performance measure, if density of destinations of opportunity, transit connections and safety issues noted above are addressed. It is clear that more measurement, before and after projects and network improvements are made, and analysis are needed to identify the types of comprehensive neighborhood improvements that will result in improvements in this indicator.

3.3.11. Pedestrian Miles Traveled / Bicycle Miles Traveled

Pedestrian miles traveled (PMT) and bicycle miles traveled (BMT) are indicators that measure the total miles traveled in a specific location for a particular period of time by person and bicycle, respectively. PMT and BMT are useful measures for determining the distance traveled for each mode (Ostovar et al., 2022; Harvey et al., 2018; Caltrans, 2017a).

Walking and cycling modes are more common in communities with enough destinations and facilities as well as enough appropriate inter-neighborhood connections and connections with more advantaged neighborhoods. Creating bike lanes and pedestrian lanes by complete street design can be an important factor in making active transportation more viable in disadvantaged neighborhoods, resulting in a huge improvement in PMT and BMT performance measures if the density of destinations of opportunity, transit connections, and safety issues are addressed. According to Ewing et al.'s (2010) study, walking is related to land use diversity, intersection density, and the number of destinations within walking distance.

PMT and BMT can be calculated by multiplying the number of trips by the average trip length. The change in PMT and BMT after implementing a complete streets project indicates the project's impact. PMT and BMT encourage people to use active transportation. So, these indicators are justifiable for getting public grants. Besides, higher BMT and PMT encourage bike renting companies to invest their money into the neighborhood and improve its economy.

3.3.12. Green Space Changes

Open spaces are defined by the US EPA as “any open piece of land that is undeveloped (has no buildings or other built structures) and is accessible to the public. Open space can include:

- Green space (land that is partly or completely covered with grass, trees, shrubs, or other vegetation). Green space includes parks, community gardens, and cemeteries.
- Schoolyards
- Playgrounds
- Public seating areas
- Public plazas
- Vacant lots

There are other definitions of green space, which are discussed below.

“Green Space Changes” indicates the consumption or production of green spaces. It can be expanded to include the consumption or production of open spaces. Green space can be created as part of complete streets projects. Green space consumption describes the amount of land that will be consumed by a project including the two following types of land: green spaces that are not already used for built infrastructure and other human activities (undeveloped green lands) or green spaces that are taken from areas such as parks (developed green lands) (Harvey et al., 2018 and Semler et al., 2016).

3.3.13. Street Trees

This indicator can be defined as the number of trees on a street and can be measured as tree counts, percent of street tree canopy coverage, number of trees per mile, and tree spacing. Street trees improve livability and safety by narrowing the roadway, contributing to traffic calming. Wastewater diversion, CO_2 sequestration, air quality improvement, and habitat for wildlife are some of the environmental co-benefits of street trees (Ostovar et al., 2022 and Harvey et al., 2016 adapted from Semler et al., 2018). Appropriate street shade trees have a large canopy that provides a physical and psychological barrier between vehicles and pedestrians. Shade trees also cause pedestrian comfort and physical well-being, especially in warm climates, in addition to giving sidewalks a sense of security and adding beauty (Ostovar et al., 2022, Harvey et al., 2018 adapted from Change Lab Solution, 2017). The change in street trees is used to assess the impacts of a complete street project on livability. Regarding the three steps for evaluating equity bias discussed in Section 3.2.2, the Street Trees indicator passes all three steps.

3.4. Summary

The tasks completed in this study and the results of the research project include:

- Review of the literature for background on complete streets, complete streets guidelines and LCA of complete streets
    - The literature shows no previous application of Social LCA to evaluate complete streets projects
- Considering social indicators
- Current processes do not address social impact performance well
- There are no commonly used indicators for social impacts
- Focus on the neighborhood as a scaling unit
- Focus on neighborhood needs that can be helped as by a complete street is an approach that will help improving the equity of social impacts as opposed to the complete street itself being the focus
  - Adaption of social and economic indicators and performance measures
    - Different systems of social impact indicators and performance measures were compared, and a set was identified covering the categories in the different systems, and more importantly addressing many of the concerns identified from the data

    - An approach for evaluating how the indicators and measures can be considered for equity of comparison was developed
    - The approach was applied to the initial set of indicators and measures, and used to remove some and change others
- The next chapter describes the testing of the full framework by using it to quantify the environmental and social impacts of complete streets and compare them with leaving the street in its vehicle-centric configuration.

3.4.1. Discussion

This chapter described selected categories and sub-categories based on the FHWA guidebook as well as the Caltrans white paper's categories and performance measures. Jobs, accessibility, mobility/connectivity, safety/public health, and livability were the selected categories to provide comprehensiveness to the use of social performance measures. For each category, one or more performance measures were selected based on their importance, independence, data availability, and obtainable measurement methodologies.

For several categories, one or more indicators were created based on complete street characteristics. For instance, "access to schools" was a new performance measure that was added to accessibility category because of its importance for children as a vulnerable group who are particularly different and important compared with other groups. In addition, the "green land consumption" indicator was created and defined since it showed a better match with the complete street approach compared to the indicator "land consumption."

The data resources and appropriate references for methodologies were almost the same for several performance measures, such as access to community destinations, access to jobs, and access to schools or the resources for average travel time and average trip length performance measures. In these cases, the indicator that appeared to best match with the scope of complete streets, and that had what appeared to be the easiest data collection/estimation requirements was selected.

The idea was to avoid the syndrome where a potential project in a disadvantaged neighborhood ranks poorly because the indicator makes it look like a “complete street to nowhere.” Examples are the access to community destinations and access to schools indicators, which as originally written in the FHWA (Semler et al., 2016) document, would have scored complete street projects in destination-rich neighborhoods higher than similar projects in disadvantaged neighborhoods that often have far fewer destinations. A recommended solution for these indicators was to first do an assessment of the richness of opportunity destinations in a neighborhood and include complete streets as part of a larger investment in increasing these destinations.

After trying the indicators on several projects, the same process is used for a second review. Those are not complete street social indicators but provide an indication of the types of investments that may be necessary along with smart growth amenities like complete streets to move towards more equity of opportunity for children and human quality of life as influenced by public investments in transportation infrastructure.

Reviewing the required data resources and appropriate methodologies for quantifying social indicators was the most challenging task. The indicators were selected in part on the expected ability to collect data, especially on a project level. These performance indicators are to be reviewed with early stakeholders who provided input regarding indicators and will be piloted with several agencies. Their strengths and weaknesses with regard to comprehensiveness, difficulty of calculating or estimating, and relevance to stakeholder’s values and goals will be tested in those case studies.

CHAPTER 4. CASE STUDIES TO DEMONSTRATE THE USE OF SOCIAL LCA AND ENVIRONMENTAL LCA FOR COMPLETE STREETS

This chapter involves the application of LCA to calculate environmental impacts for complete street case studies, and to demonstrate the use of social LCA and environmental LCA for complete streets. Case study evaluation is based on project design for those not yet constructed or completed. Where case study projects are completed, projects are evaluated based on performance before and after project completion. Case studies include i. San Fernando Street, San Jose, CA, ii. Franklin Blvd., Sacramento, CA, and iii. Kentucky Ave, Woodland, CA.

The framework developed in CHAPTER 3 did not include a method for considering environmental justice concerns in minority and low-income neighborhoods. In this chapter, the framework is expanded through the use of the CalEnviroScreen tool from the California Environmental Protection Agency to assess the exposure of neighborhoods and their vulnerability to environmental impacts in conjunction with the performance indicators. Other tools similar to CalEnvironScreen can be used with the framework.

Funding to create complete streets is increasing in some locations. There is dedicated funding for complete streets in the California Road Repair and Accountability Act of 2017 (SACOG, undated). The federal Bipartisan Infrastructure Bill of 2021 includes new funding for bicycling and walking, as well as first-ever requirements for states to address bicycling and walking safety and to write complete streets policies and plans (LAB, 2021). An unpassed bill in the US House of Representatives would require states to provide a grant for design and construction of complete streets (Complete Streets Act of 2021). As funding increases, the processes by which complete streets are located and funded have become more important. Issues that have come to the forefront include the processes and metrics for prioritizing and awarding investments in transportation infrastructure, including complete streets. Some of the issues that exist are the processes that decide where complete street projects get built, what goals they are designed to achieve, and whether they are beneficial or disruptive, including contributing to the displacement of existing residents, particularly in disadvantaged communities.

This chapter also aims to test the complete streets LCA framework by using it to quantify the environmental and social impacts of complete streets through three case studies. The results are compared with the existing streets that were configured to be vehicle-centric. To test the framework, case studies were solicited in both high and low resource neighborhoods on corridors in three cities with different infrastructure and socio-economic characteristics. This allowed the researchers to evaluate changes in how users of complete street improvements gain access to public resources and how and where public infrastructure investments are deployed. Of particular interest is understanding how complete streets projects can facilitate access to publicly managed social determinants of health that affect access to opportunity and social mobility. Case study evaluation was based on the project design for those that had not yet been started or completed. Where the case study project had been completed, the project was evaluated based on performance before and after project completion.

Complete streets are expected to benefit all neighborhoods, contingent on how well they are designed. The expected outcomes from this study are comparisons of how the change in performance indicators in the framework differ in value for complete streets projects in disadvantaged and well-resourced neighborhoods, and to see if the use of SLCA can help identify opportunities for infrastructure investment that can help move distressed neighborhoods towards economic productivity and social mobility. Complete streets can create access or improve existing access to social determinants, which in turn creates access to opportunity.

Then, a framework to quantify environmental impacts using LCA for complete streets developed by Harvey et al. is used in the next part of this chapter of the dissertation for the complete case studies. (Harvey et al., 2018).

4.1. Goal and Scope

The goal of this chapter is to test and demonstrate the complete street LCA framework developed in CHAPTER 3 by performing three case studies. The case studies have been solicited in different parts of California and in more and less advantaged neighborhoods to evaluate results from the framework for both types of neighborhoods. The case studies include projects in urban/suburban areas and suburban/rural area.

The case studies considered are:

- Urban: San Fernando Street complete street project located in an advantaged neighborhood of San Jose, CA
    - Complete street length: 1.3 miles
    - Type of street: mixed-use commercial and downtown two-way
- Suburban: Franklin Boulevard complete street project located in a disadvantaged neighborhood of Sacramento, CA
    - Complete street length: 1.6 miles
    - Type of street: four-lane arterial
- Suburban/Rural: Kentucky Avenue complete street project located in Woodland, CA
    - Complete street length: 1 mile
    - Type of street: mixed-use corridor

The evaluation of the San Fernando Street and Kentucky Avenue complete street projects, which were already built at the time of evaluation, is based on performance before and after the project's completion. In contrast, the Franklin Boulevard complete street project assessment, which had not yet been constructed, is based on proposed designs.

The system boundary for this study considers the impacts of changes in each of the case studies before and after constructing the complete street projects, considering the entire neighborhood and also the project within the larger active transportation road network. The functional unit for the environmental LCA is the complete street project itself. The functional unit for the SLCA is defined for each performance measure separately, and the data are then collected for each performance measure. The following sections present case studies details, quantification of socio-economic indicators, followed by presenting the quantification of the environmental impacts using the socio-economic and environmental LCA framework.

4.1.1. Urban: San Fernando Street, San Jose, CA

San Fernando Street, located in downtown San Jose, is a mixed-use commercial street that connects San Jose State University to the Diridon Caltrain station (mainly in district 3). This two-lane street includes class II bike lanes[1] and parallel parking lanes. The existence of multiple restaurants, bars, and residential buildings on San Fernando Street provides opportunities for active transportation to support urban street life. Santa Clara Street is one of the most important streets parallel to San Fernando Street. When Bay Area Rapid Transit (BART) construction on Santa Clara Street redirected auto traffic, bike, and pedestrian activities to adjacent streets, the function and identity of San Fernando Street changed considerably. This change leads to San Fernando Street becoming the east-west spine of downtown San Jose. Therefore, San Fernando Street as a

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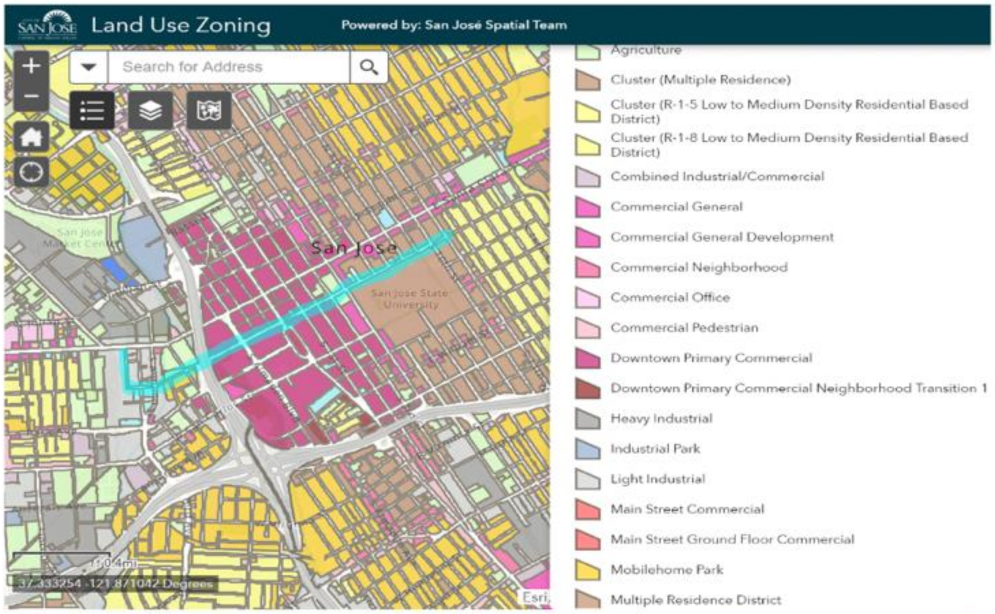
[1] Bike lanes that are defined by pavement striping and signage on a portion of a roadway along streets.

main pedestrian and bicycle route that connects Caltrain to downtown San Jose needed an appealing, clear, and strong path. Figure 4-1 shows the San Fernando Street land-use zoning map a) in 2020 and b) in 2040, based on the general plan of San Jose (City of San Jose, 2020a; City of San Jose, 2018). Table 4-1 shows the surrounding land use zones of San Fernando Street This street is surrounded by a mix of commercial and residential neighborhoods in addition to downtown San Jose and San Jose State University.



a) San Fernando Street land-use zoning map in 2020, based on the general plan (project location highlighted in light blue)

b) San Fernando Street land-use zoning map in 2040, based on the general plan (project location highlighted in light blue)

Figure 4-1. San Fernando Street land-use zoning map before (a) and after (b) the construction of complete street (City of San Jose, 2020a)

Table 4-1. Current Land Use Zones in the surroundings of the San Fernando Street

San Fernando Street	Destinations on the right of the street	Destinations on the left of the street
Between 10th-9th Street	Offices	Offices
Between 9th-8th Street	Residential	Offices
Between 8th-7th	Offices-	Offices-
Between 7th-6th Street	Offices-	Offices-
Between 6th-5th Street	Offices-	Offices-
Between 5th-4th Street	Offices-	Offices-
Between 4th-3rd Street	Offices-	Offices-
Between 3rd-2nd Street	Offices-	Offices-
Between 2nd-1st Street	Offices-	Park
Between 1st-Lightson	Offices-	Offices
Between Lightson Street-	Offices-	Offices
Between Market Street -	Offices-	Offices
Between San Pedro Street -	Offices-	Offices-
Between Almaden	Offices-	Offices-
Between Almaden	Park-Offices	Offices-
Between Guadalupe Pkwy-	Parks	Parks-
Between Delmas Avenue-	Parks	Residential
Between Gifford Avenue-	Parks	Residential-
Between Autumn Street -	Parks	Parks
Between Montgomery	Parks	Not

Two complete street projects have been implemented on San Fernando Street during the last ten years. The first project was funded by the Metropolitan Transportation Commission (MTC) in 2010 and is entitled “San Fernando Street enhanced bikeway and pedestrian access”, with the goal of “encouraging pedestrian and bicycle mobility by providing accessible, safe, and comfortable connections between transit, businesses, housing and recreation, and enhancing downtown environment and experience for workers, visitors, students, and residents” (MTC, 2020a). This project improved the existing bicycle and pedestrian facilities of San Fernando Street between Cahill Street and 10th Street. The scope of the project was to install an enhanced colored bike lane with a buffer zone on both sides of the street, install energy-efficient lighting, street trees, sidewalks, curb gutter, signage, pavement markings, and striping; to enhance all existing crosswalks; to upgrade wheelchair ramps to American disability act (ADA) compliance; and to improve drainage, traffic signal, and bulb-outs.

The performance of the street was expected to be improved by this project as follows:

I. facilitate a safe and convenient walking and bicycling experience to and from the public transit facilities to enhance pedestrian and bicycle accessibility,
II. provide a direct route for pedestrians and bicycles to the Diridon Station, as the main transit hub in the city of San Jose for BART, High-Speed Rail, and Caltrain.
III. provide a direct connection between San Jose State University and the Diridon Station in addition to connections to the downtown business district, housing, and recreational facilities along the San Fernando Street

The second project was funded by MTC in 2018 entitled "Better Bikeway San Jose- San Fernando Corridor". The scope of this was an investment in the San Fernando Street corridor's traffic and bicycle signals, transit boarding islands, and construction of Dutch-style protected intersections. The focus of this project is to improve and build class II [2]and class IV [3]bike lanes, bicycle parkings, sidewalks, lighting, ADA compliant ramps, traffic signal push buttons, pedestrian countdown signals, widening curb lanes, installing transit vehicle stops, directional signages, improving intersections, mid-block crossings, ADA facilities, and installing traffic signals responsive to bicycles and right turn only lanes (San Jose Downtown Association, 2016;

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[2] "Class II bikeways are bike lanes established along streets and are defined by pavement striping and signage to delineate a portion of a roadway for bicycle travel. Bike lanes are one-way facilities, typically striped adjacent to motor traffic travelling in the same direction. Contraflow bike lanes can be provided on one-way streets for bicyclists travelling in the opposite direction" (Caltrans, 2017b).

[3] "Class III bikeways, or bike routes, designate a preferred route for bicyclists on streets shared with motor traffic not served by dedicated bikeways to provide continuity to the bikeway network. Bike routes are generally not appropriate for roadways with higher motor traffic speeds or volumes. Bike routes are established by placing bike route signs and optional shared roadway markings (sharrow) along roadways" (Caltrans, 2017b).

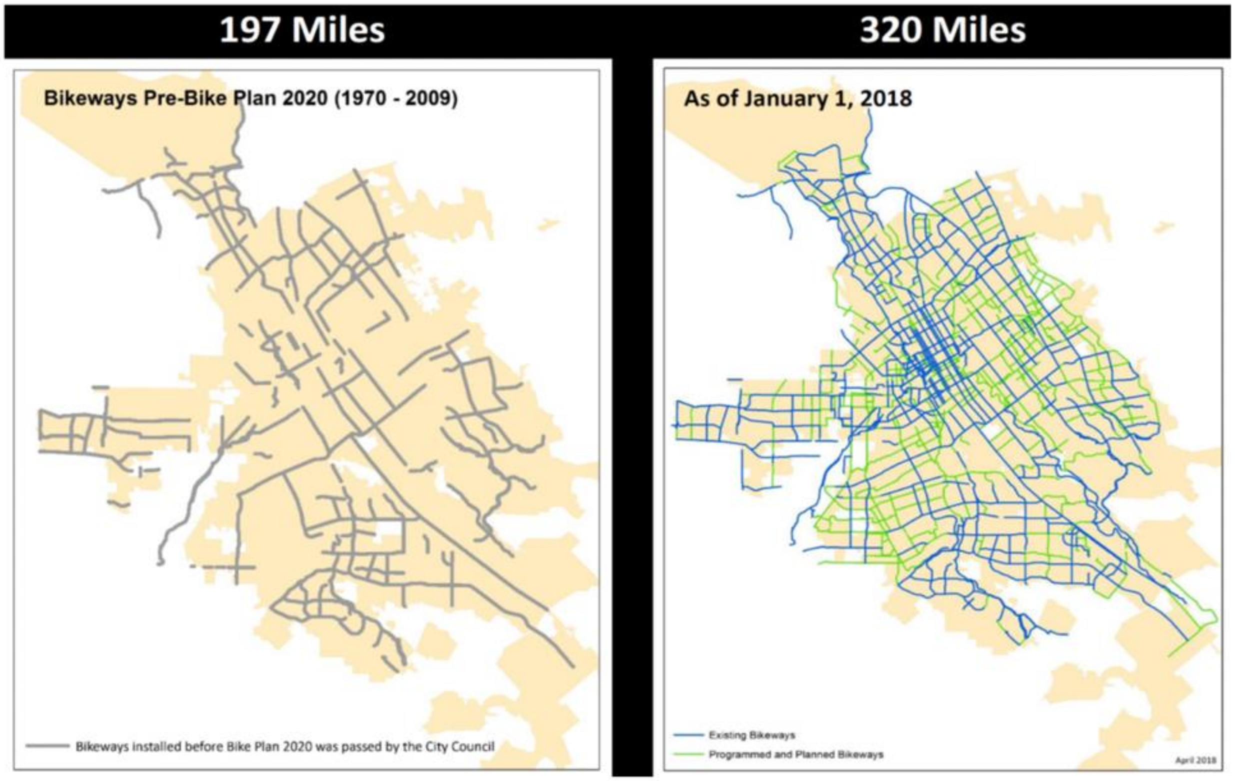
MTC, 2020b) compares the elements of the complete street considered in this case study. Figure 4-2 shows the intersection on San Fernando Street and 10th Street before and after constructing the second complete street project in 2018.

a) Before the complete street implementation (Google Map, 2016)

b) After adding the complete street features (Google Earth, 2020)

Figure 4-2. The intersection of San Fernando Street and 10th Street, before (a) and after (b) the construction of the complete street project

The San Fernando complete street project is part of the city of San Jose's better bike plan network. The left side of Figure 4-3 shows the 197 miles bikeway put into service between 1970 and 2009. The right side of Figure 4-3 , which illustrates the bikeway before the San Jose city council had passed the bike plan 2020 (pre-planned), and in 2018 (during the implementation of the 2020 bike plan).



a. *San Jose Bikeway maps showing routes added to 2009 and completed (as of 2018*

b. *San Jose Bikeway maps showing planned following the San Jose Bike Plan 2020 (City of San Jose, 2020a)*

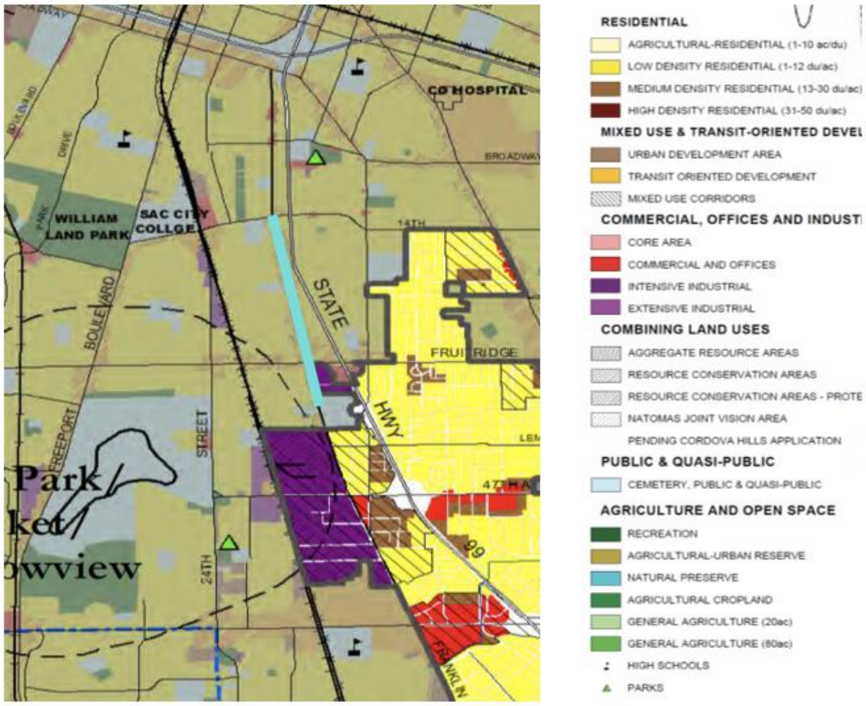
Figure 4-3. San Jose Bikeway maps showing (a) routes added to 2009 and completed (as of 2018) and (b) planned following the San Jose Bike Plan 2020 (City of San Jose, 2020a)

According to the San Jose better bike plan (adopted in 2009) and the San Jose 2040 general plan (City of San Jose, 2018) a network of separated bike lanes and protected intersections is to be installed throughout the downtown of San Jose through the Better Bikeways projects in 2018 and 2019, including the San Fernando complete street project. The build-out of the bicycle network is to eventually include 320 miles of routes.

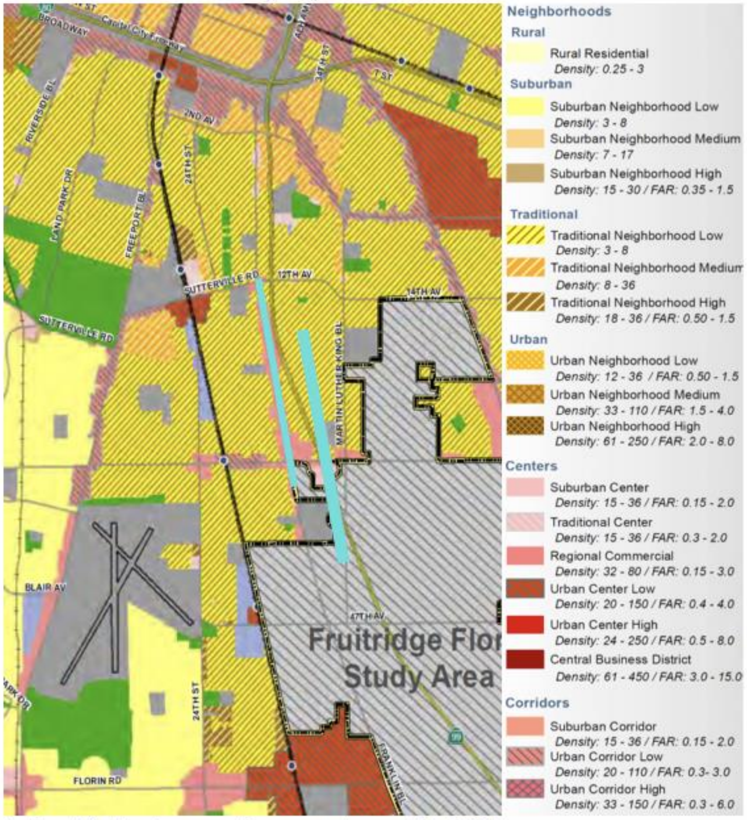
4.1.2. Suburban: Franklin Boulevard, Sacramento, CA

The Franklin Boulevard corridor is currently a four-lane arterial with limited pedestrian and bicycle amenities. It does not have bike lanes, ADA accessible sidewalks, and it currently supports high levels of truck traffic. This boulevard is in an economically disadvantaged area that needs investment and economic revitalization. In 2018, the City of Sacramento proposed a master plan for the development of Franklin Boulevard to convert it to a complete street (City of Sacramento and Department of Public Works, 2018). The purpose of this complete street project, which is located between Sutterville Road (12th Avenue) and 38th Avenue, is to improve pedestrian and bicycle mobility, increase safety, provide access to businesses, and enhance connectivity for all users through improved roadways and streetscape designs.

Figure 4-4 shows maps from the general plan for Franklin Boulevard land-use zoning map a) in 2020 and b) planned by 2035. As can be seen in the figure, Franklin Boulevard between 12th Avenue and 38th Avenue includes commercial and residential neighborhoods.



a. *Franklin land-use zoning map in 2020*



b. *Franklin land-use zoning map planned for 2035*

Figure 4-4. Franklin Boulevard land-use zoning map before (a) and after (b) the construction of complete street, based on the Sacramento County General Plan (Sacramento County, 2020)

The proposed complete street will remove two travel lanes and substitute them with Class IV bike lanes[4] and accessible sidewalks. This project, which is located in the historic Monterey Trail district, is planned to transform the corridor into a welcoming and attractive gateway to the district, and adjacent neighborhoods. The Franklin Boulevard complete street project aims to create a pleasant destination for living and working via improving sidewalks, and enhancing buffered bicycle lanes, marked pedestrian crossings, and lighting. This project is funded by the Sacramento Area Council of Governments (SACOG) Community Design Grant and local funds through preliminary engineering, which includes environmental, public outreach, and conceptual design (City of Sacramento, 2020a; MIG, 2019). Figure 4-5 shows the current view of Franklin Boulevard and the expected view after the proposed complete street project on this Boulevard is completed.

a) Franklin Blvd, before transforming to a complete street (currently) (Google map, 2020)

b) Franklin Boulevard, prposed view after implementing the proposed complete street project (MIG, 2019)

Figure 4-5. Current (a) and expected (b) views of Franklin Boulevard

Figure 4-6 shows the existing bike facilities as well as the proposed bicycle facilities for this project. According to the Sacramento County Bike Master Plan, a network of different classes of existing and proposed bicycle facilities is planned in which the Franklin Boulevard complete

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[4] Bikeways/lanes or cycle tracks that are separated from other modes usually by vertical separators.

street project is included (City of Sacramento and Department of Public WorksCity of Sacramento Bicycle Master Plan, 2016)).

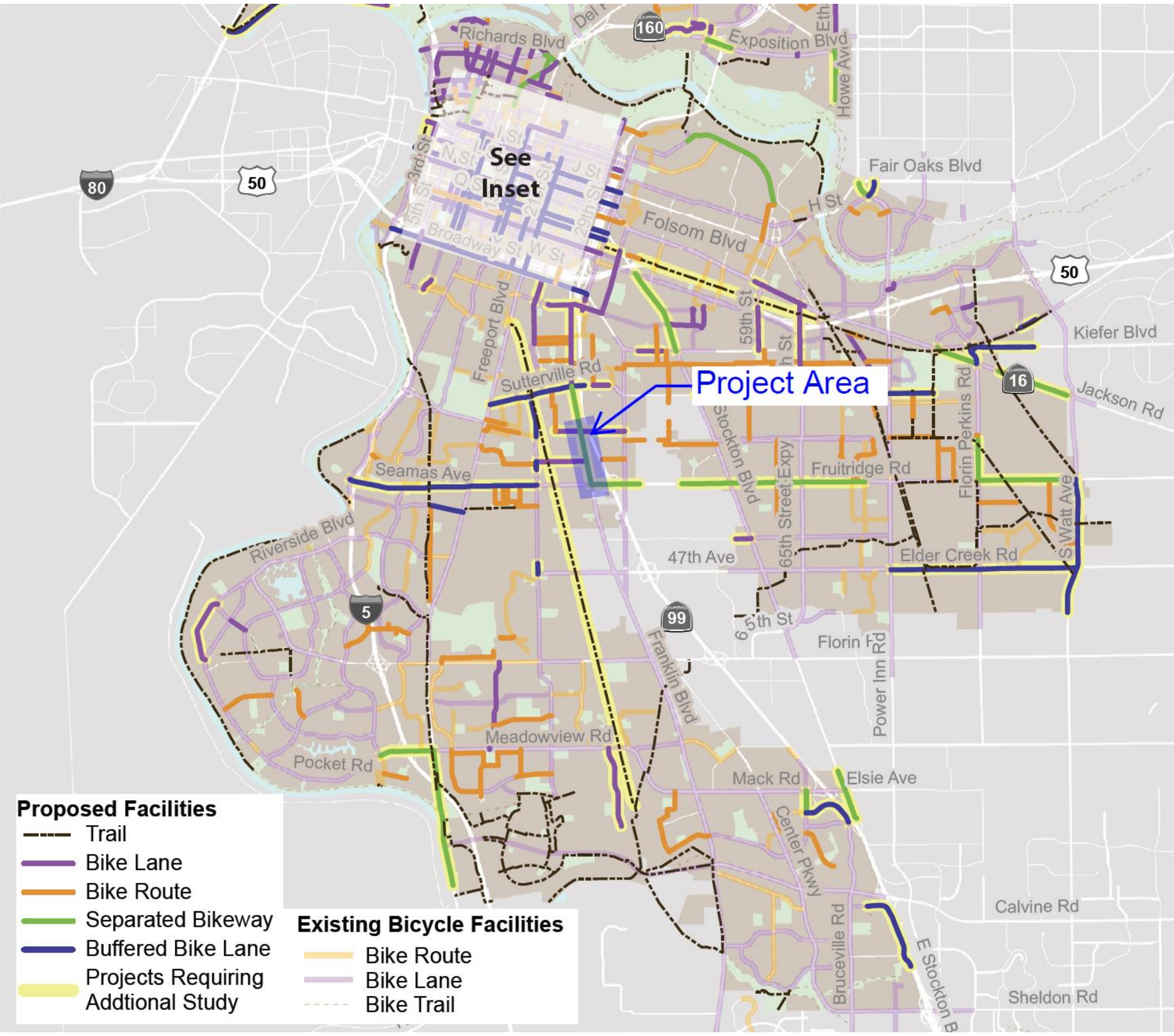
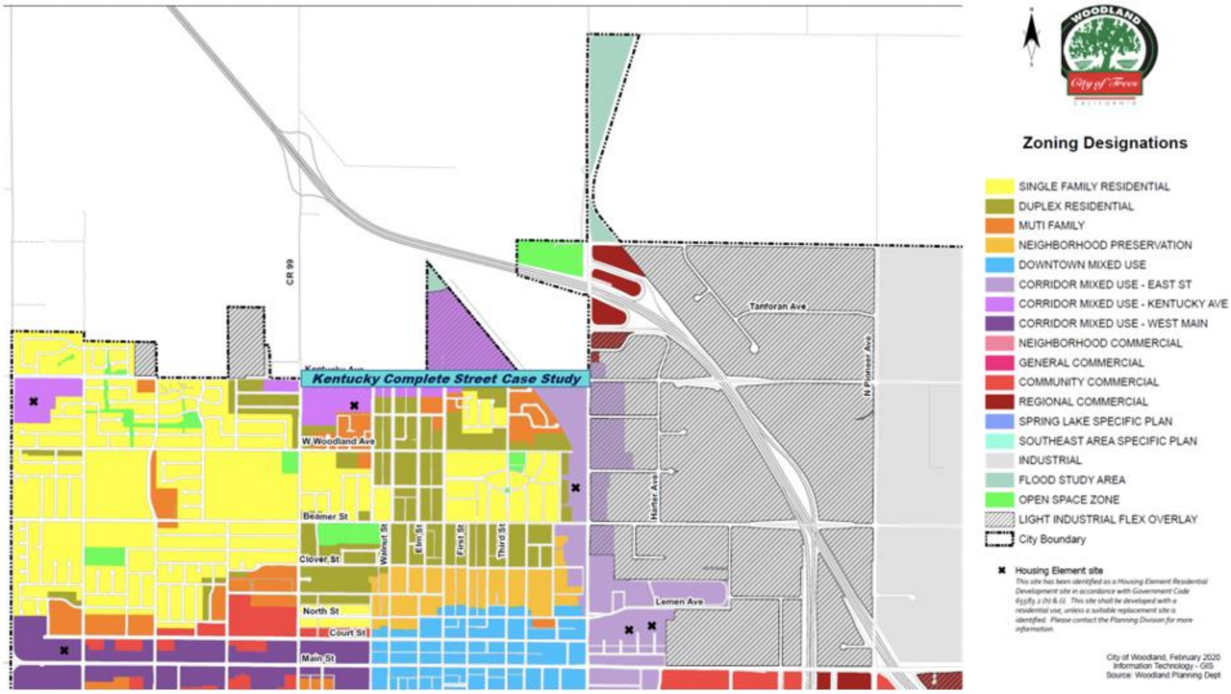


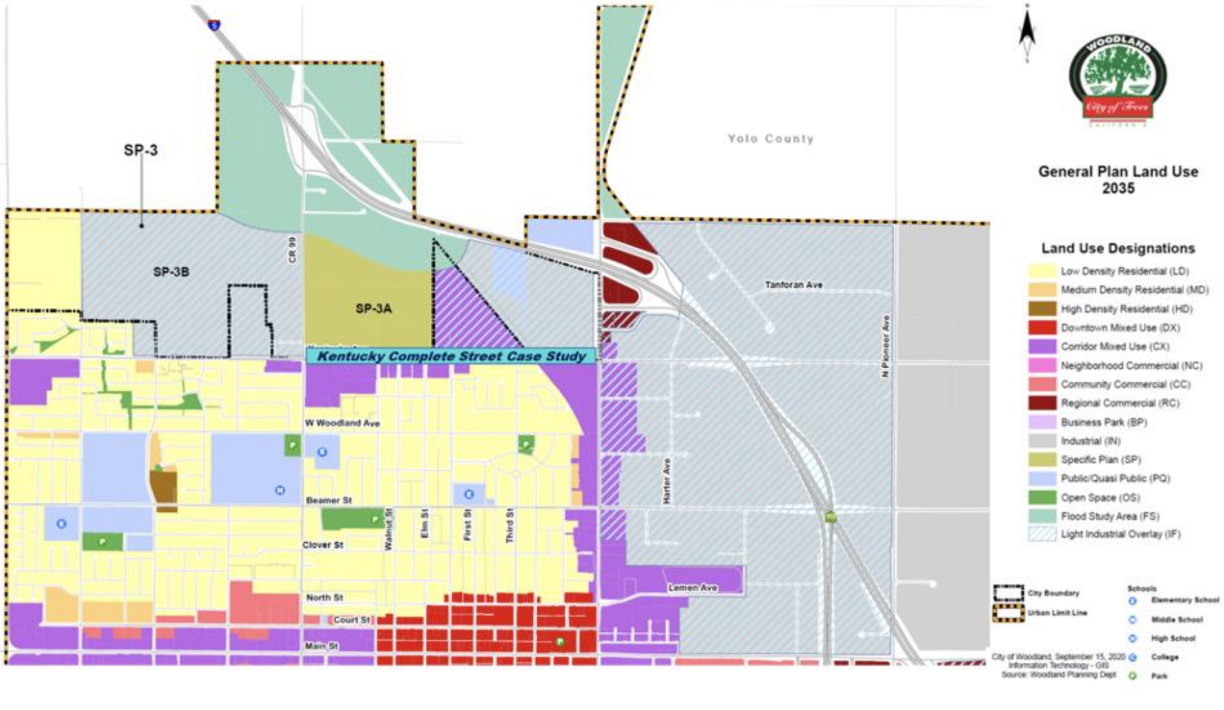
Figure 4-6. A network of different classes of existing and proposed bicycle facilities (City of Sacramento and Department of Public Works, 2018)

4.1.3. Suburban/Rural: Kentucky Avenue, Woodland, CA

Kentucky Avenue is a mixed-use corridor located in the northern part of the City of Woodland. As part of the complete street project, Kentucky Avenue was recently widened from 2 to 4 lanes from East Street to College Street and the roadway from East Street to West Street was reconstructed. The avenue previously had incomplete sidewalks and no bicycle lanes. The complete street project includes a major redesign, including new landscaped-separated sidewalks, new bicycle lanes, drainage improvements, landscape medians, a new traffic signal at College Street, and modifications to signals at West Street and East Street. Figure 4-7 shows a map from the general plan of the Kentucky Avenue land-use zoning a) in 2020 and b) planned for 2035. This segment of Kentucky Avenue does not appear to be part of the planned network of bicycle routes in the 2002 Bicycle Transportation Master Plan (it does not appear in the list of planned routes, and the maps are difficult to read, (Woodland, 2002).



a) Kentucky Avenue land-use zoning map in 2020, based on the general plan

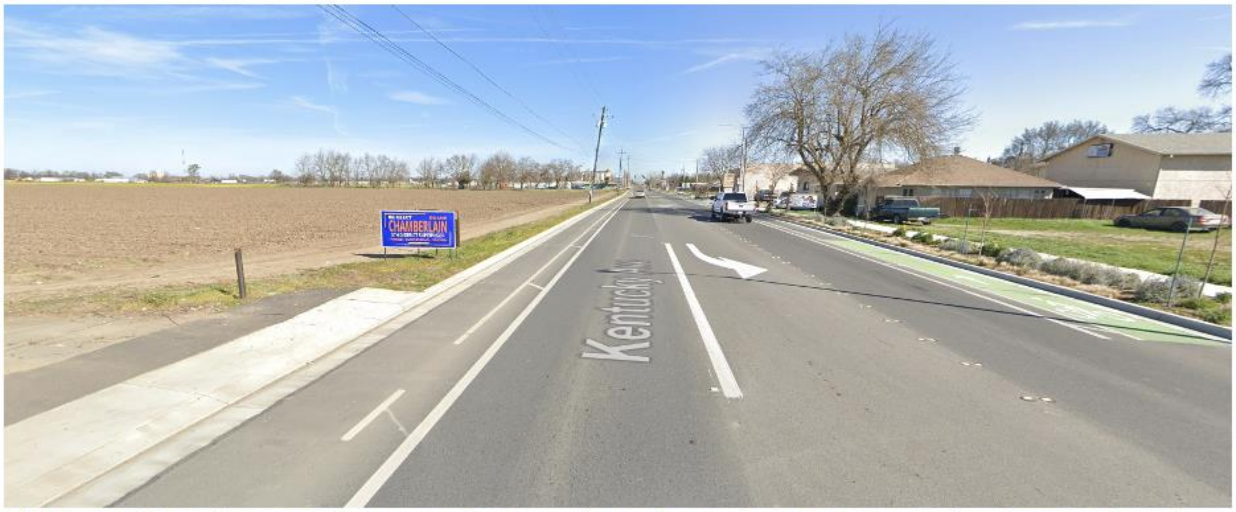


b) Kentucky Avenue land-use zoning map in 2035, based on the general plan

Figure 4-7. Kentucky Avenue land-use zoning map before (a) and after (b) the construction of complete street (City of Woodland, 2021)

Figure 4-8 shows the existing Kentucky Avenue (a) from 2017 Google Maps™ and the newly built complete street (b) from 2020 Google Maps™ that has been updated with dedicated bike lanes and sidewalks.

a) Before the complete street implementation (Google Map, 2017)



b) After adding the complete street features (Google Earth, 2020, Avenue has been updated with dedicated bike lanes and sidewalks)

Figure 4-8. The existing Kentucky Avenue (a) and newly built Kentucky Avenue complete street (b) (Before and after the construction of the Kentucky Avenue complete street project)

4.2. Social Life Cycle Assessment (SLCA) for the Case Studies

Most of the work on SLCA to date has been looking at relatively large-scale systems, such as countries, companies, or commonly available products. There has not been much work on SLCA for projects at the typical scales of a complete streets project: the neighborhood scale where the project is built, and the network-scale for the network that the project contributes to. A framework to quantify environmental impacts using LCA for complete streets was developed in CHAPTER 3 of this dissertation as well as Harvey et al.'s study (Harvey et al., 2018). The framework developed qualitative, quantitative, and semi-quantitative indicators selected from a Federal Highway Administration (FHWA) guidebook for pedestrian and bicycle performance measures (Semler et al., 2016), and a California Department of Transportation (Caltrans) set of performance measures (Caltrans, 2017a). The framework proposed that the neighborhood is the best scale for determining and interpreting SLCA impacts. Two other scales were not selected for the calculation of indicators: the individual and the region. Transportation infrastructure investments such as complete streets affect space at the scale, and it is difficult, if not impossible, to apply the use of that space to individuals. At the same time, regions often contain distinct neighborhoods with different densities of destinations, different transit options, and different social and economic demographics. Complete streets are built at the scale of one or several neighborhoods and affect people at that scale in terms of transportation. Regions should also be considered when looking at inter-neighborhood connectivity (Ostovar et al., 2022)

The following sections evaluate the socio-economic indicators in the case studies include access to community destinations, access to school, access to jobs, job creation, connectivity index, active transportation to local and regional transit connectivity index, pedestrian and bicyclists' delays, level of service, crashes, pedestrian and bike miles traveled, and street trees. The considerations regarding the interpretation of indicator values for more and less advantaged neighborhoods and the comparison of values between projects in different neighborhoods is also discussed in each performance measure section separately. Where applicable, a complete street that has not yet been constructed or completed has been evaluated using the design documents of that street.

A socio-economic base map derived from the California Communities Environmental Health Screening (CalEnviroScreen) tool has also been used to evaluate the case studies (OEHHA, 2020) and is discussed in detail later. CalEnviroScreen was used as an example of combining the use of the indicators with the use of a tool to evaluate the vulnerability and existing health, social, and environmental burdens of a neighborhood. This tool helps to identify the California communities, especially vulnerable ones most affected by several sources of pollution. CalEnviroScreen tool uses environmental, health, and socio-economic information to produce comparison scores for every census tract tied to census data for California. An area with the highest score experiences the highest socio-economic and environmental pollution burden. Color coding is also provided in these maps, along with the scores.

4.2.1. San Fernando Street Case Study

4.2.1.1. Access to Community Destinations

For the complete street case study, destinations within 0.5-mile walking and 2-mile bicycling radii of San Fernando Street were found using Google Earth™ and Google Maps™ (see Figure 4-9). The average walking speed is assumed to be three mph, while the bicycling speed is assumed to be 12 mph (Yang and Diez-Roux, 2012).

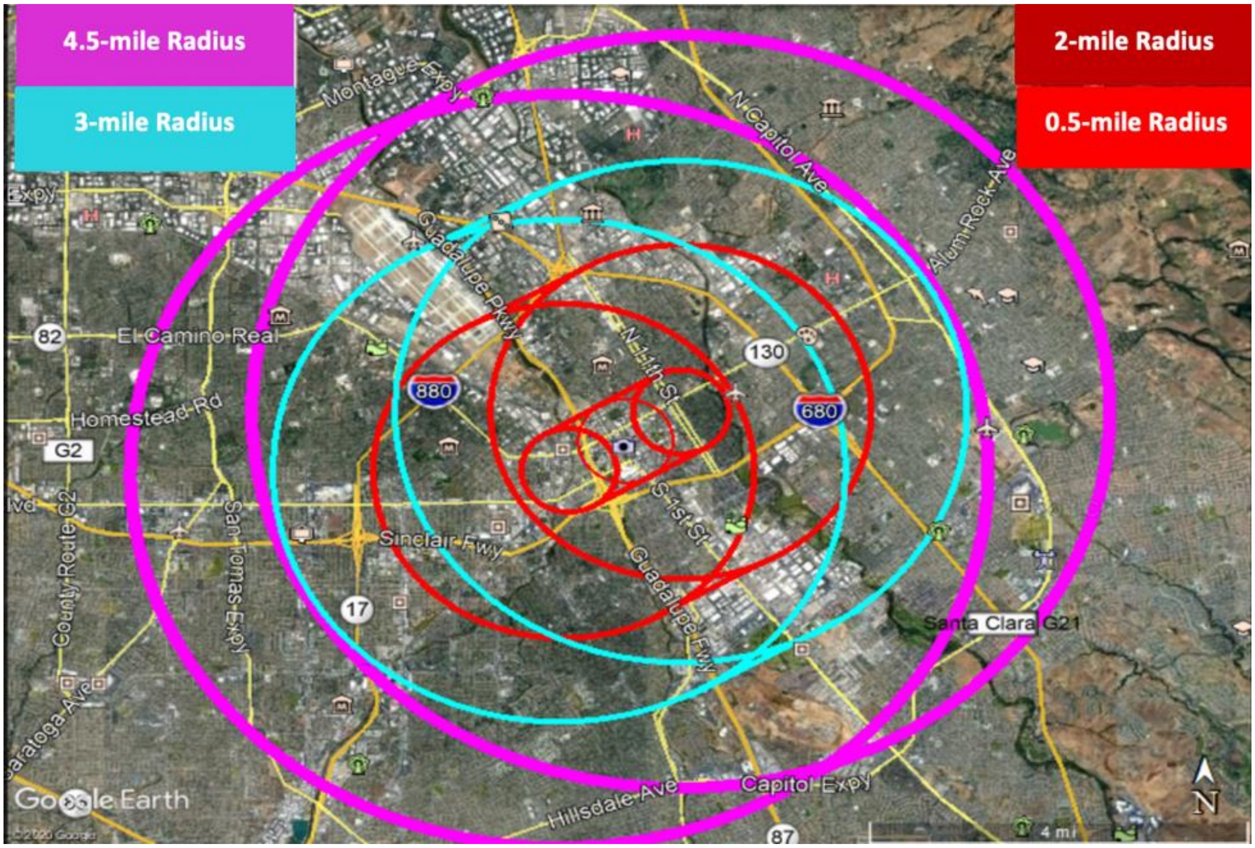


Figure 4-9. Access to Destination Buffer Area for Walking, Cycling, and Transit Modes of Transportation, San Fernando Complete Street Project

To consider the transit-accessible area around the San Fernando complete street, there are many possibilities when combining walking and biking with train, bus, and light rail. Therefore, the most probable scenarios were selected, considering 20 minutes for a combined-mode trip. The recommended buffers include 3-mile (bike and bus, bike and train, walk and light rail) and 4.5-mile (bike and light rail, bus, light rail). The list of buffers for each mode of transportation, assumptions for the speed and delay, and the calculation can be seen in APPENDIX A. Table 4-2 shows the recommended buffer distances used for different modes of transportation for 20 minute trips.

Table 4-2. The Recommended Buffer Distances Using in Different Modes of Transportation in 20 minutes

Recommended Buffer Distance	**Mode**
0.5 mile	Walking
2 mile	Biking
3 mile	Bus+Biking, Train+Biking, Light Rail+Walking
4.5 mile	Light Rail+Biking, Bus, Light Rail

The destinations considered in this case study include coffee shops, restaurants, banks, gas stations, grocery stores, pharmacies, hospitals, post offices, libraries, police stations, places of worship, and museums. The number of customers and employees for each destination was estimated using the best available resources, including government statistics, company information, and web research (see APPENDIX A). Access to community destinations calculations can be found in APPENDIX B. The calculation for a number of pharmacies, including Walgreens, CVS, and Rite Aid, is explained here as an example for the number of destinations' calculations:

- There are approximately 4 pharmacists and 6 technicians per Walgreen store. (Walgreens, 2007, Walgreens, 2020).

There are cashiers and retail workers that are working in the store as well. If the pharmacy is open between 8 am – 11 pm, and there are two 8-hour shifts, including 5 workers per shift. Thus the total employee working per day will be: 4 + 6 + (2 x 5) = **20 employees per day.**

- According to the CVS data (CVS, 2020), almost 4.5 million customers are served at 9,900 CVS stores per day in the US. Thus the total number of customers served is

$$\frac{4.5\ million\ customers}{day} \div 9900\ stores\ = \textbf{455 customers per day per store}.$$

  - $\frac{8\ million\ customers}{day} \div 9277 stores\ \frac{customers}{day} = \frac{862\ customers}{day}$

- Based on data from Rite Aid (Rite Aid, 2020), around 1.6 million customers visit 2,464 Rite Aid stores per day in the US. Thus the total number of customers served is

$$\frac{1.6\ million\ customers}{day} \div 2464\ stores\ = \textbf{650 customers per day per store.}$$

The average daily number of customers of these three popular pharmacies is thus estimated to be **635 customers per day.**

An example of access to community destinations in a 0.5-mile circular buffer for San Fernando Street in 2019 is provided in Table 4-3. The quantified performance measure for walking (0.5-mile), biking (2-mile), and transit (3-mile and 4.5-mile) transport modes in 2015 and 2019 (before and after building the complete street, respectively) for San Fernando Street is shown in Table 4-4, Table 4-5, and Table 4-6.

Table 4-3. Access to Community Destinations Example, in a 0.5-mile Circular Buffer for San Fernando Street in 2019

Destination Category	**Coffee Shop**	**Restaurant**	**Bank**	**Gas Station**	**Grocery Store**	**Pharmacy**	**Hospital**	**Post Office**	**Library**	**Police Station**	**Place of Worship**	**Museum**
Number of destinations in 0.5-mile buffer	27	142	19	8	12	9	0	2	2	1	18	6
Estimated number of employees	7	18	7	6	33	20	1,962	16	15	762	5	30
Estimated number of customers	350	230	42	682	853	350	225	71	682	100	27	273
Employee accessibility	189	2,556	133	48	396	180	0	32	30	762	90	180
Customer accessibility	9,450	32,660	798	5,456	10,236	3,150	0	142	1,364	100	486	1,638
Total Accessibility: 0.5-mile buffer	9,639	35,216	931	5,504	10,632	3,330	0	174	1,394	862	576	1,818
Total Accessibility in 0.5-mile buffer= 72641												

Example: Total Accessibility in 0.5-mile Buffer =27 (7+350) = 9639*

As observed from Table 4-4, Table 4-5, and Table 4-6 access to destinations along the San Fernando Street decreased for most destination types, stayed the same for some of them and increased for a few destination types from 2015 to 2019. The number of post offices, hospitals, and restaurants increased, while the number of gas stations, grocery stores, and places of worship decreased from 2015 to 2019. Access to destination decreasing can be explained by the changes in the San Fernando complete street typology that required demolishing several of the buildings around the street.

Table 4-4. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes in 2015 for San Fernando Street

Buffer		**Coffee shop**	**Restaur-ant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Library**	**Police station**	**Places of Worship**	**Museum**
0.5	Number of Destinations	37	218	24	9	13	9	0	2	2	1	23	5
	Total Accessibility:	*13,209*	*54,064*	*1,176*	*6,192*	*11,518*	*3,330*	*0*	*174*	*1,394*	*862*	*736*	*1,515*
2	Number of Destinations	55	218	44	45	69	23	0	4	9	2	93	17
	Total Accessibility:	*19,635*	*54,064*	*2,156*	*30,960*	*61,134*	*8,510*	*0*	*348*	*6,273*	*1,724*	*2,976*	*5,151*
3	Number of Destinations:	94	365	60	78	99	51	4	7	17	3	141	20
	Total Accessibility:	*33,558*	*90,520*	*2,940*	*53,664*	*87,714*	*18,870*	*8,748*	*609*	*11,849*	*2,586*	*4,512*	*6,060*
4.5	Number of Destinations	140	523	103	138	150	78	5	12	23	5	233	23
	Total Accessibility:	*49,980*	*129,704*	*5,047*	*94,944*	*132,900*	*28,860*	*10,935*	*1,044*	*16,031*	*4,310*	*7,456*	*6,969*
Total Accessibility in 0.5-mile buffer= 94,170													
Total Accessibility in 2-mile buffer= 192,931													
Total Accessibility in 3-mile buffer= 321,630													
Total Accessibility in 4.5-mile buffer= 488,180													

Table 4-5. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes in 2019 (after building the CS) for San Fernando Street

Buffer (mile)		**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Library**	**Police station**	**Places of Worship**	**Museum**
0.5	Number of Destinations	27	142	19	8	12	9	0	2	2	1	18	6
	Total Accessibility:	*9,639*	*35,216*	*931*	*5,504*	*10,632*	*3,330*	*0*	*174*	*1,394*	*862*	*576*	*1,818*
2	Number of Destinations	51	231	37	38	55	22	0	4	9	2	63	17
	Total Accessibility:	*18,207*	*57,288*	*1,813*	*26,144*	*48,730*	*8,140*	*0*	*348*	*6,273*	*1,724*	*2,016*	*5,151*
3	Number of Destinations:	81	424	57	68	96	41	5	7	16	3	126	20
	Total Accessibility:	*28,917*	*105,152*	*2,793*	*46,784*	*85,056*	*15,170*	*10,935*	*609*	*11,152*	*2,586*	*4,032*	*6,060*
4.5	Number of Destinations	135	560	94	117	144	58	6	17	22	5	201	23
	Total Accessibility:	*48,195*	*138,880*	*4,606*	*80,496*	*127,584*	*21,460*	*13,122*	*1,479*	*15,334*	*4,310*	*6,432*	*6,969*

Total Accessibility in 0.5-mile buffer= 70,076

Total Accessibility in 2-mile buffer= 175,834

Total Accessibility in 3-mile buffer= 319,246

Total Accessibility in 4.5-mile buffer= 468,867

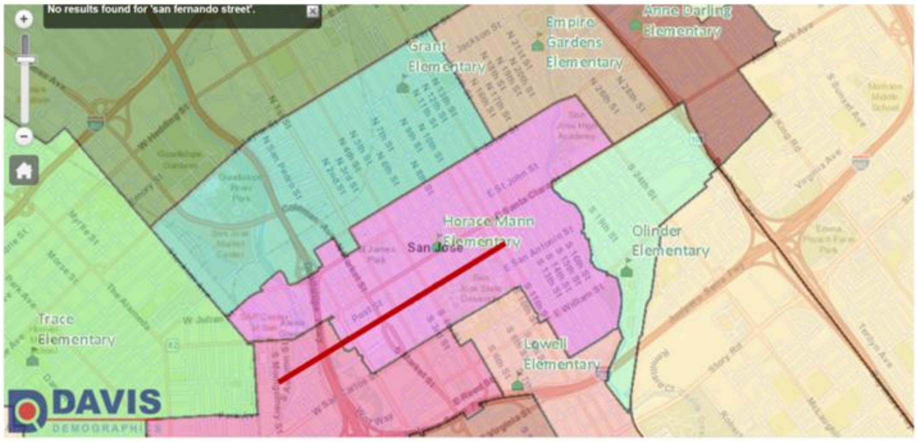
Table 4-6. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes- Before the construction versus After the construction of the San Fernando Street

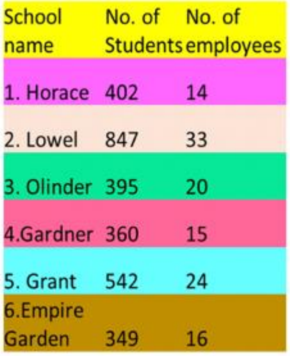
Total Accessibility to community Destinations	**Before**	**After**
Total Accessibility in 0.5-mile buffer (Walking)	94,170	70,076
Total Accessibility in 2-mile buffer (Bicycling)	192,931	175,834
Total Accessibility in 3-mile buffer (Transit)	321,630	319,246
Total Accessibility in 4.5-mile buffer (Transit)	488,180	468,867

4.2.1.2. Access to Schools

4.2.1.2.a. Results using Framework Methodology

According to the framework's suggestions, circular buffers around the complete street were considered first. However, these measurements do not seem appropriate because this area includes many schools (97 schools) in a 2-mile bicycling distance as well as different school districts, which results in complicated situations that do not consider the vulnerability of the student population. Therefore, the current study proposed a school district boundary instead of considering circular buffer areas to measure the "access to school" performance measure. A school attendance boundary, or a catchment area, is defined as a geographic area where the students are assigned to attend a local school (Figure 4-10).





School name	No. of Students	No. of employees
1. Horace	402	14
2. Lowel	847	33
3. Olinder	395	20
4.Gardner	360	15
5. Grant	542	24
6.Empire Garden	349	16

Figure 4-10. Access to school (considering school district boundary)- San Fernando StreetCase Study

Table 4-7 presents the access to school results according to school district boundaries within walking (0.5-mile) and bicycling (2-mile) distances. The complete list of schools, number of students, and employees for the San Fernando Street case study can be found APPENDIX C.

Table 4-7. Accessibility to School considering school district boundary in particular mile circle buffer, San Fernando Street Case Study.

Distance	Accessibility
0.5-mile (Walking)	402
2-mile (Cycling)	2,895

The Access to School indicator for both before (2017) and after (2019) completing the complete street is the same due to no change in the number of schools between these two years. However, this interpretation is not enough; because this indicator is supposed to indicate how many students have access to a complete street for going to school. Therefore, considering only the number of schools near the complete street does not adequately convey the impact of the complete street on this indicator. Hence, surveys were provided for principals to find out the accessibility of students to their schools (next section).

4.2.1.2.b. Survey of Principals

Access to school surveys were sent to the principals of six schools in the San Fernando Street area based on the boundary discussed earlier above. None were returned. The survey was sent out at the beginning of summer in 2020 and again later in the summer. The extra work being undertaken by principals at that time to deal with changing Covid protocols and the return to in-person teaching makes the lack of response understandable.

4.2.1.3. Access to Jobs

Locations of jobs within 0.5-mile walking and 2-mile bicycling circular buffer of San Fernando Street were found using Google Earth™ and Google Maps™. The average walking and bicycling speed are considered 3 miles per hour and 12 miles per hour, respectively (Yang and Diez-Roux, 2012). Considering delay, the average walking distance is 0.5-mile, while the average bicycling distance is 2-mile.

Like access to community destinations, considering the transit buffer area around San Fernando Street, there are many possibilities when combining walking and biking with train, bus, and light rail. Therefore, the most probable scenarios were selected considering 20 minutes for a multi-modal trip assuming 3-mile (bike and bus, bike and train, walk and light rail) and 4.5-mile (bike and light rail, bus, light rail) radii. The recommended buffer distances using different modes of transportation in 20 minutes can be seen in Table 4-2.

Job location types considered for this case study include office buildings, governmental buildings, coffee shops, restaurants, banks, gas stations, grocery stores, pharmacies, hospitals, post offices, libraries, police stations, places of worship, and museums. The number of employees per location was estimated using the available resources, including government statistics (U.S.

government accountability Office, 2018; Virginia Tech, 2020; California State University, 2012), company information, and web research (see APPENDIX C).

The number of office jobs in proximity to the complete street is required. Common building codes, which are not publicly available, were used to estimate the number of employees per office building. The method to calculate the number of government and private offices employees per building using Google Earth is explained below.

According to the County of Santa Clara, where San Fernando Street is located, office workers are typically assigned 331 square feet per person, also referred to as assignable square feet (ASF) (SCCGOV, 2014). The gross square footage (GSF) of each building was measured using the measure tool in Google Maps. To estimate the ASF per building, the number of floors was multiplied by the footprint of the building to calculate the total GSF followed by use of common ratios of ASF to GSF; these ratios are 60% and 70%, according to the policies adopted by California State University system (Cal State University, 2012) and Virginia Institute of Technology (Virginia Tech, 2020). Therefore, an average value of 65% was assumed for this ratio to determine the number of employees in governmental or non-governmental office buildings near the complete street (following equation presents an example of how the measurement tool was used to evaluate the GSF of an office building in San Fernando Street (Figure 4-11).

Number of Employees for government and private offices

$$\boldsymbol{Number\ of\ Employees} = \frac{GSF * 65\%}{331\,\frac{ft^2}{Person}}$$

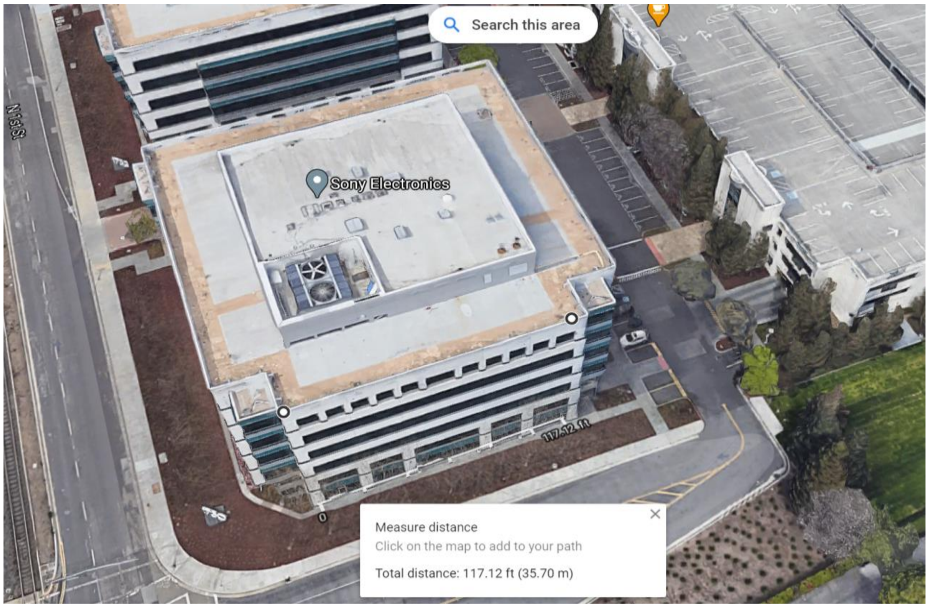


Figure 4-11. Example of the measurement tool used for evaluating the GSF of an office building in San Fernando Street (Google Maps™)

Table 4-8 and Table 4-9 present the results for access to jobs for walking (0.5-mile), biking (2-mile), and transit (3-mile and 4.5-mile) modes in 2015 (before building the CS) and 2019 (after building the CS), respectively, for San Fernando Street. As can be observed from Table 4-10, there is a slight decrease in accessibility to jobs within the walking and biking distances after the completion of complete street construction; this is likely due to the changes in the San Fernando complete street typology that required demolishing several buildings around the street.

Table 4-8. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes in 2015 (before building the CS) for San Fernando Street

Buffer		Coffee shop	Restaurant	Bank	Gas station	Grocery store	Pharmacy	Hospital	Post office	Library	Police station	Places of Worship	Museum	Govt. Building	Office Building
0.5 miles	**Number of job sites**	37	218	24	9	13	9	0	2	2	1	23	5	12	52
	Accessibility	259	3924	168	54	429	180	0	32	30	762	115	150	3,724	1,1226
2 miles	**Number of job sites**	55	218	44	45	69	23	0	4	9	2	93	17	10	8
	Accessibility	385	3924	308	270	2277	460	0	64	135	1524	465	510	4,889	11,998
3 miles	**Number of job sites**	94	365	60	78	99	51	4	7	17	3	141	20	12	31
	Accessibility	658	6570	420	468	3267	1020	7848	112	255	2286	705	600	6,624	19,189
4.5 miles	**Number of job sites**	140	523	103	138	150	78	5	17	23	5	233	23	4	68
	Accessibility	980	9,414	721	828	4,950	1,560	9,810	192	345	3,810	1,165	690	7,064	35,001

Total Accessibility in 0.5-mile buffer= 21,053

Total Accessibility in 2-mile buffer= 27,209

Total Accessibility in 3-mile buffer= 50,022

Total Accessibility in 4.5-mile buffer= 76,530

Table 4-9. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes in 2019 (after building the CS) for San Fernando Street

Buffer		**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Library**	**Police station**	**Places of Worship**	**Museum**	**Govt. Building**	**Office Building**
0.5 miles	**Number of job sites**	27	142	19	8	12	9	0	2	2	1	18	6	12	52
	Accessibility	189	2,556	133	48	396	180	0	32	30	762	90	180	3,724	11,226
2 miles	**Number of job sites**	51	231	37	38	55	22	0	4	9	2	63	17	10	8
	Accessibility	357	4,158	259	228	1,815	440	0	64	135	1,524	315	510	4,889	11,998
3 miles	**Number of job sites**	81	424	57	68	96	41	5	7	16	3	126	23	12	31
	Accessibility	567	7632	399	408	3168	820	9,810	112	240	2,286	630	600	6,624	19,189
4.5 miles	**Number of job sites**	135	560	94	117	144	58	6	17	22	5	201	27	4	68
	Accessibility	945	10,080	658	702	4,752	1,160	11,772	272	330	3,810	1,005	690	7,064	35,001
Total Accessibility in 0.5-mile buffer= 19,546															
Total Accessibility in 2-mile buffer= 26,692															
Total Accessibility in 3-mile buffer= 52,485															
Total Accessibility in 4.5-mile buffer= 78,241															

Table 4-10. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes- Before the construction versus After the construction of the San Fernando Street

Total Accessibility Jobs	**Before**	**After**
Total Accessibility in 0.5-mile buffer (Walking)	21,053	19,546
Total Accessibility in 2-mile buffer (Bicycling)	27,209	26,692
Total Accessibility in 3-mile buffer (Transit)	50,022	52,485
Total Accessibility in 4.5-mile buffer (Transit)	76,530	78,241

4.2.1.4. Job Creation

The Political Economy Research Institute at the University of Massachusetts, Amherst, published a research paper presenting the correlation between job creation and project budgets (Garrett-Peltier, 2011). According to this study, a total of 7.61 full-time equivalent jobs are created per $1 million spent on bike and pedestrian infrastructure projects. The data for Garrett-Peltier's report were collected in the U.S. from departments of transportation and public works departments from 11 cities and 58 separate projects. These projects include road construction and rehabilitation, building new multi-use trails, and widening roads, bike lanes, and sidewalks. The input-output economic model with state-specific data was used to estimate the employment impacts of each project.

IMPLAN version 3 is used in the Garrett-Peltier study (2011) to model job creation and the same model has been used for modeling job creation in this case study. The job creation is broken down into three categories:

- 50% Direct jobs (e.g., at the engineering/construction firm)
- 25% Indirect jobs (supply chain-related, e.g., cement/paint manufacturing)
- 25% Induced jobs (e.g., fast food, retail)

IMPLAN uses employment data as defined in the US Bureau of Economic Analysis Regional Economic Accounts and Bureau of Labor Statistics Census of Employment and Wages and is based on the full-time and part-time averages. According to this model, one job lasting 12 months is equal to two jobs lasting six months each, or a job with a three-month length is considered a 0.25 job.

The author of the current study contacted the City of San Jose in District 3 and the city was unable to provide a response regarding whether the jobs created due to the construction of the San Fernando complete street were temporary or permanent. According to the literature review (Garrett-Peltier, 2011; SCAG, 2016), jobs are not necessarily located in the community where the complete street project is located. Therefore, since distinguishing between permanent and temporary jobs is not easy based on available data, this study used Garrett-Peltier study's job category, including direct, indirect, and induced jobs. According to the definition, direct jobs are created in the engineering and construction firms which are involved in infrastructure projects. In contrast, indirect jobs are created in the supply chain of industries such as cement manufacturing, sign manufacturing, and trucking. Moreover, workers in the direct and indirect sectors spend their earnings, leading to creating demand in industries such as food services and retail establishments, resulting in the induced effects and creating induced jobs (Garrett-Peltier, 2011).

The project budget of $9.9 million for this final project on San Fernando Street was obtained from the Active Transportation Program (ATP) Project List District documents (Caltrans, 2019; CTC, 2019). Calculation of job creation is shown below:

Jobs = Total budget x 7.61 jobs per every $1 million project budget x job category (in %)

- $9.99 * 7.61 * 50% = 38 Direct jobs
- $9.99 * 7.61 * 25% = 19 Indirect jobs
- $9.99 * 7.61 * 25% = 19 Induced jobs

From the budget of $9.99 million spent on transportation infrastructure, a total of 76 jobs were estimated to be created for the construction of the San Fernando complete street project.

4.2.1.5. Connectivity Index

A number of specific measures are used to assess walking and bicycling connectivity in a specific area. Different routes and options in a 1.3-mile rectangular buffer around San Fernando Street between Diridon station and 11 streets were calculated (see Figure 4-12). 1.3 mile was the measured length of the San Fernando Street complete street for this performance measure. As shown in Figure 4-12, three circles with a 1.3-mile diameter were drawn in the center and edges of San Fernando complete street, which resulted in a 2.6-mile by 1.3-mile rectangle when the boundaries of the three circles were connected. The area of this rectangle was then measured to calculate the connectivity index via Google Earth and Google Maps.

Figure 4-12. Considered area for measuring the Connectivity Index, San Fernando Street Case Study

Connectivity indices use various metrics, which are completely discussed in Harvey et al.'s study (Harvey et al., 2018). Table 4-11 presents the selected indices used in the current study and the connectivity results for the San Fernando Street project. The results indicate that the connectivity was increased by the complete streets project but that the index still does not reach the value of “good connectivity” from Semler et. al (2016).

Table 4-11. Connectivity Results for San Fernando Street Case Study Based on the Selected Connectivity Indices

Measure	**Definition and Calculation**	**Notes**	**Before complete street construction (2017)**	**After complete street construction (2019)**
Intersection Density	Number of intersections in a given land area, such as a square mile or acre.	Limited to "4-leg intersections", Typical Range For "Good" Connectivity: 100-160 (Semler et al., 2016)	281/ (2.6*1.3)= **83**	320/ (2.6*1.3)= **95**
Intersections per Linear Mile	Number of intersections in a given land area is divided by the linear network miles in the same area.	Limited to "4-leg intersections" (Semler et al., 2016)	281/2.6/ (2.6*1.3) = **64**	320/2.6 (2.6*1.3)= **73**

4.2.1.6. Active Transportation to Local and Regional Transit Connectivity Index

Aerial imagery using WHAT, Google Earth™, and a static map (City of San Jose, 2020b) was used to calculate this measure by selecting all the bikeway/walking path segments within a 1.3-mile buffer of regionally significant transit stations. The total bikeway mileage within the buffer was then divided by land area within the buffer. The 3.4 square mile (2.6 by 1.3 miles) rectangular buffer around the train station located at the intersection of First Street and San Fernando Street was considered a network area (see Figure 4-13) because the location of this station is almost at the center of the San Fernando Street project. Table 4-12 depicts the results for the active transportation transit connectivity index for the project. The results show that the San Fernando Street project resulted in a considerable increase in connectivity to transit.

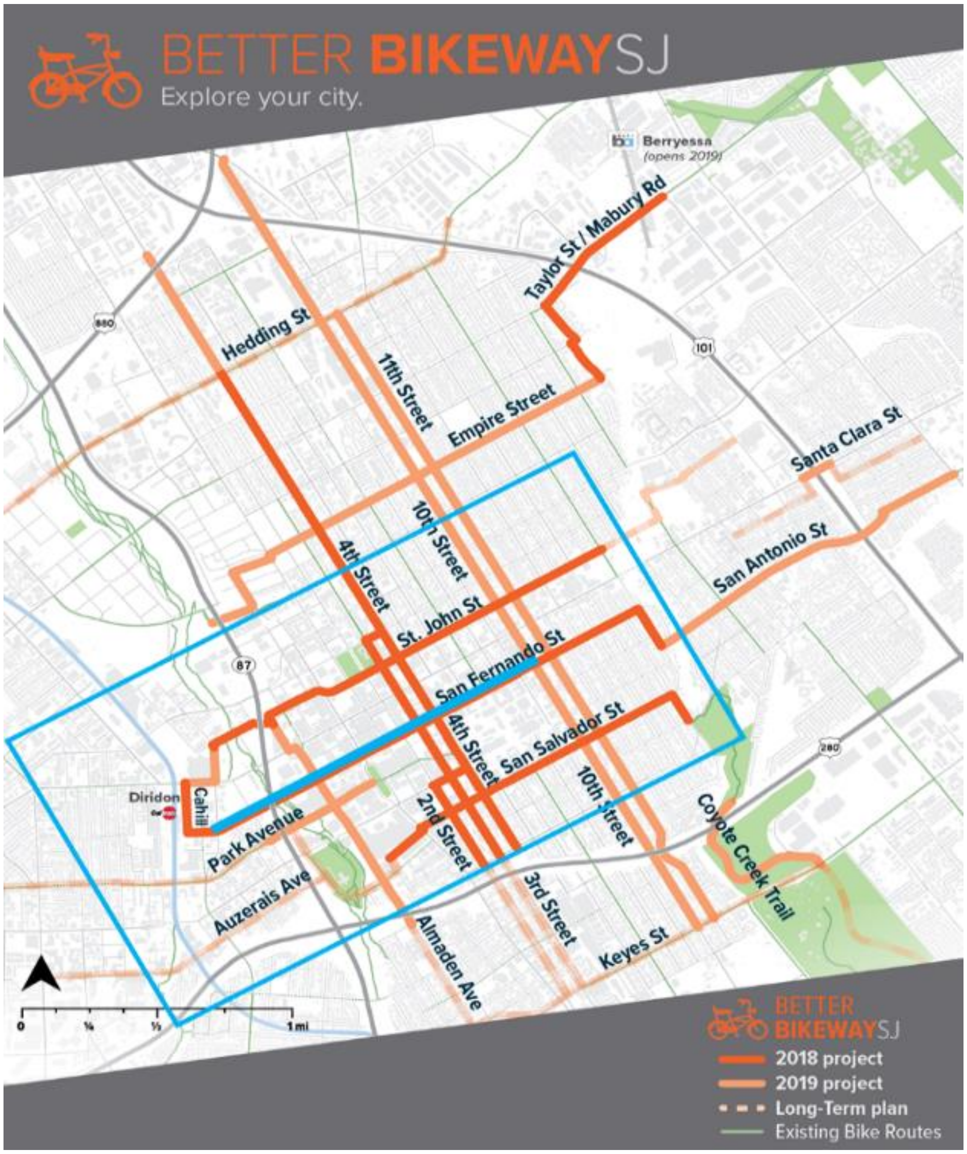


Figure 4-13. City of San Jose's bike network is based on the San Jose Better Bikeway Project with San Fernando Street project and transit served area highlighted in blue (overlaid on City of San Jose, 2020b)

Table 4-12. Results for the Active Transportation Transit Connectivity Index for San Fernando Complete Street Project

Measurement	Before the construction of complete street (2017)	After the construction of complete street (2019)
Mileage of bike/ ped. Lane (2-side)	**19.4** mile	**38** mile
Bike/ ped facility density (2-side)	19.4/(2.6*1.3)= **5.8**	38/(2.6*1.3)= **11.2**

4.2.1.7. Pedestrian and Bicyclist Delay

This indicator was calculated for 2019 (after the complete street was built) using Google Earth™ and Google Earth historical imagery features. Calculations for the total delays in a rectangular buffer (1.3-mile*2.6-mile) around the San Fernando Street project before and after the construction of the complete street are presented in Table 4-13 and Table 4-14, respectively. According to the results shown in the tables, there about a 30% increase in bicycle and pedestrian travel delays between 2017 (before the construction of complete street) and 2019 (after the construction of complete street). This indicates that the complete streets project made active transportation somewhat slower compared to before the project was built.

Table 4-13. Total delays in a rectangular buffer (1.3-mile*2.6-mile) around the San Fernando- Before the Complete Street Construction

g: vehicular green signal Formula	**d: Average delay (s) for narrow roadway (Minor arterial)**	**d: Average delay (s) for narrow roadway (Major arterial)**	**No. of arterial within 1.3-mile* 2.6-mile buffer (Minor Arterial)**	**No. of arterial within 1.3-mile* 2.6-mile buffer (Major Arterial)**	**Total delay(s) for Minor arterial**	**Total delay(s) for Major arterial**	**Total delay(s) in 1.3mile* 2.6mile buffer**
minimum green interval duration: Minor arterial: 4-10 s (avg 7 s) Major arterial: 7-15 s (avg 11 s)	d= [(7+15)^2]/ [2*(7+20)]= **9 s**	d= [(11+10)^2]/ [2*(11+15)]= **8.5**	16	26	144	221	**365**
maximum green interval duration: Minor arterial: 40-50 s (avg 40 s) Major arterial: 40-60 s (avg 50 s)	d= [(40+15)^2]/ [2*(40+20)]= 25.2~ **25 s**	d= [(50+10)^2]/ [2*(50+15)]= 27.7 ~ **28**	16	26	400	588	**988**
Average Delay					272	405	**677 sec (11min)**

Table 4-14. Total delays in a rectangular buffer (1.3-mile*2.6-mile) around the San Fernando - After the Complete Street Construction

g: vehicular green signal Formula	**d: Average delay (s) for narrow roadway (Minor arterial)**	**d: Average delay (s) for narrow roadway (Major arterial)**	**No. of arterial within 1.3-mile* 2.6-mile buffer (Minor Arterial)**	**No. of arterial within 1.3-mile* 2.6-mile buffer (Major Arterial)**	**Total delay(s) for Minor arterial**	**Total delay(s) for Major arterial**	**Total delay(s) in 1.3mile* 2.6mile buffer**
minimum green interval duration: Minor arterial: 4-10 s (avg 7 s) Major arterial: 7-15 s (avg 11 s)	d= [(7+15)^2]/ [2*(7+20)]= **9 s**	d= [(11+10)^2]/ [2*(11+15)]= **8.5**	19	30	171	255	**426**
maximum green interval duration: Minor arterial: 40-50 s (avg 40 s) Major arterial: 40-60 s (avg 50 s)	d= [(40+15)^2]/ [2*(40+20)]= 25.2**~ 25 s**	d= [(50+10)^2]/ [2*(50+15)]= 27.7 ~ **28**	19	30	475	840	**1315**
Average Delay					323	548	**871 sec (14min)**

4.2.1.8. Level of Service

4.2.1.8.a. PLOS and BLOS

The problem in calculating PLOS and BLOS for the San Fernando Street case study was a lack of traffic data before the construction of the complete street, making a before-and-after comparison of LOS difficult. Table 4-15 to Table 4-19 show the PLOS and BLOS results for the complete street project using the HCM and NCHRP methodologies (as discussed in Sections above).

Table 4-15. NCHRP Link PLOS for San Fernando Case Study

	Before	After
Link PLOS Number	4.12	4.12

Due to the lack of traffic data before the construction of the complete street project, it is difficult to calculate how NCHRP Link PLOS changed Table 4-15 shows the link PLOS score assuming the same traffic data before and after the construction of the complete street project. A letter grade cannot be assigned to the NCHRP Link PLOS value because the letter LOS grade applies only to the full facility score and not to the link score. Besides, without calculating intersection BLOS, there is a lack of data; NCHRP PLOS was not recommended.

Table 4-16. Segment-Based LOS by Average Pedestrian Space for San Fernando Complete Street

Methodology	Before complete street was built	After complete street was built
Segment-Based LOS by Average Pedestrian Space	A (309)	A (309)

The sidewalks were wide both before and after the construction of the San Fernando complete street. Since the road's width which is measured inside of the lane to the curb did not change (just re-striped), the pedestrians’ proximity to the traffic remained unchanged; therefore, PLOS by average pedestrian space did not change as can be seen in Table 4-16.

Table 4-17. HCM Link PLOS for San Fernando Complete Street

	Before complete street was built		After complete street was built	
HCM Link PLOS	NB	SB	NB	SB
	B	B	B	B
	B (1.95)		B (1.95)	

**NB: North Bound, and SB: South Bound*

HCM link PLOS didn't change, as can be seen in Table 4-17 because there is no change in the distance between the traffic lanes and the sidewalk. The sidewalks were already spacious in the downtown area that San Fernando Street cuts through. Due to lack of data, HCM intersection BLOS analysis of the complete street was not done, Table 4-18 presents only HCM link BLOS.

Table 4-18. HCM Link BLOS Before and After Construction of San Fernando Complete Street

	Before complete street was built		After complete street was built	
Link BLOS	NB	SB	NB	SB
	C	C	C	C
	C (3.34)		C (3.34)	

Some significant safety improvements can be observed in San Fernando Street complete street, including fresh green paint, plastic bollards to protect the bike lane, and putting the bike lane on the other side of on-street parking. However, some of the important parameters that the HCM methodology considers (e.g., bike lane width) did not change as can be seen in Table 4-18. The HCM methodology considers the road's width instead of the bike lane's width or consideration of the bike lane separation from the road. Therefore, the use of a different BLOS methodology is suggested when Class IV bike lanes are involved. Since HCM does not provide a way to consider the presence of these safety elements, HCM BLOS is not always the best methodology for analyzing complete street projects.

The recommended set of BLOS using the NCHRP equations (NCHRP Report 616, 2008, Eq. 30-32) for the entire facility was calculated. Unlike the HCM methodology, calculating Intersection BLOS is quite doable and is not too data intensive.

Table 4-19. NCHRP Link BLOS Before and After the Construction of San Fernando Complete Street

	Before complete street was built		After complete street was built	
Link BLOS	NB	SB	NB	SB
	D	D	D	D
	D (3.83)		D (3.83)	

The constant score of BLOS before and after constructing the complete street indicates that the NCHRP BLOS methodology is not appropriate for Class IV bike lanes since this methodology's equations and parameters do not match up well. For instance, the width of paving between the outside lane stripe and the edge of the pavement is the shoulder of the road for a Class II bike lane. If there is no shoulder and a barrier with a bike lane on the other side, the input distance is unclear. In addition, the inflexibility of the NCHRP BLOS equations limits the applicability of this model and makes it less useful.

LOS of score 'D' seems to be low for this complete street project (even if given to this street before constructing the complete street). The NCHRP methodology is very sensitive to the number of access points (e.g., driveways, side streets, two-way stop intersections), resulting in a much lower LOS score for segments with higher access point density (see Table 4-19). There are many parking lots and side streets which result in unacceptable BLOS scores.

Although it is evident that cyclist safety along the complete street did improve from 2013 to 2019, there is no change in NCHRP and HCM BLOS. Safety improvement was achieved by improving lane striping and marking and moving the bike lane to the other side of the parking lane. The BLOS methodologies were not designed to analyze such bike lanes, so they could not accurately reflect the improvements in bike safety. Therefore, Bicycle Level of Traffic Stress (LTS), which can be applied to all of these scenarios, is the recommended approach for all complete street projects instead of BLOS methodologies (HCM and NCHRP) which may be useful in certain contexts.

4.2.1.8.b. Urban LOS

Equations for calculating urban LOS are derived from chapter 18 of HCM (Ostovar et al., 2022 and Harvey et al., 2018 adapted from HCM, 2016). LOS for a segment is determined based on travel speed. Travel speed is influenced by on-street parking, curbs, medians, segment length, and the number of access points. It should be noted that shorter segments have slower travel speeds (Table 4-20). Data on average daily traffic (ADT) was collected from the San Fernando Street case study's interactive traffic map (City of San Jose, 2020c).

Table 4-20. Travel Speed Threshold by Base Free-Flow Speed (mi/h) (HCM, 2016)

	Travel Speed Threshold by Base Free-Flow Speed (mi/h)						
LOS	**55**	**50**	**45**	**40**	**35**	**30**	**25**
A	>44	>40	>36	>32	>28	>24	>20
B	>37	>34	>30	>27	>23	>20	>17
C	>28	>25	>23	>20	>18	>15	>13
D	>22	>20	>18	>16	>14	>12	>10
E	>17	>15	>14	>12	>11	>9	>8
F	≤17	≤15	≤14	≤12	≤11	≤9	≤8
F	Any						

According to the FHWA Traffic Data Pocket Guide (FHWA, 2018), the hourly design volume should be around 8% of the average daily traffic (ADT). This amount (8% suggested by FHWA, 2018) is higher than the amount of ADT divided by 24 hours (4.16%). ADT for San Fernando Street was determined to be 9,957 (City of San Jose, 2020c), and multiplying ADT by 8% gives 797 vehicles per hour. Since there are no traffic data from after the completion of complete street, the same value for before and after was used. The important factors that affect Urban LOS are the number of lanes, the number of access points, and the speed limit that did not change after the completion of the complete street; therefore, no change in the score is seen for Urban LOS.

Table 4-21. Urban Streets Level of Service for Before and After the Construction of San Fernando Complete Street

Segment	Travel Speed (mph)	LOS	Segment Length (feet)	BFFS*
Cahill to S Montgomery	13.9	E	255	36.9
Montgomery to S Autumn	11.8	E	247	36.9
S Autumn to Delmas	19.4	C	709	33.5
Delmas to Almaden	24.1	C	1395	37.5
Almaden to Market	22.6	B	990	25.7
Market to 1st	17.5	C	550	33.5
1st Street to 2nd Street	13.4	E	265	35.3
2nd Street to 3rd Street	13.3	E	265	35.3
3rd Street to 4th Street	12.7	E	255	35.4
4th Street to 7th Street	22.9	B	1082	32.2
7th Street to 9th Street	17.9	C	716	31.2
9th Street to 10th Street	12.2	E	276	33.9
10th Street to 11th Street	13.9	E	279	33.9
Weighted average Speed	**19.4**			**33.2**
Travel Speed/BFFS = LOS	**58.20%**	**C**		

**BFFS is Base Free Flow Speed*
Urban LOS is scored based on how fast traffic moves compared to the BFFS.

As shown in Table 4-21, LOS C indicates that the traffic flow is about half of the base free-flow speed (BFFS). The calculation of intersection LOS is required to determine the amount of delay experienced by vehicles at signalized intersections and analyze an Urban LOS. Due to a lack of signal timing data and detailed traffic movement data, the intersection LOS could not be calculated.

An article published in the San Jose Mercury News was used to determine how intersection LOS along San Fernando Street had been affected by constructing the complete street (Pizarro, 2019). According to the article, the Santa Clara Valley Transportation Authority needed to find a different bus route for the buses on San Fernando Street because of heavy traffic congestion.

Significant bus delays resulted in re-routing most of San Fernando Street bus service to a parallel street (Santa Clara Street)

4.2.1.8.c. Transit LOS

Transit LOS (TLOS) measures the quality of service provided by buses along with the facility by segment. The HCM methodology (NCHRP 616, 2008) and the Transit LOS Calculator (TCRP) were used to calculate TLOS of San Fernando Street (TRB, 2013). Transit LOS depends on the frequency of bus services, road geometry, and PLOS.

Required Steps for calculating the Transit LOS include:

- the transit vehicle running speed
- the travel speed of transit vehicles along the segment
- the effective width of the sidewalk
- the pedestrian link LOS.

Due to severe congestion issues being experienced on the San Fernando Street complete street, most bus stops were moved to other streets (six bus stops from San Fernando Street were moved. The current bus stops (two bus stops) operate at transit LOS C, while the rest of the segment has an automatic LOS F score due to the lack of bus stops (see Table 4-22). Transit LOS for the San Fernando Street complete street before construction could not be calculated because of the lack of data on the historical bus schedules. Table 4-22 presents the Transit LOS after the construction of San Fernando complete street.

Table 4-22. Transit LOS after the construction of San Fernando complete street

Segment	Score	LOS	Segment Length (feet)
Cahill to S Montgomery	6.29	F	255
Montgomery to S Autumn	6.32	F	247
S Autumn to Delmas	6.27	F	709
Delmas to Almaden	6.24	F	1395
Almaden to Market	6.24	F	990
Market to 1st	6.31	F	550
1st Street to 2nd Street	6.22	F	265
2nd Street to 3rd Street	6.23	F	265
3rd Street to 4th Street	6.23	F	255
4th Street to 7th Street	6.24	F	1082
7th Street to 9th Street	3.16	C	716
9th Street to 10th Street	3.23	C	276
10th Street to 11th Street	3.25	C	279
Weighted Average Score	**5.73**		
Weighted average LOS		**F**	

4.2.1.8.d. Level of Traffic Stress (LTS)

The methodology in the Montgomery County Bicycle Master Plan (Montgomery County Bicycle Master Plan, 2018) was used to measure LTS for San Fernando Street. LTS improved from 2.5 to 1 after the San Fernando Street complete street was built, as shown in Table 4-23. LTS score 1 indicates very low traffic stress, which is suitable for most of the vulnerable groups. The tables from the appendix of the Montgomery Master Plan (2018) used to arrive at the scores are presented in APPENDIX D.

Table 4-23. Level of Traffic Stress (LTS) Score Comparing Before and After Building the San Fernando Complete Street

LTS Method	Before complete street was built	After complete street was built
Intersection LTS	1	1
Bike Lane LTS	2.5	1
Separated Bike Lane LTS	NA	1
Summary	**2.5 (Moderately Low)**	**1 (Very Low)**

4.2.1.9. Crashes

For the San Fernando Street complete street project, the number of bicycle-involved and pedestrian-involved crashes over five years were considered. The San Jose crash table 2015-2019 database was used for this measurement (City of San Jose, 2020d). The 1.3-mile buffer areas around San Fernando complete street were considered for calculating this indicator.

Table 4-24. Number of Crashes in the 1.3-mile buffer areas around San Fernando complete street

Years	Number of Crashes	
2015	85	Before the complete street was build= Average (2015-2018) = (85+81+68+83)/4 = **79**
2016	81	
2017	68	
2018	83	
2019	92	After the complete street was build= **92**

Table 4-24 presents the crash performance measure before and after the transition of San Fernando Street to the complete street. The crash data show fluctuations before the project was built, and a small increase in crashes after the project was completed. These results are inconclusive but indicate that the crash levels should continue to be monitored to see how the project influenced crash risks. This statistic should probably be normalized by pedestrian and bicycle miles traveled, because an increase in miles traveled will increase the risk of crashes.

4.2.1.10. Pedestrian Miles Traveled / Bicycle Miles Traveled

According to the San Jose traffic planning report, walking and biking trips were modeled for the City of San Jose (Hexagon, 2018). PMT and BMT depend on the number of pedestrian trips and bicyclist trips and the distance traveled. PMT and BMT are calculated for average trip lengths of 0.5 miles and 2 miles.

Bike and pedestrian data and projections were gathered on the number of bicycle and pedestrian trips, followed by multiplying them by the respective distances.

According to the San Jose traffic planning report, walking and biking trips were modeled for the City of San Jose (Hexagon, 2018). PMT and BMT depend on the number of pedestrian trips and bicyclist trips and the distance traveled. PMT and BMT are calculated for average trip lengths of 0.5 miles and 2 miles. Bike and pedestrian data and projections were gathered on the number of bicycle and pedestrian trips, followed by multiplying them by the respective distances.

Projections are based on the Metropolitan Transportation Commission (MTC)'s regional model. According to the model calibrated to 2015 traffic data, the mean squared error (MSE) was 34%, the R squared was 87%, and the projections were made to 2040 based on the general plan. The model gives the number of biking and walking trips within downtown San Jose and to/from downtown San Jose. Based on the general plan 2040, bike mode share and pedestrian mode share will increase by 0.01% and 2 % for Downtown San Jose, respectively (Hexagon, 2018). Table 4-25 presents PMT and BMT for average trip lengths of 0.5 miles and 2 miles for the entire downtown San Jose area, not just the San Fernando Street complete street area. An increase in PMT and BMT was seen that may be partly associated with the San Fernando complete street, as well as other city policies.

Table 4-25. Pedestrian Miles Traveled, and Bicycle Miles Traveled for San Fernando Street Case Study for Entire Downtown San Jose (not just the complete street)

Year	Trip Length	PMT	BMT
Before complete street is built (2015)	0.5 miles	7,799	2,279
	2 miles	31,194	8,916
After complete street is built (2040)	0.5 miles	31,135	6,101
	2 miles	124,540	24,404

4.2.1.11. Street Trees

The number of trees was counted along San Fernando Street from Diridon Station to the 11th Street. San Jose's Interactive TreeMap was used to count Street Trees (Figure 4-14). (City of San Jose, 2020e)

Figure 4-14. Trees Map view of San Fernando Street (taken from City of San Jose, 2020e)

Table 4-26. Number of Street Trees along the San Fernando Complete Street

Year	**Number of street trees**
2013 (before building the complete street)	136
2019 (after building the complete street)	127

As can be observed from Table 4-26, the number of street trees has slightly decreased because of the redesign of the San Fernando Street as a complete street.

4.2.2. Franklin Boulevard Case Study

4.2.2.1. Access to Community Destinations

For the complete street case study, destinations within 0.5-mile walking and 2-mile bicycling radii of Franklin Boulevard were found using Google Earth™ and Google Maps™ (see

Figure 4-15). The average walking speed is assumed to be three mph, while the bicycling speed is assumed to be 12 mph (Yang and Diez-Roux, 2012).

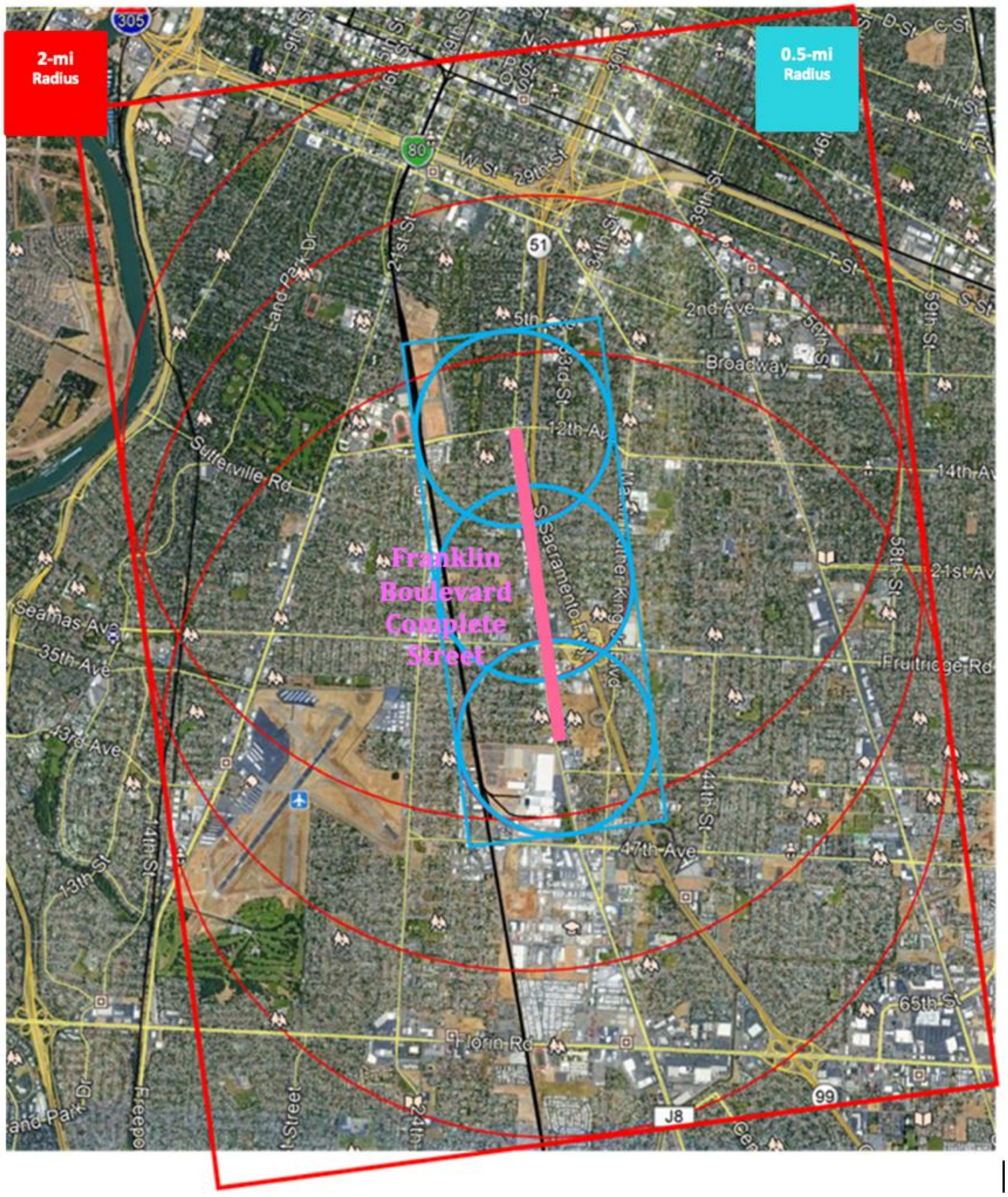
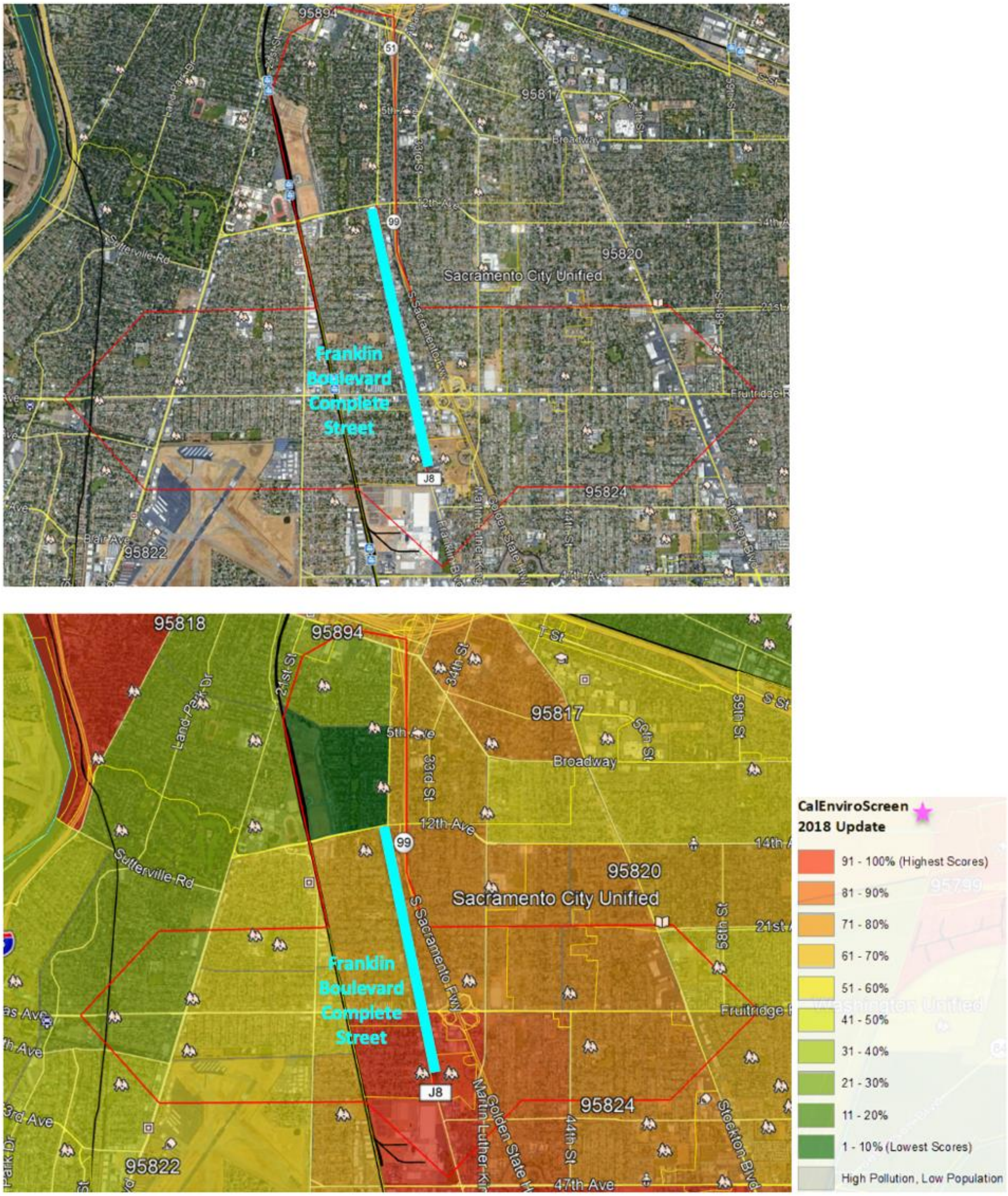


Figure 4-15. Access to Destination Buffer Area for Walking and Cycling Modes of Transportation, Franklin Boulevard Complete Street Project

To consider the transit accessible area around Franklin Boulevard, there are many possibilities when combining walking and biking with train, bus, and light rail. Therefore, the most probable scenarios were selected considering 20 minutes for a combined-mode trip.

The first option that can be considered around the Franklin Boulevard complete street is a circular buffer. However, due to geographical barriers and variability in population around this project, the circular buffer is too simple and cannot encompass the barriers created by the freeway and the railroad around the future complete street. Therefore, a polygon buffer was used to define the distance-time boundaries for the street, as shown in Figure 4-16. As seen in the proposed polygon buffer, the south part of the Franklin Boulevard complete street has a higher socio-economic score compared to the north part. It can also be observed from this figure that the southern part and the eastern part of the Franklin Boulevard complete street are a transit desert area (there is no transit service). State Route 99 is considered an eastern side geographical boundary for Franklin Boulevard complete street, while the Sacramento South Railroad is regarded as a west side geographical boundary. According to Google Map, Google Earth, and CalEnviroScreen Map (Figure 4-16), since Fruitridge Road includes many bus stations and light rail stations, the geographical boundary around the intersection of Franklin Blvd and Fruitridge Road is considered to be 2-mile from the eastern and 2-mile from the western side of Franklin Boulevard (10 minutes for each side). In addition to considering 10 minutes of transit, 10 minutes of walking mode (0.5 miles) is also considered around Fruitridge Road (Figure 4-16).



** an area with a high score experiences higher cumulative impacts (combination of pollution burden and population characteristics).*

Figure 4-16. Access to Destinations Buffer Area for Transit Modes of Transportation, Franklin Complete Street Project

Table 4-27 shows the recommended buffer distances used for different modes of transportation for 20-minute trips.

Table 4-27. The Recommended Buffer Distances Used for Different Modes of Transportation for 20-minute Trip

Recommended Buffer Distance	**Mode**
0.5 mile (Figure 4-15)	Walking
2 mile (Figure 4-15)	Biking
Polygon Buffer Area (Figure 4-16)	Bus+Walking, Train+Walking, Light Rail+Walking

Destinations considered for this case study include coffee shops, restaurants, banks, gas stations, grocery stores, pharmacies, hospitals, post offices, libraries, police stations, places of worship, and museums. The number of customers and employees for each destination was calculated using the best available resources, including government statistics (APPENDIX B), company information, and web research. The example calculations were shown earlier in the San Fernando complete street case study. Table 4-28 shows the example of access to community destinations in a 0.5-mile circular buffer for Franklin Boulevard in 2019. Table 4-29 presents the data for this performance measure for walking (0.5-mile), biking (2-mile), and transit (polygon buffer) modes for the polygon area considering the freeway and railroad barriers before the construction of the Franklin Boulevard complete street. As shown in Figure 4-16, the Franklin Boulevard project area is a transit desert. Therefore, the cycling buffer around Franklin Boulevard complete street project gives more accessibility to community destinations compared to the transit buffer area around the complete street project.

One of the main reasons for constructing the Franklin Boulevard complete street is to help create social development and economic revitalization for this area. According to the Franklin Boulevard economic development plan (Hernandez, 2016), there needs to be an improvement in the accessibility to the community destinations for the Franklin Boulevard. Several potential projects suggested by the economic development plan include a senior living center, a park, an expanded veterinary clinic, an education center, and a small transit-oriented development. According to the Franklin Boulevard complete street project design for 2040, a report prepared for SACOG in 2018 published as “Franklin Boulevard Complete Street Phase 2”, accessibility to community destinations will increase about 11% (City of Sacramento and Department of Public Works, 2018) because of the complete street. Figure 4-17 shows the access to community destinations for walking (0.5-mile), biking (2-mile), and transit (polygon buffer) transport modes before the construction and expected after the construction of the Franklin Boulevard complete street project. The Franklin Boulevard complete street construction has not yet started, therefore the results shown in Table 4-30 are estimates.

Table 4-28. Details of Access to Community Destinations in a 0.5-mile Circular Buffer for Franklin Boulevard in 2019

Destination category	**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Libraries**	**Police station**	**Places of Worship**	**Museum**
Number of destinations in 0.5-mile buffer	3	27	1	5	12	3	0	0	0	1	19	0
Estimated employees	7	18	7	6	33	20	1,962	16	15	762	5	30
Estimated customers	350	230	42	682	853	350	225	71	682	100	27	273
Employee accessibility	21	486	7	30	396	60	0	0	0	762	95	0
Customer accessibility	1,050	6,210	42	3,410	10,236	1,050	0	0	0	100	513	0
Total Accessibility: 0.5-mile buffer	**1,071**	**6,696**	**49**	**3,440**	**10,632**	**1,110**	**0**	**0**	**0**	**862**	**608**	**0**
Total Accessibility in 0.5-mile buffer= 24,468												

Example: Total Accessibility in 0.5-mile Buffer =3 (7+350) = 1071*

Table 4-29. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon Buffer) Modes in 2019 (before building the CS) for Franklin Boulevard

Buffer		Coffee shop	Restaur-ant	Bank	Gas station	Grocery store	Pharmacy	Hospital	Post office	Library	Police station	Places of Worship	Museum
0.5	Number of destinations	3	27	1	5	12	3	0	0	0	1	19	0
	Total Accessibility:	1,071	6,696	49	3,440	10,632	1,110	0	0	0	862	608	0
2	Number of destinations	26	125	18	42	51	22	2	4	7	2	110	1
	Total Accessibility:	9,282	31,000	882	28,896	45,186	8,140	4,374	348	4,879	1,724	3,520	303
Polygon Buffer	Number of destinations	4	44	5	14	20	6	0	0	1	1	33	0
	Total Accessibility:	1,428	10,912	245	9,632	17,720	2,220	-	-	697	862	1,056	-
Total Accessibility in 0.5-mile buffer= 24,468													
Total Accessibility in 2-mile buffer= 138,534													
Total Accessibility in Polygon Transit buffer= 44,772													

Table 4-30. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon buffer) Transport Modes- Before the construction versus After the construction of the Franklin Boulevard Complete Street Project

Total Accessibility to community Destinations	Before	After
Total Accessibility in 0.5-mile buffer (Walking)	24,468	27,159
Total Accessibility in 2-mile buffer (Bicycling)	138,534	153,773
Total Accessibility in Polygon buffer (Transit)	44,772	49,697

4.2.2.2. Access to Schools

4.2.2.2.a. Results using Framework Methodology

In the Franklin Boulevard complete street case study, school district boundaries around the complete street between 12th Avenue and 38th Avenue were considered. However, the school district boundaries for this case study do not seem appropriate because of the large number of schools (81 schools) in the Sacramento City Unified School District, which results in complicated boundaries. Therefore, the current case study used a City of Sacramento neighborhood map to consider a 0.5-mile walking and 2-mile bicycling circular buffer around the complete street (Figure 4-17). Then, accessibility to the schools encompassed by the neighborhoods located within the walking and bicycling circular buffers around the complete street was calculated.

Table 4-31 presents the access to school results according to the Franklin Boulevard complete street project neighborhood map and walking and bicycling circular buffers around the project including two schools within a 0.5-mile and 14 schools within a 2-mile circular buffer. A third school at the south end of the complete street was previously within the 0.5-mile buffer, but was closed. Students from that school in particular would primarily be using the complete street to get to their newly assigned school near the middle of the complete street. The complete list of schools and the number of students for the Franklin Boulevard case study can be found in APPENDIX C.

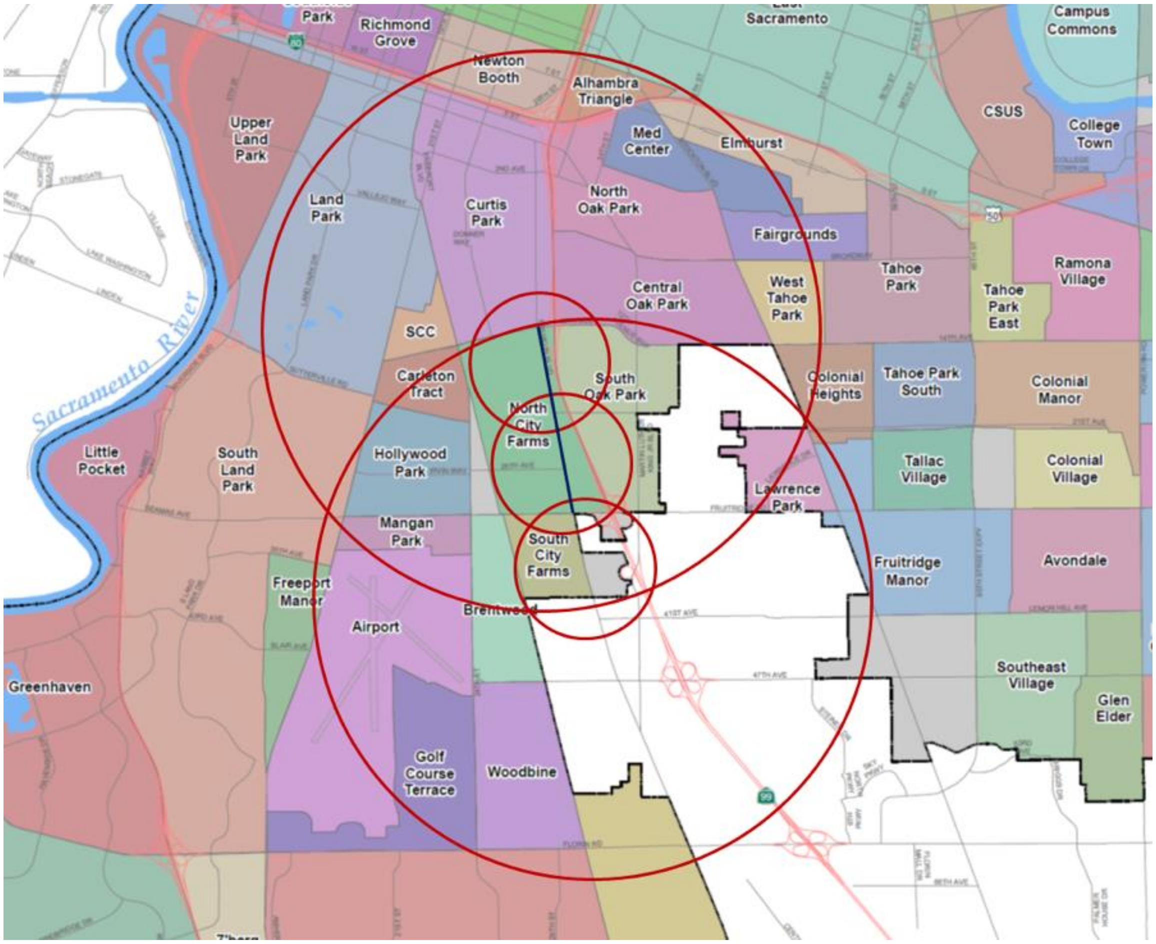


Figure 4-17. Combination of a city of Sacramento's neighborhood map showing a 0.5-mile walking and 2-mile bicycling circular buffer around the Franklin Boulevard case study.

Table 4-31. Accessibility to School considering school district boundary in particular mile circle buffer, Franklin Case Study

Situation	**Accessibility**
d: 0.5-mile (Walking)	762
d: 2-mile (Cycling)	7,666

No information regarding any change in the number of schools and students was found. The access to school indicator for both before and after constructing the complete street was assumed the same due to no change in the number of schools between these two years.

4.2.2.2.b. Surveys of Principals

Access to school surveys were sent to the principals of 18 schools in the Franklin Boulevard study area based on the boundary discussed above. One was returned from an elementary school that is within the biking buffer but outside the walking buffer. That school is also on the east side of the State Route 99 freeway that cuts off most access between the Franklin Boulevard complete street and the school and the school is therefore in a different neighborhood. The survey was sent out at the beginning of summer in 2020 and again later in the summer. The extra work being undertaken by principals at that time to deal with changing Covid protocols and the return to in-person teaching makes the lack of response understandable. The one response to the survey to the survey provides useful qualitative and quantitative answers from the principal who responded and suggests that further use of the survey instrument in future research will provide important information that cannot be obtained otherwise.

The principal estimated that 30 to 50% of students walked, depending on the season (most in spring, least in winter, fall in between), 5% biked, 10% took transit, and 35 to 55% were driven, again with seasonal differences mirroring those walking. It was estimated that those who walk have about a 5-minute trip. The percentages of students who walked without adult supervision (a sub-set of the total who walk) increases from 7% in kindergarten, to 10% for grades 1-3, and 15% for grades 1-5.

The principal identified that those students using active transportation mostly do not use Franklin Boulevard and identified two other schools (another elementary school and a middle school) whose students would be more likely to use it, in neighborhoods that are not isolated from the school by the freeway. Although the school is three blocks from Franklin Boulevard and in the Franklin Boulevard biking and walking buffers, the principal identified another boulevard that is diagonal to Franklin, roughly parallel to and then intersecting Franklin, that students use and whose safety issues would be more important because its conditions are a challenge for those wanting to use active transportation. In particular, the principal identified the presence of liquor stores and gatherings of homeless people at those stores, and the high volume of vehicle traffic traveling past the school coming from students using a nearby high school. The former issue cannot be addressed by a complete street but the second could be.

The principal noted that students would feel safe and comfortable when using transit, but the students and their parents would not feel that it is safe and comfortable for walking and biking alone to school because of the busy street the school is on (not Franklin Boulevard), fast traffic, and unsafe young drivers attending the nearby high school. The school has adequate bicycle parking but has a new bike rack that has not been installed. The principal thought that parents would be comfortable if the students walked or biked to school with at least one adult.

As noted, the principal was surveyed because the school was within the biking buffer, but the school is mostly cut off from Franklin Boulevard by the freeway. It is therefore not surprising that the principal did not think that the Franklin Boulevard complete street would improve biking and walking to the school. The principal did note three other streets on the east side of the freeway that if converted to complete streets would improve biking and walking to the school.

4.2.2.3. Access to Jobs

A similar method used for calculating access to jobs for the San Fernando Street case study. Table 4-32 was used for the Franklin Boulevard complete street case study. presents the results for access to jobs for walking (0.5-mile), biking (2-mile), and transit (polygon buffer) modes before the construction of the complete street.

The expectation for accessibility to jobs after the construction of Franklin Boulevard complete street is that there will be an increase in investments and jobs along the road segment. According to the Franklin Boulevard complete street project design for 2040 prepared by the City of Sacramento and the Department of Public Works (2018), a 62% increase will be seen in the accessibility to jobs (see Table 4-33). Job retention at current businesses is also a priority of the neighborhood and the complete street treatment is one key strategy for meeting this priority by increasing the viability of the existing businesses.

Table 4-32. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon buffer) Modes in 2019 (before building the CS) for Franklin Case Study

Buffer		**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Library**	**Police station**	**Places of Worship**	**Museum**	**Govt. Building**	**Office Building**
0.5 miles	**Number of job sites**	3	27	1	5	12	3	0	0	0	1	19	0	0	0
	Accessibility	21	486	7	30	396	60	0	0	0	762	95	0	0	0
2 miles	**Number of job sites**	26	125	18	42	51	22	2	4	7	2	110	1	22	4
	Accessibility	357	4,158	259	228	1,815	440	0	64	135	1,524	315	510	3,470	194
Polygon Buffer	**Number of job sites**	4	44	5	14	20	6	0	0	1	1	33	0	4	0
	Accessibility	28	792	35	84	660	120	0	0	15	762	165	0	1,010	0
Total Accessibility in 0.5-mile buffer= 1,857															
Total Accessibility in 2-mile buffer= 13,469															
Total Accessibility in Polygon buffer= 3,671															

Table 4-33. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon Buffer) Modes- Before versus After the construction of the Franklin Boulevard

Total Accessibility Jobs	**Before**	**After**
Total Job Accessibility in 0.5-mile buffer (Walking)	1,857	3,008
Total Job Accessibility in 2-mile buffer (Bicycling)	13,469	21,820
Total Job Accessibility in Polygon buffer (Transit)	3,671	5,947

4.2.2.4. Job Creation

The same methodology used for calculating job creation for the San Fernando Street case study was used for the Franklin Boulevard complete street case study. SACOG's proposed budget for the construction of the Franklin Boulevard complete street project is around $9.148 million (City of Sacramento and Department of Public Works, 2018). Thus, the total number of jobs associated with the project based on modeling are expected to be:

- $9.148 * 7.61 * 50% = 35 Direct jobs
- $9.148 * 7.61 * 25% = 18 Indirect jobs
- $9.148 * 7.61 * 25% = 17 Induced jobs

This results in a total of 70 jobs estimated to be created by the construction of the Franklin Boulevard complete street project.

As mentioned previously job retention is a key priority, and the Franklin Boulevard plan is intended to help improve the viability of existing locally owned businesses and the jobs they provide. This is particularly important in disadvantaged neighborhoods where loss of existing businesses can contribute to gentrification when outside businesses move into a distressed neighborhood. A metric for business and job retention has not yet been developed for this effect of a complete street.

4.2.2.5. Connectivity Index

Different routes and options in a 1.6-mile long (the length of the complete street project) rectangular buffer (Figure 4-18) around Franklin Boulevard between 12th Avenue and 38th Avenue were calculated. As shown in Figure 4-18, three circles with a 1.6-mile diameter were drawn in the center and edges of the Franklin Boulevard complete street, which made a 3.2 by 1.6 square miles rectangle. The area of this rectangle was then measured to calculate the connectivity index via Google Earth and Google Maps.

Figure 4-18. Considered area for measuring the Connectivity Index, Franklin Boulevard Case Study

Table 4-34 shows the description and calculations for the selected indices considered for connectivity for Franklin Boulevard Since the northern part of Franklin Boulevard has a lower socio-economic score compared to the southern part, Table 4-34 presents the connectivity for these two parts separately and as well as together.

According to the Franklin Boulevard complete street project design for 2040 published by SACOG in 2018 (City of Sacramento and the Department of Public Works, 2018), the number of 3 and 4-leg intersections will increase by about 13%, which results in an increase in the connectivity index performance measure in Franklin Boulevard complete street project.

Table 4-34. Connectivity Results for Franklin Boulevard Case Study Based on the Selected Connectivity Indices

Measure	**Definition and Calculation**	**Notes**		**Before the complete street construction**	**After the complete street construction**
Intersection Density	Number of intersections in a given land area, such as a square mile or acre.	Limited to "3 and 4-leg intersections", Typical Range For "Good" Connectivity: 100-160 (Harvey et al., 2018, adapted from Semler et al., 2016)	South part of Franklin Boulevard	245/ (3.2*1.6)= **48**	**164**
			North part of Franklin Boulevard	486/ (3.2*1.6)= **95**	
			Total	**145**	
Intersections per Linear Mile	Number of intersections in a given land area is divided by the linear network miles in the same area.	Limited to "3 and 4-leg intersections" (Harvey et al., 2018, adapted from Semler et al., 2016)	South part of Franklin Boulevard	245/3.2/ (3.2*1.6) = **15**	**51**
			North part of Franklin Boulevard	486/3.2/ (3.2*1.6) = **30**	
			Total	**45**	

4.2.2.6. Active Transportation to Local and Regional Transit Connectivity Index

Aerial imagery, Google Earth, and a static map were used to calculate this measure by selecting all the bikeway/walking path segments within a 1.6-mile buffer of regionally significant transit stations. The total bikeway miles within the buffer were then divided by land area within the buffer (see Figure 4-19). The 3.2*1.6 square mile rectangle buffer around the transit station at the intersection of Fruitridge Road and Franklin Boulevard was considered a network area; the location of the station is almost at the center of the Franklin Boulevard complete street. Table 4-35 depicts the results for the active transportation transit connectivity index for Franklin Boulevard complete street.

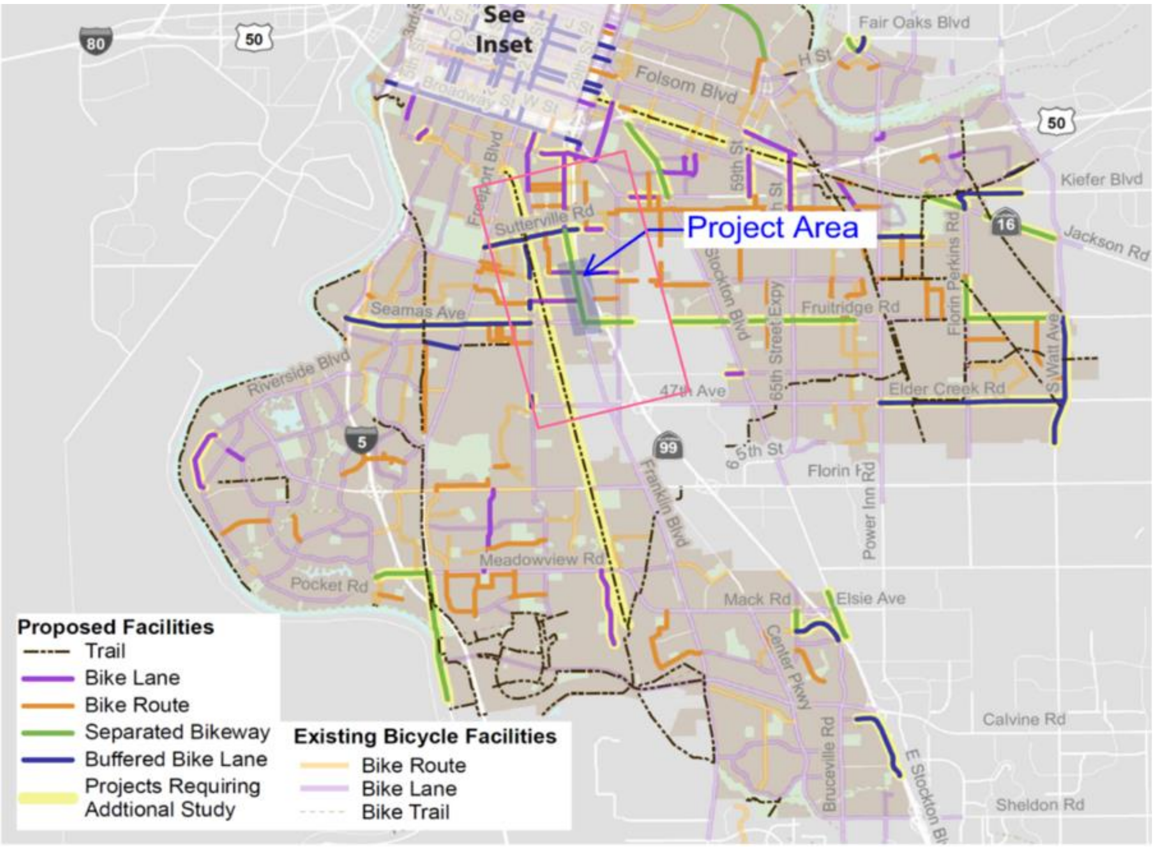


Figure 4-19. Bike network around Franklin Boulevard derived from Project Performance Assessment (PPA) Tool (SACOG, 2020, and City of Sacramento and Department of Public Works, 2018)

Table 4-35. Results for the Active Transportation Transit Connectivity Index for Franklin Boulevard Complete Street Project

Measurement	Current conditions (no complete street build)	Expected outcome (after the complete street is build)
Mileage of bike/ ped. Lane (2-side)	**15.6** mile	**40.2**
Bike/ ped facility density (2-side)	7.8/(3.2*1.6)= **3**	**7.8**

4.2.2.7. Pedestrian and Bicyclist Delay

Dunn and Pretty's equations (Dunn and Pretty, 1984; FHWA, 1998) mentioned in the section of Performance Measures Considered in Complete Street Case Studies were used to calculate pedestrian delay at signalized pedestrian crossings for the Franklin Boulevard case study. Dunn and Pretty’s equations and the FHWA guidance were also used to calculate the green interval duration. Calculations for the total delays in a rectangular buffer (1.6-mile*3.2-mile) around the Franklin Boulevard case study are presented in

Table 4-36 and

Table 4-37.

This indicator was calculated for the year 2019 since the complete street project had not been built yet, using Google Earth™ and Google Earth historical imagery features. According to these tools and the Sacramento County general plan (Sacramento County General Plan, 2020), there will be a small difference (13% increase in the number of intersections) between before (2019) and after (2040) the construction of the Franklin Boulevard complete street project. Calculations for the total delays in a rectangular buffer (1.6-mile*3.2-mile) around the Franklin Boulevard complete street before building the complete street and after the construction of this project are presented in

Table 4-36 and

Table 4-37, respectively.

Table 4-36. Total delays in a rectangular buffer (1.3-mile*2.6-mile) around the Franklin Boulevard case study- Before the Complete Street Construction

g: vehicular green signalFormula	**d: Average delay (s) for narrow roadway (Minor arterial)** $d = \frac{(g+15)^2}{2\,(g+20)}$	**d: Average delay (s) for narrow roadway (Major arterial)** $d = \frac{(g+10)^2}{2\,(g+15)}$	**No. of arterial within 1.6-mile* 3.2-mile buffer (Minor Arterial)**	**No. of arterial within 1.6-mile* 3.2-mile buffer (Major Arterial)**	**Total delay(s) for Minor arterial**	**Total delay(s) for Major arterial**	**Total delay(s) in 1.6mile* 3.2mile buffer**
minimum green interval duration: Minor arterial: 4-10 s (avg 7 s) Major arterial: 7-15 s (avg 11 s)	d= [(7+15)^2]/ [2*(7+20)]= **9 s**	d= [(11+10)^2]/ [2*(11+15)]= **8.5**	208	6	1872	51	**1923**
maximum green interval duration: Minor arterial: 40-50 s (avg 40 s) Major arterial: 40-60 s (avg 50 s)	d= [(40+15)^2]/ [2*(40+20)]= 25.2~ **25 s**	d= [(50+10)^2]/ [2*(50+15)]= 27.7 ~ **28**	208	6	5200	168	**5368**
Average Delay					3536	109	**3645 (61min)**

Table 4-37. Expected total delays in a rectangular buffer (1.3-mile*2.6-mile) around the Franklin Boulevard case study- After the Complete Street Construction

g: vehicular green signal Formula	**d: Average delay (s) for narrow roadway (Minor arterial)** $d=\frac{(g+15)^2}{2\,(g+20)}$	**d: Average delay (s) for narrow roadway (Major arterial)** $d=\frac{(g+10)^2}{2\,(g+15)}$	**No. of arterial within 1.6-mile* 3.2-mile buffer (Minor Arterial)**	**No. of arterial within 1.6-mile* 3.2-mile buffer (Major Arterial)**	**Total delay(s) for Minor arterial**	**Total delay(s) for Major arterial**	**Total delay(s) in 1.6mile* 3.2mile buffer**
minimum green interval duration: Minor arterial: 4-10 s (avg 7 s) Major arterial: 7-15 s (avg 11 s)	d= [(7+15)^2]/ [2*(7+20)]= **9 s**	d= [(11+10)^2]/ [2*(11+15)]= **8.5**	235	7	1998	61	**2059**
maximum green interval duration: Minor arterial: 40-50 s (avg 40 s) Major arterial: 40-60 s (avg 50 s)	d= [(40+15)^2]/ [2*(40+20)]= 25.2~ **25 s**	d= [(50+10)^2]/ [2*(50+15)]= 27.7 ~ **28**	235	7	5876	190	**6066**
Average Delay					3536	125	**4062 (68min)**

4.2.2.8. Level of Service

4.2.2.8.a. PLOS and BLOS

The HCM methodology was tested, and required data were found for the Link PLOS, Segment PLOS, and Pedestrian Space LOS. However, the Intersection PLOS could not be calculated due to data unavailability. Segment PLOS is equivalent to the link PLOS in the HCM methodology. The HCM Link PLOS methodology is used to get a letter grade for link PLOS. The HCM Pedestrian Space methodology is followed to get a letter grade for the facility PLOS.

Unavailable traffic data was the main problem in calculating PLOS and BLOS in the Franklin Boulevard case study making before-and-after LOS comparison difficult. Data on ADT was acquired from the planning documents of Franklin Boulevard (City of Sacramento Department of Public Works, 2018). Table 4-38 to Table 4-42 shows the PLOS and BLOS results for the Franklin Boulevard case study.

Table 4-38. NCHRP Link PLOS for Franklin Complete Street

Methodology	**Before complete street was built**	**After complete street was built**
Link PLOS Score	2.54	0.15

Due to traffic data unavailability, after the complete street was built, it is difficult to predict how Link PLOS changed (see Table 4-38). As mentioned before, a lower number indicates better quality of services. A letter grade cannot be assigned to the NCHRP Link PLOS value because the letter LOS grade applies only to the full facility score and not to the link score.

Table 4-39. Segment-Based LOS by Average Pedestrian Space for Franklin Boulevard Complete Street

Methodology	**Before complete street was built**	**After complete street was built**
Segment-Based LOS by Average Pedestrian Space	A (2006)	A (2408)

The sidewalks in many parts of Franklin Boulevard prior to the complete street were generally narrow, with electrical poles and numerous driveway cutouts on the sidewalks creating unsafe conditions for pedestrians, particularly those in wheelchairs or walking with children or strollers. The sidewalks will be widened after the expected construction of the Franklin Boulevard complete street. The PLOS methodology did not provide much recognition to these changes regarding the space and particularly the quality of the space, as can be seen in Table 4-39 (A: best, and F: worst quality of service, and lower number indicates better quality of services).

Table 4-40. HCM Link PLOS for Franklin Boulevard Complete Street

	Before complete street was built		**After complete street was built**	
HCM Link PLOS	NB	SB	NB	SB
	D	E	B	B
	D (4.24)		B (2.2)	

**NB: North Bound, and SB: South Bound*

As shown in Table 4-40, HCM Pedestrian link LOS score was D (average of northbound and southbound) before the complete street was built and is assigned B after the complete street is built. This significant improvement is because of the new bike lane and parking buffer and the expanded sidewalk. It should be noted that, since the current framework does not consider the accessibility of sidewalks for ADA and this was very important for Franklin Boulevard, adding consideration of accessibility for disabled people to the BLOS performance measure will be valuable.

The HCM intersection BLOS was not calculated due to a lack of data. The NCHRP methodology, which is not very data-intensive, was used to calculate link BLOS, as presented in Table 4-42.

Table 4-41. HCM Link BLOS Before and After Construction of Franklin Boulevard Complete Street

	Before complete street was built		**After complete street was built**	
Link BLOS	NB	SB	NB	SB
	C	D	A	A
	D (3.73)		A (1.44)	

**NB: North Bound, and SB: South Bound*

Table 4-42. NCHRP Link BLOS Before and After the Construction of Franklin Boulevard Complete Street

	Before complete street was built		**After complete street was built**	
Link BLOS	NB	SB	NB	SB
	D	D	D	D
	D (3.69)		D (3.98)	

**NB: North Bound, and SB: South Bound*

HCM Link BLOS, as can be seen in Table 4-41, gives realistic results before and after the complete street construction. The constant score of BLOS before and after the construction of the complete street indicates that the NCHRP BLOS methodology is not appropriate for Class IV bike lanes since this methodology’s equations and parameters do not match up well. For instance, the width of paving between the outside lane stripe and the edge of the pavement is the shoulder of the road for a Class II bike lane. If there is no shoulder and a barrier with a bike lane on the other side, the input distance is unclear.

The inflexibility of the NCHRP BLOS equations limits the applicability of this model and is not recommended for use on the Franklin Boulevard case study. Use of the HCM Link BLOS performance measure is recommended. The level of Traffic Stress (LTS) indicator is also recommended to be used as a more qualitative measure of bicycle comfort.

4.2.2.8.b. Urban LOS

According to the FHWA Traffic Data Pocket Guide (FHWA, 2018), the hourly design volume should be around 8% of the average daily traffic (ADT). This amount is larger than the amount of ADT divided by 24 hours (4.16%). ADT for Franklin Boulevard is 12,960 and 11,016 before and after the complete street was built, respectively (City of Sacramento, 2020b). Hourly traffic volume data are needed to calculate Urban LOS, which can be calculated by multiplying the ADT by 8%. The result is 1,039 (12,960 ADT*8%=1,037) vehicles per hour before the complete street was built and 881 (11016 ADT*8%=881) vehicles per hour after the complete street was built.

Due to a lack of signal timing data and detailed traffic movement data, the intersection LOS could not be calculated. Since there are only four traffic signals in the Franklin Blvd case study, the traffic congestion along this boulevard will not be changed much by signal timing changes. Table 4-43 presents the urban streets level of service for before and after the construction of Franklin Boulevard complete street.

Table 4-43. Urban Streets Level of Service for Before and After the Construction of Franklin Boulevard Complete Street

Segment	Travel Speed (mph)	LOS	Segment Length (feet)	BFFS*
Urban Streets LOS BEFORE Construction				
12th-21st	31.2	B	2,752	40.1
21st-26th	16.8	D	1,828	38.6
26th-Fruitridge	28.3	B	1,418	37.7
Fruitridge-38th	33.4	A	2,490	40.7
Weighted Average	**28.2**	**B**	**-**	**39.6**
Urban Streets LOS AFTER Construction				
12th-21st	24.2	B	2,752	35.99
21st-26th	22.7	C	1,828	37.54
26th-Fruitridge	22.9	C	1,418	37.83
Fruitridge-38th	28.6	B	1,418	39.92
Weighted Average	**24.4**	**C**	**-**	**37.48**

Segment	Travel Speed (mph)	LOS	Segment Length (feet)	BFFS*
**BFFS is Base Free Flow Speed* *Urban LOS is scored based on how fast traffic moves compared to the BFFS*				

4.2.2.8.c. Transit LOS

The HCM methodology (HCM, 2016) and the Transit LOS Calculator (TCRP) were used to calculate TLOS in Franklin Boulevard (TRB, 2013).

Transit LOS for before the construction of the Franklin Boulevard complete street was calculated as LOS D, which is served by one bus route. The Northbound (NB) direction includes four bus stops, while three bus stops are in the Southbound (SB) direction. Since only one bus route serves Franklin Boulevard (Sac RT Route 67), and one-fifth of the residents do not have access to a car (MIG INC., 2019). An in-depth traffic analysis would be helpful to determine exactly how bus delays will be affected by the complete street project after the construction. Table 4-44 presents the TLOS for segments with transit service, and Table 4-45 shows the entire facility TLOS before and after the construction of Franklin complete street. Note that the construction of Franklin Boulevard has not been completed yet.

Table 4-44. Transit LOS Segments with Transit Service Before and After Construction for the Franklin Boulevard Complete Street

	Before complete street was built		**After complete street was built**	
Transit LOS for the Segment	NB	SB	NB	SB
	C	D	C	C
Average Transit LOS for the Segment	**D**		**C**	

Table 4-45. Transit LOS Entire Facility Before and After the Construction of Franklin complete street

Segment	Score	LOS	Segment Length (feet)
Transit Streets LOS BEFORE Construction			
12th Street to 21st Street	3.69	D	2752

Segment	Score	LOS	Segment Length (feet)
21st to 38th	4.26	D	5755
Weighted Average Score	**5.68**		
Weighted average LOS		**F**	
Transit Streets LOS AFTER Construction			
12th Street to 21st Street	3.02	C	2752
21st to 38th	6.35	F	5755
Weighted Average Score	**5.27**		
Weighted average LOS		**F**	

Franklin Boulevard lies between State Route 99, the Union Pacific Railroad, and it does not have parallel streets to redirect buses into them. There is no plan to expand the bus services after the construction of the complete street. However, to serve the Franklin Boulevard community, a new on-demand shuttle service (SmaRT) was implemented by Sac RT in 2018. Using a mobile app or making phone calls can be used by the riders to schedule a pick-up at a nearby bus stop followed by departing at a drop-off location near their choice of destination. In July 2020, and despite COVID 19 impacts on public transit, more than 12,000 rides were provided by SmaRT Ride (SacRT 2020). Since the value of the SmaRT Ride shuttle service cannot be expressed in terms of LOS, expanding the performance measure, including other metrics such as transit ridership, would be useful. It is not expected that the 12,000 rides carried on the shuttle will include many riders from Franklin to the light rail station. It was outside the ability of this study to consider this additional transit connection.

The combination of Franklin Boulevard complete street with projects that aim to improve transit service in the community will lead to the TLOS improvements.

4.2.2.8.d. Level of Traffic Stress (LTS)

The Montgomery County Bicycle Master Plan (2018) cannot be used to measure the LTS for Franklin Boulevard due to the absence of bike lanes. Instead, the LTS tables derived from Northeastern University are used for measuring Franklin Boulevard LTS (Furth, 2017) and are presented in APPENDIX D.

According to the Northeastern University tables, the LTS for Franklin Boulevard is usually between 3 and 4. There is a bike lane from 38th Avenue to 35th Avenue based on the report by the City of Sacramento and the Department of Public Works in 2018. There are no bike lanes from 35th Avenue to 32nd Avenue, from Fruitridge Road to Sutterville Rd. on the west side, and from 34th Avenue to Sutterville Rd. on the east side. The following definitions are derived from the Northeastern University study,

- No bike lane: mixed traffic
    - LTS = 4
- A bike lane with no parking
    - LTS ≥ 3
- Intersection LTS
    - LTS = 4
- Unsignalized crossings:
    - LTS = 3

According to the LTS criteria tables in the Northeastern University study, shown in APPENDIX D, LTS improves from 4 to 1 after the completion of the Franklin Boulevard complete street (see Table 4-46). LTS score of 1 indicates very low traffic stress, which is suitable for most vulnerable groups.

Table 4-46. Level of Traffic Stress (LTS) Scores Comparing Before and After Building the Franklin Boulevard Complete Street

LTS Method	Before complete street was built	After complete street was built
Northeastern University Method	4 (High)	1 (Very Low)

4.2.2.9. Crashes

For the Franklin Boulevard complete street project, the number of bicycle-involved and pedestrian-involved crashes (i.e., Skateboard, non-motorized scooter, wheelchair crashes) over five years were considered. The Transportation Injury Mapping System (TIMS) database 2015-2019 was used for this measurement (TIMS, 2020). The 1.6-mile buffer area around the Franklin Boulevard case study was considered for calculating this indicator.

Table 4-47. Number of Crashes in the 1.3-mile buffer areas around Franklin case study

Years	Number of Crashes	
2015	20	Before the CS= Average (2015-2019) = (20+30+12+11+15)/5 = **18**
2016	30	
2017	12	
2018	11	
2019	15	After the CS = **-**

Table 4-47 presents the crash performance measure before the construction of Franklin Boulevard complete street. As the complete street has not been built yet, therefore, the indicator cannot be calculated.

4.2.2.10. Pedestrian Miles Traveled / Bicycle Miles Traveled

The Franklin Boulevard Complete Street Phase 2 report (City of Sacramento and Department of Public Works, 2018) was used to find data for this performance measure. According to this report, there were 444 pedestrians and 170 bicyclists per day using Franklin Boulevard in 2018. PMT and BMT are calculated for average trip lengths of 0.5 miles and 2 miles. As the complete street project is not completed yet, therefore, the Sacramento County design documents were used to find the number of bike and pedestrian trips. Based on the general plan 2035, bike mode share and pedestrian mode share are expected to increase by 1.8% and 12.4%, respectively (City of Sacramento and Department of Public Works, 2018). Table 4-48 presents PMT and BMT for average trip lengths of 0.5 miles and 2 miles. Increases in PMT and BMT are expected after the construction of the Franklin Boulevard complete street.

Table 4-48. Pedestrian Miles Traveled, and Bicycle Miles Traveled for Franklin Boulevard Case Study

Year	Trip Length	PMT	BMT
Before complete street is built (2018)	0.5 miles	222	85
	2 miles	888	340
After complete street is built (2035)	0.5 miles	1,433	261
	2 miles	5,732	1,044

4.2.2.11. Street Trees

The number of trees was counted along Franklin Boulevard from 12th Avenue to 38th Avenue. The grant application for the SACOG Regional Active Transportation Program was used to count the street trees after the complete streets project (City of Sacramento and Department of Public Works, 2018).

Table 4-49. Number of Street Trees along the Franklin Boulevard Complete Street

Year	Number of street trees
Current count from 2018	49
Expected in 2040 (after building the complete street)	349

As can be observed from Table 4-49, the number of street trees will be increased to meet a complete streets goal for improving livability and safety.

The addition of street trees is likely to increase carbon sequestration in the trees, change human thermal comfort cause by the shade, and have an effect on the overall urban heat island. At this time there is no methodology for calculating change in GWP or human thermal comfort, and no simple way to calculate the change in urban heat island. Development of these indicators would add value to the Street Trees indicator.

4.2.3. Kentucky Avenue Case Study

4.2.3.1. Access to Community Destination

For the complete street case study, destinations within 0.5-mile walking and 2-mile bicycling radii of Kentucky Avenue were found using Google Earth ™ and Google Maps™ (see Figure 4-20). The average walking speed is assumed to be three mph, while the bicycling speed is assumed to be 12 mph (Yang and Diez-Roux, 2012). The average walking distance is 0.5 miles, while the average bicycling distance is 2 miles, considering delay.

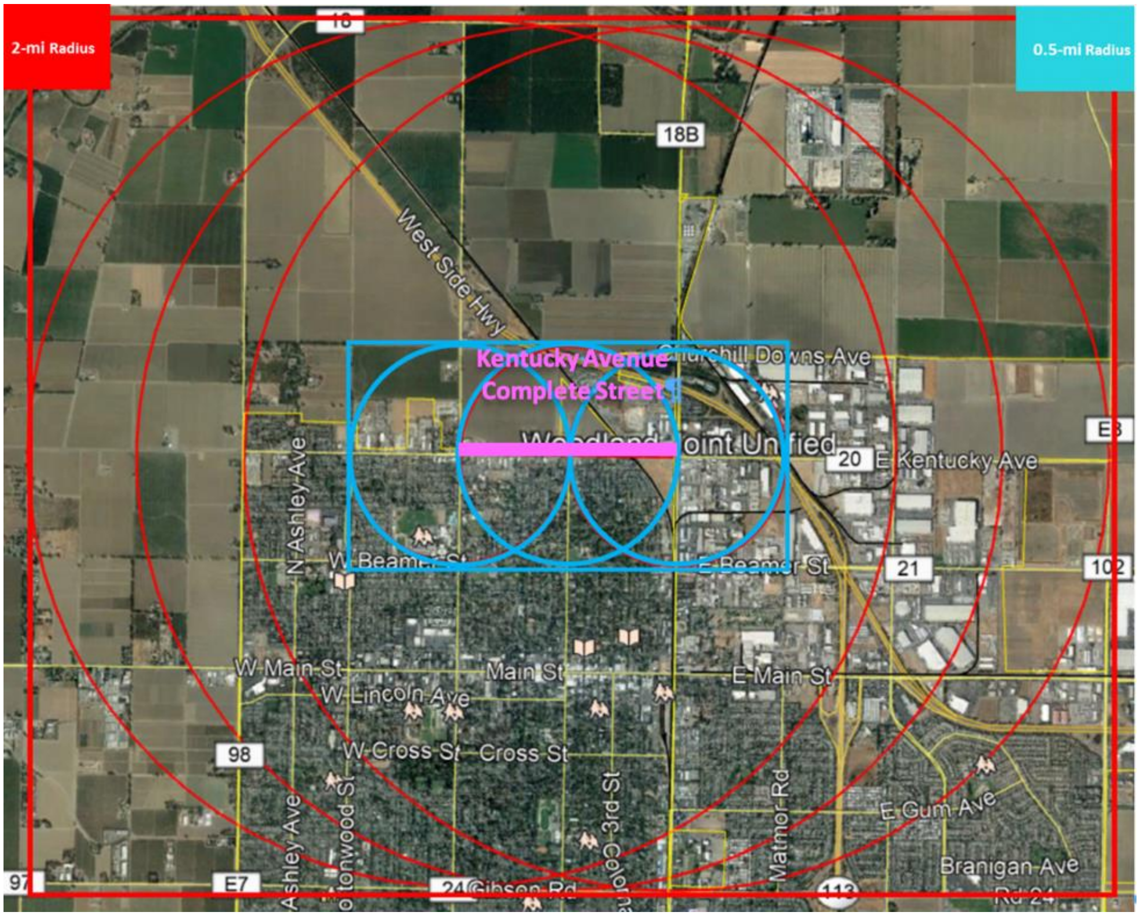


Figure 4-20. Access to Destination Buffer Area for Walking and Cycling Modes of Transportation, Kentucky Avenue Complete Street Project

To consider the transit buffer area around the Kentucky Avenue complete street, there are many possibilities when combining walking and biking with train, bus, and light rail. According to Yang and Diez-Roux's study (2012), there is considerable variability in the distance and duration of walking trips by purpose and population subgroups. The most probable scenarios were selected considering 20 minutes for a combined-mode trip.

A circular buffer was the first option considered around the Kentucky Avenue complete street. However, due to geographical barriers and the limited number of transit stations, especially in the northern and western parts around this project's area, the circular buffer was not used. The proposed alternative buffer can be seen in Figure 4-21. As shown in the figure, the right side of the buffer includes a 0.5-mile buffer around Kentucky Avenue. The buffer extends 2 miles south along Ashley Ave and extends 0.5-mile to the East and 0.5 miles to the west of the complete street. The center part of this buffer contains several bus stops, as the map shows (Figure 4-21).

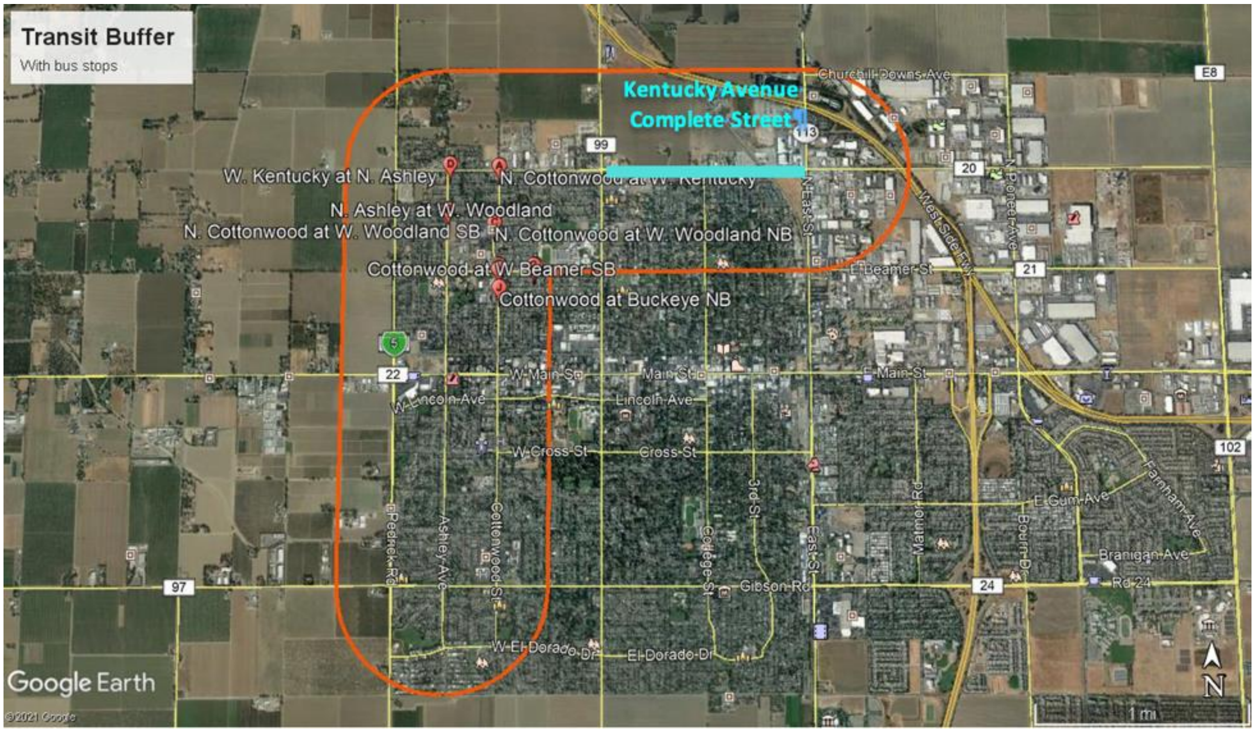


Figure 4-21. Access to Destination Buffer Area for Transit Modes of Transportation, Kentucky Complete Street Project

Table 4-50 shows the recommended buffer distances using in different modes of transportation in 20 minutes.

Table 4-50. The Recommended Buffer Distances Using in Different Modes of Transportation in 20 minutes

Recommended Buffer Distance	Mode
0.5 mile (Figure 4-20)	Walking
2 mile (Figure 4-20)	Biking
Transit Buffer Area (Figure 4-21)	Bus+Walking, Bus+Biking

The destinations considered in this case study include coffee shops, restaurants, banks, gas stations, grocery stores, pharmacies, hospitals, post offices, libraries, police stations, places of worship, and museums. The number of customers and employees for each destination were estimated using the best available resources, including government statistics, company information, and web research (see APPENDIX B). Access to community destinations calculations can be found in APPENDIX B**.**

The example calculations were shown earlier in the San Fernando complete street case study. Table 4-51 shows the example of access to community destinations in a 0.5-mile circular buffer for Kentucky Avenue in 2018. Table 4-52 and Table 4-53 present this performance measure for walking (0.5-mile), biking (2-mile), and transit (polygon buffer) modes before (2018) and after (2021) the construction of the Kentucky Avenue complete street.

Table 4-51. Access to Community Destinations in a 0.5-mile Circular Buffer for Kentucky Avenue in 2018

Destination category	**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Libraries**	**Police station**	**Places of Worship**	**Museum**
Number of destinations in 0.5-mile buffer	0	5	0	3	5	0	0	0	0	0	6	0
Estimated employees	7	18	7	6	33	20	100	16	15	762	5	30
Estimated customers	350	230	42	682	853	350	225	71	682	100	27	273
Employee accessibility	0	90	0	18	165	0	0	0	0	0	30	0
Customer accessibility	0	1,150	0	2,046	4,265	0	0	0	0	0	162	0
Total Accessibility: 0.5-mile buffer	0	1,240	0	2,064	4,430	0	0	0	0	0	192	0

Total Accessibility in 0.5-mile buffer= 7,926

Example: Total Accessibility in 0.5-mile Buffer = 5(18+230) = 1240*

As observed from Table 4-52, Table 4-53, and Table 4-54, access to destinations along Kentucky Avenue decreased in most destinations, stayed the same in some of them, and increased in a few destinations from 2018 to 2021. Thus, the changes in the typology of the complete street that required demolishing several of the buildings around the street, can be justified by the changes in the typology of the complete street.

Table 4-52. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon Buffer) Modes in 2018 (before building the CS) for Kentucky Avenue

Buffer		**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Library**	**Police station**	**Places of Worship**	**Museum**
0.5	Number of destinations	0	5	0	3	5	0	0	0	0	0	6	0
	Total Accessibility :	0	1,240	0	2,064	4,430	0	0	0	0	0	192	0
2	Number of destinations	7	89	9	18	29	13	2	2	4	1	33	5
	Total Accessibility :	2,499	22,072	441	12,384	25,694	4,810	650	174	2,788	862	1,056	1,515
Transit Buffer	Number of destinations	2	19	2	5	9	4	2	1	1	0	13	0
	Total Accessibility :	714	4,712	98	3,440	7,974	1,480	650	87	697	-	416	-
Total Accessibility in 0.5-mile buffer= 7,926													
Total Accessibility in 2-mile buffer= 74,945													
Total Accessibility in Transit buffer= 20,268													

Table 4-53. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon Buffer) Modes in 2021 (after building the CS) for Kentucky Avenue

Buffer		**Coffee shop**	**Restaurant**	**Bank**	**Gas station**	**Grocery store**	**Pharmacy**	**Hospital**	**Post office**	**Library**	**Police station**	**Places of Worship**	**Museum**
0.5	Number of destinations	0	5	0	3	5	0	0	0	0	0	6	0
	Total Accessibility :	0	1,240	0	2,064	4,430	0	0	0	0	0	192	0
2	Number of destinations	5	90	11	21	25	10	2	2	3	1	32	5
	Total Accessibility :	1,785	22,320	539	14,448	22,150	3,700	650	174	2,091	862	1,024	1,515
Transit Buffer	Number of destinations	2	21	2	5	9	3	2	1	1	0	14	0
	Total Accessibility :	714	5,208	98	3,440	7,974	1,110	650	87	697	-	448	-
Total Accessibility in 0.5-mile buffer= 7,926													
Total Accessibility in 2-mile buffer= 71,258													
Total Accessibility in Transit buffer= 20,4260													

Table 4-54. Access to Community Destinations for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon buffer) Transport Modes- Before the construction versus After the construction of the Kentucky Avenue Complete Street Project

Total Accessibility to community Destinations	**Before**	**After**
Total Accessibility in 0.5-mile buffer (Walking)	7,926	7,926
Total Accessibility in 2-mile buffer (Bicycling)	74,945	71,258
Total Accessibility in Transit buffer (Transit)	20,268	20,426

4.2.3.2. Access to School

School district boundaries around the Kentucky Avenue complete street are shown in Figure 4-22.

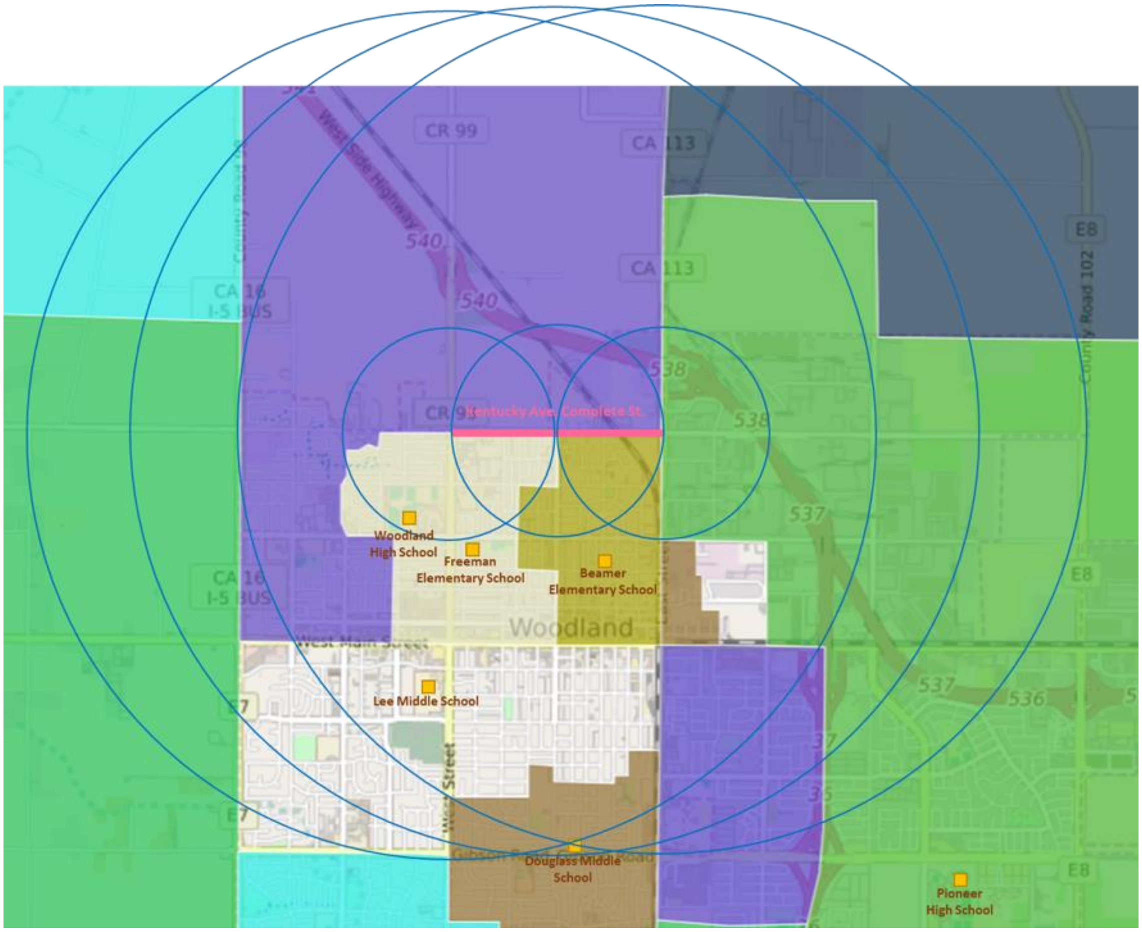


Figure 4-22. Access to School (considering school district boundaries)- Kentucky Avenue Case Study

Table 4-55 presents the access to school results according to school district boundaries within walking (0.5-mile) and bicycling (2-mile) distances. The complete list of schools, number of students, and employees for the Kentucky Avenue case study can be found in APPENDIX C.

Table 4-55. Accessibility to School considering school district boundary for each buffer, Kentucky Avenue Case Study.

Distance	Accessibility
0.5-mile (Walking)	1,285
2-mile (Cycling)	5,361

The Access to School indicator for both before building the complete street (2018) and after building the complete street (2021) is the same due to no change in the number of schools between these two years.

The area long the Kentucky Avenue complete street does not have schools close to it. Transit can be included in those destination development projects to provide active transportation access. While it is not known how many students live within the bicycling and walking buffers for Kentucky Avenue, having nearby schools is more important for disadvantaged neighborhoods such as Kentucky Avenue because they tend to have fewer transportation alternatives.

4.2.3.2.a. Surveys of Principals

Access to school surveys were sent to the principals of six schools in the Kentucky Avenue study area based on the boundary discussed earlier above. One was returned from a middle school. As was noted for the other two case studies, the survey was sent out at the beginning of summer in 2020 and again later in the summer. The extra work being undertaken by principals at that time to deal with changing Covid protocols and the return to in-person teaching makes the lack of response understandable. The one response to the survey provides useful qualitative and quantitative answers from the principal who responded and suggests that further use of the survey instrument in future research will provide important information that cannot be obtained otherwise.

The principal noted that Kentucky Avenue is "quite a ways from out campus" but said that some students and their parents may use the street to get to the school. The principal estimated that 25 to 45% of students walked, depending on the season (most in fall and spring, least in winter), 10 to 15% biked, 10% took transit, and 30 to 55% were driven, bike and car travel mirroring the seasonal differences of walking. A travel pattern that was not considered when putting the survey together is that the principal estimated that many students are travel by car in the morning and walk home in the afternoon. The principal also noted that the transit use is by district school bus and represents students being bussed in from a neighboring town that is in the district. The principal estimated that these percentages did not change with the completion of Kentucky Avenue complete street. The travel times for students to commute to school are shown in Table 4-56. The estimated percentages of students traveling to school without an adult are shown in Table 4-57.

Table 4-56. Estimated commute times by mode

Time	**Walk (6th to 8th grade)**	**Bike (6th to 8th grade)**	**Bus/Train (6th to 8th grade)**	**Car (6th to 8th grade)**	**Combination trip (6th to 8th grade)**	**Other**
0-10 minutes	5-10%	10%		30%		
10-20 minutes	20%	5%		10%		
20-30 minutes	5%		10%	5%		
30-40 minutes						

Table 4-57. Estimated percentages of students biking or walking alone by grade.

Grade	**6th**	**7th**	**8th**
Percentage Biking		10-15%	10-15%
Percentage Walking		45%	45%

The principal identified that those students using active transportation mostly do not use Kentucky Avenue. The principal thought that the complete street would make Kentucky Avenue safer for those students who use it. The principal noted four other streets nearer to the school that would benefit from a complete streets treatment. The school has bike racks. The principal thought that students generally feel safe walking and biking with or without an adult, although it was noted that there is speeding traffic around the school, and that students oftentimes do not wear helmets and engage in risky behavior on bicycles.

Overall, the principal did not think that the Kentucky Avenue complete street would improve biking and walking to the school except for the few students who may come from the neighborhood near it and identified another arterial street much closer to the school that students use.

4.2.3.3. Access to Jobs

A similar method used for calculating access to jobs for the San Fernando case study was used for the Kentucky Avenue complete street case study. Table 4-58 and Table 4-59 present the results for access to jobs for walking (0.5-mile), biking (2-mile), and transit modes before and after the construction of Kentucky Avenue complete street.

As can be observed from Table 4-60, there is a decrease in accessibility to jobs after constructing the complete street within walking and cycling distances which is the result of changes in the typology of the Kentucky Avenue complete street that required demolishing several buildings located on this street.

Table 4-58. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes in 2015 (before building the CS) for Kentucky Avenue

Buffer		Coffee shop	Restaurant	Bank	Gas station	Grocery store	Pharmacy	Hospital	Post office	Library	Police station	Places of Worship	Museum	Govt. Building	Office Building
0.5 miles	**Number of job sites**	0	5	0	3	5	0	0	0	0	0	6	0	1	3
	Accessibility	0	90	0	18	165	0	0	0	0	0	30	0	114	88
2 miles	**Number of job sites**	5	90	11	21	25	10	2	2	3	1	32	5	19	17
	Accessibility	35	1,620	77	126	825	200	200	32	45	762	160	150	872	338
Transit Buffer	**Number of job sites**	2	19	2	5	9	4	2	1	1	-	13	-	8	6
	Accessibility	14	342	14	30	297	80	200	16	15	-	65	-	486	137
Total Accessibility in 0.5-mile buffer= 505															
Total Accessibility in 2-mile buffer= 5,618															
Total Accessibility in transit buffer= 1,696															

Table 4-59. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (3-mile and 4.5-mile) Modes in 2019 (after building the CS) for Kentucky Avenue

Buffer		Coffee shop	Restaurant	Bank	Gas station	Grocery store	Pharmacy	Hospital	Post office	Library	Police station	Places of Worship	Museum	Govt. Building	Office Building
0.5 miles	Number of job sites	0	5	0	3	5	0	0	0	0	0	6	0	1	3
	Accessibility	0	90	0	18	165	0	0	0	0	0	30	0	114	88
2 miles	Number of job sites	5	90	11	21	25	10	2	2	3	1	32	5	19	17
	Accessibility	35	1,620	77	126	825	200	200	32	45	762	160	150	872	338
Transit Buffer	Number of job sites	2	21	2	5	9	3	2	1	1	-	14	-	8	6
	Accessibility	14	378	14	30	297	60	200	16	15	-	70	-	486	137
Total Accessibility in 0.5-mile buffer= 505															
Total Accessibility in 2-mile buffer= 5,442															
Total Accessibility in transit buffer= 1,717															

Table 4-60. Access to Jobs for Walking (0.5-mile), Biking (2-mile), and Transit (Polygon Buffer) Modes- Before versus After the construction of the Kentucky Avenue

Total Accessibility Jobs	Before	After
Total Accessibility in 0.5-mile buffer (Walking)	505	505
Total Accessibility in 2-mile buffer (Bicycling)	5,618	5,442
Total Accessibility in Transit buffer	1,696	1,717

4.2.3.4. Job Creation

A method similar to that used for calculating job creation for the San Fernando case study was used for the Kentucky Avenue complete street case study. The SACOG's proposed budget for the Kentucky Avenue complete street project is $12.573 million, expected to be completed by 2022 (SACOG, 2010; SACOG, 2013). Based on the calculations shown below, the total jobs created are:

- $12.573 * 7.61 * 50% = 48 Direct jobs
- $12.573 * 7.61 * 25% = 24 Indirect jobs
- $12.573 * 7.61 * 25% = 24 Induced jobs

From the budget of $12.573 million, a total of 96 jobs were estimated to be created for the construction of the Kentucky Avenue complete street project.

4.2.3.5. Connectivity Index

Different routes and options in a one-mile rectangular buffer (Figure 4-23) around Kentucky Avenue between East Street and West Street were calculated. One mile is considered as it is the length of Kentucky Avenue complete street project. As shown in Figure 4-23, three circles with a 1-mile diameter were drawn in the center and edges of Kentucky Avenue complete street, which made two by one square miles rectangle. The area of this rectangle was then measured to calculate the connectivity index via Google Earth and Google Maps. Table 4-61 shows the selected indices description considered in the current study and connectivity results for Kentucky Avenue.

Figure 4-23. Area Considered for measuring the Connectivity Index, Kentucky Avenue Case Study

Table 4-61. Connectivity Results for Kentucky Avenue Case Study Based on the Selected Connectivity Indices

Measure	**Definition and Calculation**	**Notes**	**Before the construction of complete street (2016)**	**After the construction of complete street (2021)**
Intersection Density	Number of intersections in a given land area, such as a square mile or acre.	Can be limited to “3 and 4-leg intersections" or "intersections with pedestrian and bicycle accommodations", Typical Range For "Good" Connectivity: 100-160	106/ (2*1)= **53**	132/ (2*1)= **66**
Intersections per Linear Mile	Number of intersections in a given land area is divided by the linear network miles in the same area.	Can be limited to “3 and 4-leg intersections" or "intersections with pedestrian and bicycle accommodations.”	106/2/ (2*1)= **26**	132/2 (2*1)= **33**

4.2.3.6. Active Transportation to Local and Regional Transit Connectivity Index

Aerial imagery, Google Earth, and a static map were used to calculate this measure by selecting all the bikeway/walking path segments within a 1-mile buffer of regionally significant transit stations. The total bikeway miles within the buffer were then divided by land area within the buffer. The 2.0*1.0 square mile rectangle buffer around the County Fair Mall transit center, located at the intersection of East Gibson Road and East Street, is the only transit center in Woodland. However, because this center is more than 2-miles away from the Kentucky Avenue complete street, the bus stop located at the intersection of West Kentucky Avenue and North Cottonwood Street is considered as part of the network area (see Figure 4-24 and Figure 4-25). Table 4-62 shows the results for the active transportation transit connectivity index for Kentucky Avenue complete street.

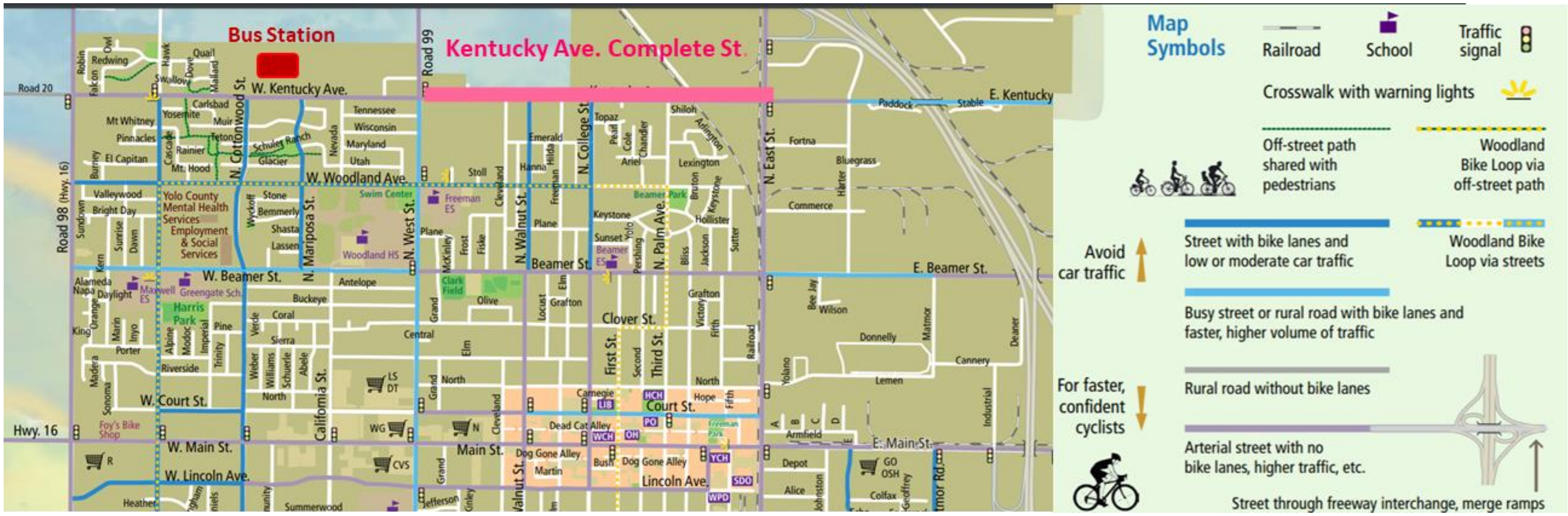


Figure 4-24. Woodland bike map based on Yolo County Bike Master Plan (Yolo County, 2013; Woodland Bike Map, 2017)

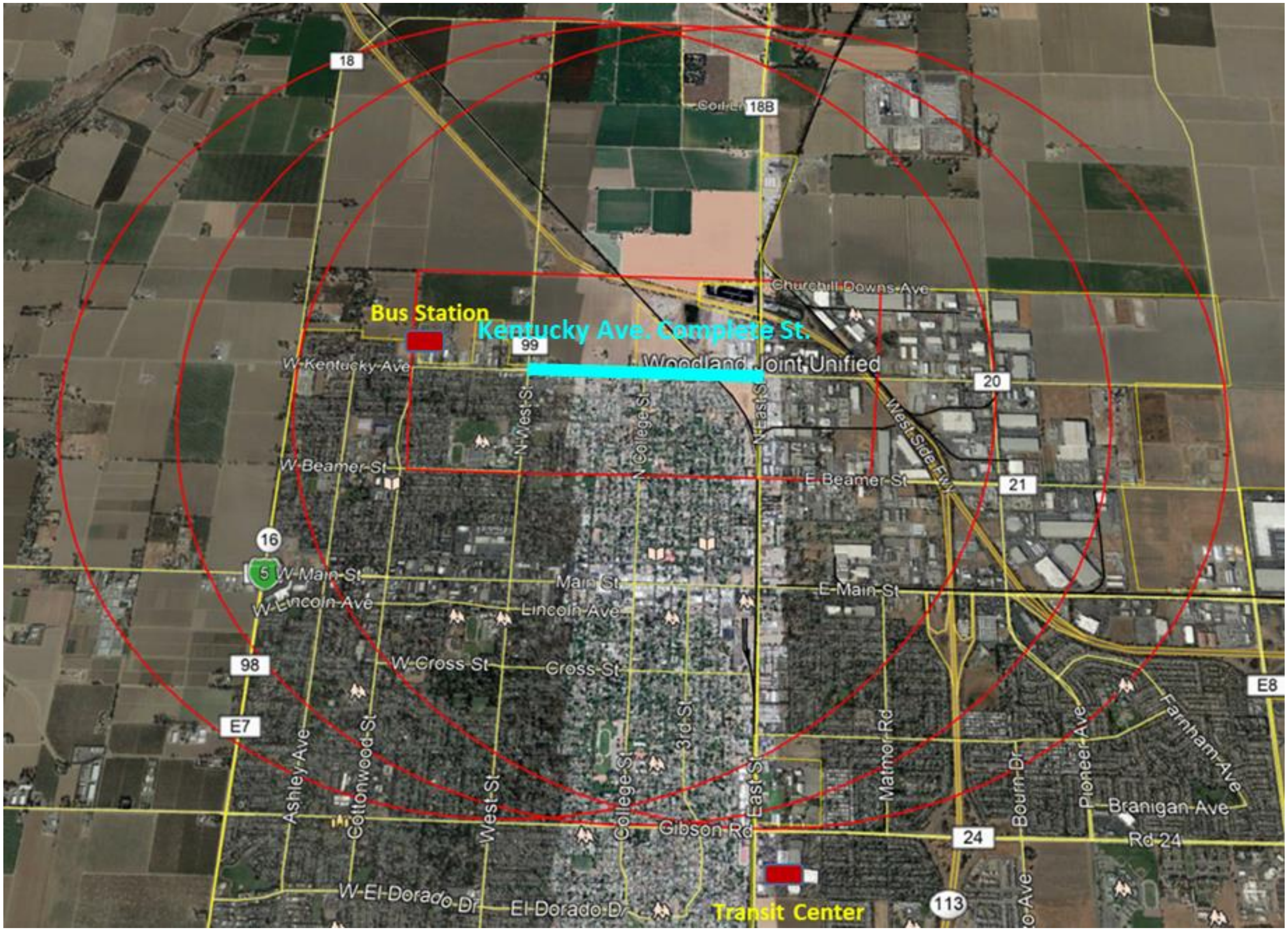


Figure 4-25. Kentucky Avenue Complete Street's buffer of regionally significant transit stations

Table 4-62. Results for the Active Transportation Transit Connectivity Index for Kentucky Avenue Complete Street Project

Measurement	**Before the construction of complete street (2017)**	**After the construction of complete street (2019)**
Mileage of bike/ ped. Lane (2-side)	**10.2** mile	**13.6** mile
Bike/ ped facility density (2-side)	10.2/(2*1)= **5.1**	13.6/(2*1)= **6.8**

4.2.3.7. Pedestrian and Bicyclist Delay

Table 4-63 and Table 4-64 were used to calculate the green interval duration.

This indicator was calculated for 2018 before the complete street was built and 2021 (after the complete street was built using Google Earth™ and Google Earth historical imagery features. Using these tools, there was a small difference (11% increase) in the amount of minor arterial delay and a considerable increase in the amount of major arterial delay (70% increase) between 2018 (before the complete street was built) and 2021 (after the complete street was built). Calculations for the total delays in a rectangular buffer (1-mile*2-mile) around the Kentucky Avenue before and after the construction of Kentucky Avenue complete street are presented in Table 4-63 and Table 4-64, respectively. Increases in pedestrian and bicycle delay are caused by changes in stop light timing and durations with changes in vehicle speed limits.

Table 4-63. Total delays in a rectangular buffer (1-mile*2-mile) around the Kentucky Avenue case study- Before the Complete Street Construction

g: vehicular green signal Formula	d: Average delay (s) for narrow roadway (Minor arterial) $d = \frac{(g+15)^2}{2\,(g+20)}$	d: Average delay (s) for narrow roadway (Major arterial) $d = \frac{(g+10)^2}{2\,(g+15)}$	No. of arterial within 1-mile*2-mile buffer (Minor Arterial)	No. of arterial within 1-mile*2-mile buffer (Major Arterial)	Total delay(s) for Minor arterial	Total delay(s) for Major arterial	Total delay(s) in 1.6mile* 3.2mile buffer
minimum green interval duration: Minor arterial: 4-10 s (avg 7 s) Major arterial: 7-15 s (avg 11 s)	d= [(7+15)^2]/ [2*(7+20)]= **9 s**	d= [(11+10)^2]/ [2*(11+15)]= **8.5**	13	14	117	119	**236**
maximum green interval duration: Minor arterial: 40-50 s (avg 40 s) Major arterial: 40-60 s (avg 50 s)	d= [(40+15)^2]/ [2*(40+20)]= 25.2~ **25 s**	d= [(50+10)^2]/ [2*(50+15)]= 27.7 **~ 28**	13	14	325	392	**717**
Average Delay					221	255	**476 sec (8 min)**

Table 4-64. Total delays in a rectangular buffer (1-mile*2-mile) around the Kentucky Avenue case study- After the Complete Street Construction

g: vehicular green signal Formula	**d: Average delay (s) for narrow roadway (Minor arterial)** $d = \frac{(g+15)^2}{2\,(g+20)}$	**d: Average delay (s) for narrow roadway (Major arterial)** $d = \frac{(g+10)^2}{2\,(g+15)}$	**No. of arterial within 1-mile* 2-mile buffer (Minor Arterial)**	**No. of arterial within 1-mile* 2-mile buffer (Major Arterial)**	**Total delay(s) for Minor arterial**	**Total delay(s) for Major arterial**	**Total delay(s) in 1.6mile* 3.2mile buffer**
minimum green interval duration:	d= [(7+15)^2]/ [2*(7+20)]= **9 s**	d= [(11+10)^2]/ [2*(11+15)]= **8.5**	15	25	135	212	**347**
Minor arterial: 4-10 s (avg 7 s)							
Major arterial: 7-15 s (avg 11 s)							
maximum green interval duration:	d= [(40+15)^2]/ [2*(40+20)]= 25.2~ **25 s**	d= [(50+10)^2]/ [2*(50+15)]= 27.7 ~ **28**	15	25	375	700	**1,075**
Minor arterial: 40-50 s (avg 40 s)							
Major arterial: 40-60 s (avg 50 s)							
Average Delay					255	456	**711 (12min)**

4.2.3.8. Level of Service

4.2.3.8.a. PLOS and BLOS

A lack of comprehensive data was a problem in calculating PLOS and BLOS for the Kentucky Avenue case study. Table 4-65 to Table 4-68 show the PLOS and BLOS results for the Kentucky Avenue complete street using both the HCM and NCHRP methodologies.

Table 4-65. NCHRP Link PLOS for Kentucky Avenue Case Study

	Before complete street was built		After complete street was built	
Average Link PLOS Number	3.52		1.79	
Link PLOS by direction	EB : 3.28	WB: 4.13	EB : 1.77	WB : 1.82

**EB: East Bound, and WB: West Bound*

Due to a lack of traffic data after constructing the complete street project, it is not easy to see how the NCHRP Link PLOS changed. A letter grade cannot be assigned to the NCHRP Link PLOS value (Table 4-65) because the letter LOS grade applies only to the full facility score and not to the link score. Besides, without calculating intersection BLOS, for which there is a lack of data, NCHRP PLOS was not recommended.

Table 4-66. HCM Link PLOS for Kentucky Avenue Complete Street

	Before complete street was built		After complete street was built	
HCM Link PLOS	EB	WB	EB	WB
	C (2.86)	D (4.17)	B (1.93)	B (1.98)
	D (3.52)		B (1.95)	

**EB: East Bound, and WB: West Bound*

The change in PLOS that can be seen in Table 4-66 is because of a change in the speed before and after the complete street.

Table 4-67. HCM Link BLOS Before and After Construction of Kentucky Avenue Complete Street

	Before complete street was built		After complete street was built	
Link BLOS	EB	WB	EB	WB
	D (3.63)	D (3.55)	C (3.42)	C (3.42)
	D (3.51)		C (3.42)	

A minor improvement in HCM link BLOS can be observed due to the change in the segment length (Table 4-67).

Table 4-68. NCHRP Link BLOS Before and After the Construction of Kentucky Avenue Complete Street

	Before complete street was built		After complete street was built	
Link BLOS	EB	WB	EB	WB
	F (5.49)	F (5.46)	E (4.71)	E (4.69)
	F (5.47)		E (4.70)	

The BLOS of E seen in Table 4-68seems too low. The NCHRP methodology is very sensitive to the number of access points (e.g., driveways, side streets, etc.), so the segments with higher access point density have much lower LOS scores.

Regarding data collection, the length of the road was measured using Google Maps™. Road widths from before the Kentucky Avenue complete street construction (such as bike lane width, sidewalk width, lane width, etc.) were measured using Google Earth™ historical imagery. Road widths after the construction of the Kentucky Avenue complete street were measured in the field using a tape measure.

4.2.3.8.b. Urban LOS

According to the FHWA Traffic Data Pocket Guide (FHWA, 2018), the hourly design volume should be around 8% of the average daily traffic (ADT). This amount (8% suggested by FHW 2018) is higher than the ADT divided by 24 hours (4.16%). For Kentucky Avenue, the ADT of 11,635 from East Street to College Street and 10,067 from College Street to West Street were multiplied by 8% and divided by 2 to obtain the directional volume (City of Woodland, 2015).

Before the construction of the Kentucky Avenue complete street, LOS A indicates that the traffic flow speed is much more than half of the base free-flow speed (Table 4-69). Since the base free-flow speed is always faster than the posted speed limit, traveling with such a free-flow speed does not result in serious delays and congestion problems. To determine the amount of delay experienced by vehicles at signalized intersections, in addition to an urban LOS analysis, the calculation of intersection LOS is needed. However, the intersection LOS could not be calculated due to a lack of signal timing data and detailed traffic movement data.

Since there are no traffic data after the complete street construction, urban LOS should be updated with available traffic counts value after constructing the Kentucky CS project. Table 4-69 presents the urban level of service before the construction of Kentucky Avenue complete street.

Table 4-69. Urban Streets Level of Service for Before the Construction of Kentucky Avenue Complete Street

Segment	Travel Speed (mph)	LOS	Segment Length (feet)	BFFS*
East Street to College Street	32.1	A	2,646	40.0
College Street to West Street	32.2	A	2,652	40.0
Weighted average Speed	**32.2**			**40**
Travel Speed/BFFS = LOS	**80%**	**A**		
**BFFS is Base Free Flow Speed; Urban LOS is scored based on how fast traffic moves compared to the BFFS.*				

4.2.3.8.c. Transit LOS

Since there is no bus service along the Kentucky complete street, TLOS before and after constructing this complete street project is F.

4.2.3.8.d. Level of Traffic Stress (LTS)

LTS tables derived from Northeastern University were used for calculating LTS for Kentucky Avenue (Furth, 2017). As shown in the detailed assessment shown in APPENDIX D, LTS after the construction of the Kentucky Avenue complete street for bikes riding on the road is 3 for westbound travel (Cleveland Street to West Street) and 4 for eastbound travel (East Street to Cleveland Street). The overall LTS improves from 4 to 3 after completing the Kentucky Avenue complete street (see Table 4-70). An LTS score of 3 indicates moderately high traffic stress, which is not suitable for most vulnerable groups.

Table 4-70. Level of Traffic Stress (LTS) Scores Comparing Before and After Building the Kentucky Avenue Complete Street

LTS Method	Before complete street was built	After complete street was built
Northeastern University Method	4 (High)	3 (Moderately High)

4.2.3.9. Crashes

For the Kentucky Avenue complete street project the number of bicycle-involved and pedestrian-involved crashes over five years was considered. Fatal car crashes and road traffic accidents in the Woodland 2014-2019 database was used for this measurement (City of Woodland Data Website, 2021). The 1-mile buffer area around Kentucky Avenue complete street was considered for calculating this indicator.

Table 4-71 presents the crash performance measure before and after the transition of Kentucky Avenue to a complete street. There is very little bicycle travel on Kentucky Avenue and only a few annual crashes occur, therefore a strong statement cannot be made regarding the influence of the Kentucky Avenue complete street project on this indicator.

Table 4-71. Number of Crashes in the 1.3-mile buffer areas around San Fernando complete street

Years	Number of Crashes (Streets within 2*1 sq miles rectangle buffer around Kentucky Avenue CS)	Number of Crashes (City of Woodland)	
2014	1	4	Before the Kentucky Avenue complete street= Average (2015-2018) = **1**
2015	1	2	
2016	1	3	
2017	1	3	
2018	0	3	
2019	0	1	After the Kentucky Avenue complete street= **0**

4.2.3.10. Pedestrian Miles Traveled / Bicycle Miles Traveled

The Yolo County Bicycle Transportation Plan report (Yolo County, 2013) was used to find the BMT performance measure data. According to this report, bike mode share will increase by 1.96% between 2010 and 2035 (Yolo County, 2013). This report show 2,600 and 2,780 bicyclists per day in Yolo county in 2018 and 2022, respectively. BMT is calculated for average trip lengths of 0.5 miles and 2 miles for Yolo County. Since no data specifically focus on Kentucky Avenue, this performance measure is not worthwhile for this rural complete street project.

4.2.3.11. Street Trees

The number of trees before building the Kentucky Avenue complete street was counted using Google Earth™ historical satellite images. The number of trees after constructing the complete street was counted using Google Maps Street-view.

Table 4-72. Number of Street Trees along the Kentucky Avenue Complete Street

Year	**Number of street trees**
2013 (before building the complete street)	35
2019 (after building the complete street)	119

As shown in Table 4-72, the number of street trees has increased because of a complete streets goal to improve livability and safety.

Street trees increase the number and duration of visits from the neighborhood because shading from trees improves the quality of walking and bicycling and brings people to the neighborhood, which is important for the neighborhood's economy. All of these factors also show the importance of street trees for business owners. They also improve air quality.

4.2.4. Incorporation of Socioeconomic Data into the SLCA Model

For this project, the initial complete streets LCA framework was expanded to include assessment of the exposure of neighborhoods and their vulnerability to environmental impacts in conjunction with the performance indicators. This was done using the CalEnviroScreen tool from the California Environmental Protection Agency. Other tools similar to CalEnvironScreen can be used with the framework, such as the Social Vulnerability Index (CDC SVI no date) mapping tool developed and hosted by the federal Centers for Disease Control and Prevention. The consideration of exposure and vulnerability is intended to support the two concepts of best practices recommended by Hernandez (2021), location and sustainability, by considering the effects of complete streets on those living in, working in, and frequenting the neighborhood the complete street is located in.

4.2.4.1. CalEnviroScreen Tool

4.2.4.1.a. Overview

Developed by the Office of Environmental Health Hazard Assessment (OEHHA) with the California Environmental Protection Agency (CalEPA), CalEnviroScreen is an index used to identify populations in California census tracts disproportionately burdened by, and vulnerable to, multiple sources of pollution, poverty, and racial concentrations of residency. The CalEnviroScreen model is based on two key components: a pollution burden consisting of an array of indicators that identify exposures to pollution and the environmental effects of such exposure; and population characteristics consisting of an array of socioeconomic factors and indicators to identify sensitive populations (e.g. health status, race, income, age, etc.). Percentiles are then used to assign scores for each indicator for each census tract in the state. Scores for each indicator are then combined to produce an overall CalEnviroScreen score for each census tract in the state. Over 70 data elements covering socioeconomic data, race, poverty, pollutants, and contaminants were used to create this index making it one of the most useful indicators of residential segregation and environmental problems – two important characteristics of Priority Population Areas now targeted for public investment in state climate change legislation.

CalEnviroScreen is a simple but effective data source to help quickly identify patterns of racial residency and poverty, and concentrations of those most at risk of exposure to adverse environmental conditions. What is important to note here is that the spatial concentration of so many important indicators that make up the CalEnviroScreen index develop over extended periods of time under the influence of political and social factors that establish economic priorities – both public and private. More important, because CalEnviroScreen uses a large array of indicators to identify long-term concentrations of poverty, race, and risk to pollution exposure, it provides compelling evidence of long-term systemic inequality.[5]

CalEnviroScreen can be used to identify disadvantaged neighborhoods for the complete street case studies on the map. Figure 4-26, Figure 4-27, and Figure 4-28 present the San Fernando Street, Franklin Boulevard, and Kentucky Avenue case study maps, respectively. Census tracts with darker red colors have higher CalEnviroScreen scores indicating relatively high pollution burdens and population sensitivities. Census tracts with lighter green colors have lower scores.

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[5] Similar index-based mapping utilities for public investment can also be used to obtain data on census tract level or zip code level socio-economic conditions. Examples include the California Tax Credit Allocation Commission's Opportunity Map https://belonging.berkeley.edu/2022-tcac-opportunity-map, the National Agency for Toxic Substances and Disease Registry's Social Vulnerability Index The Social Vulnerability Index (SVI): Interactive Map | CDC, and the Public Health Alliance's Healthy Places Index California Healthy Places Index Map.

The data for the San Fernando Street complete street project show that the project area affects neighborhoods spanning a wide range of socioeconomic conditions. Data for the Franklin Boulevard complete street show that the project is in a low socioeconomic neighborhood. For the Kentucky Avenue complete street project, low CalEnviroScreen scores on the project's south side reflect the challenging socioeconomic conditions of the area. High CalEnviroScreen scores on the project's north side reflect an area with better socioeconomic conditions primarily consisting of a low population industrial area.

Based on these maps, a summary of the neighborhoods (i.e. census tracts) identified by CalEnviroScreen to be at least partially within the 0.5 and 2.0 mile distances from each complete street case study, the census tract populations, and the census tract CalEnviroScreen percentile rankings are shown in APPENDIX F. The CalEnviroScreen percentile rankings for each neighborhood by census tract were weighted by the populations in each census tract within walking or bicycling distance to create a summary population weighted summary CalEnviroScreen percentile ranking for each of the three complete streets considered in this study. The population weighted CalEnviroScreen percentile ranking was then normalized by the sum of the populations within the walking or biking distance across all three case studies. The normalized summary population weighted percentile rankings were intended for use as a first-order ranking metric for the relative impact of the complete street in terms of number of people in disadvantaged neighborhoods who could use the complete street across the three case studies. The equations used to calculate the normalized population weighted CalEnviroScreen percentile rankings for potential walking and biking populations are:

CalEnviroScreen percentile ranking of the neighborhoods where pedestrians might use the complete street = Sum(populations in neighborhoods identified in CalEnviroscreen within

0.5 miles of the complete street*CalEnviroScreen percentile rankings for neighborhoods)/(Sum of all populations in neighborhoods within 0.5 miles of complete streets projects across all 3 case studies)

CalEnviroScreen percentile ranking of the neighborhoods where bicyclists might use the complete street = Sum(populations in neighborhoods identified in CalEnviroscreen within 2.0 miles of the complete street*CalEnviroScreen percentile rankings for neighborhoods)/(Sum of all populations in neighborhoods within 2.0 miles of complete streets projects across all 3 case studies)

This metric can be extended to consider bicycle or walking trips combined with transit.

The results are summarized in Table 4-73 for each street. The scores indicate that the San Fernando and Franklin Boulevard complete streets projects could potentially provide a benefit to more disadvantaged people compared with the Kentucky Avenue project. The results also show that the number of people living in CalEnviroScreen neighborhoods within 0.5 miles is greatest for the San Fernando and Kentucky Avenue projects compared with the Franklin Boulevard project. It can also be seen that the San Fernando project has a very large population within 2.0 miles of it, and that the Franklin Boulevard project has a greater population living within 2.0 miles of the complete street than the Kentucky Avenue project.

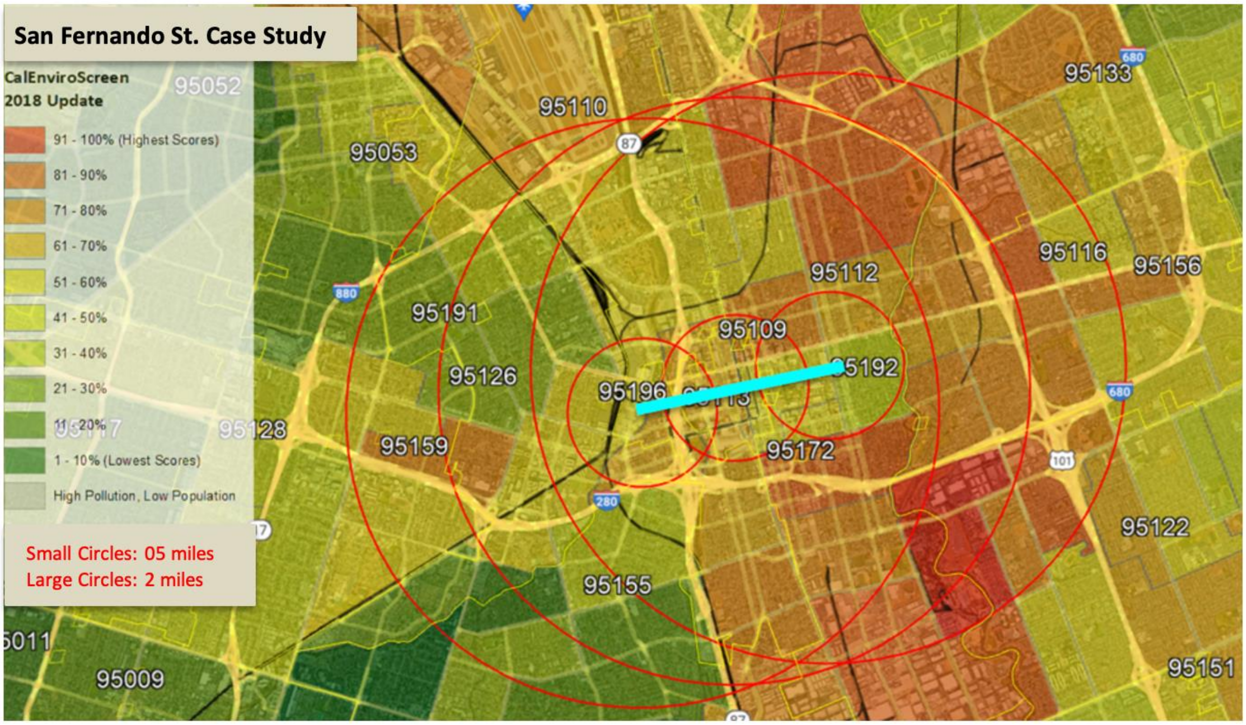


Figure 4-26. CalEnviroScreen Map showing the San Fernando Street Case Study. *Notes: blue line indicates the complete street. Small red circles indicate 0.5 mile walking distance from complete street. Large red circles indicate 2.0 bicycling distance from complete street.*

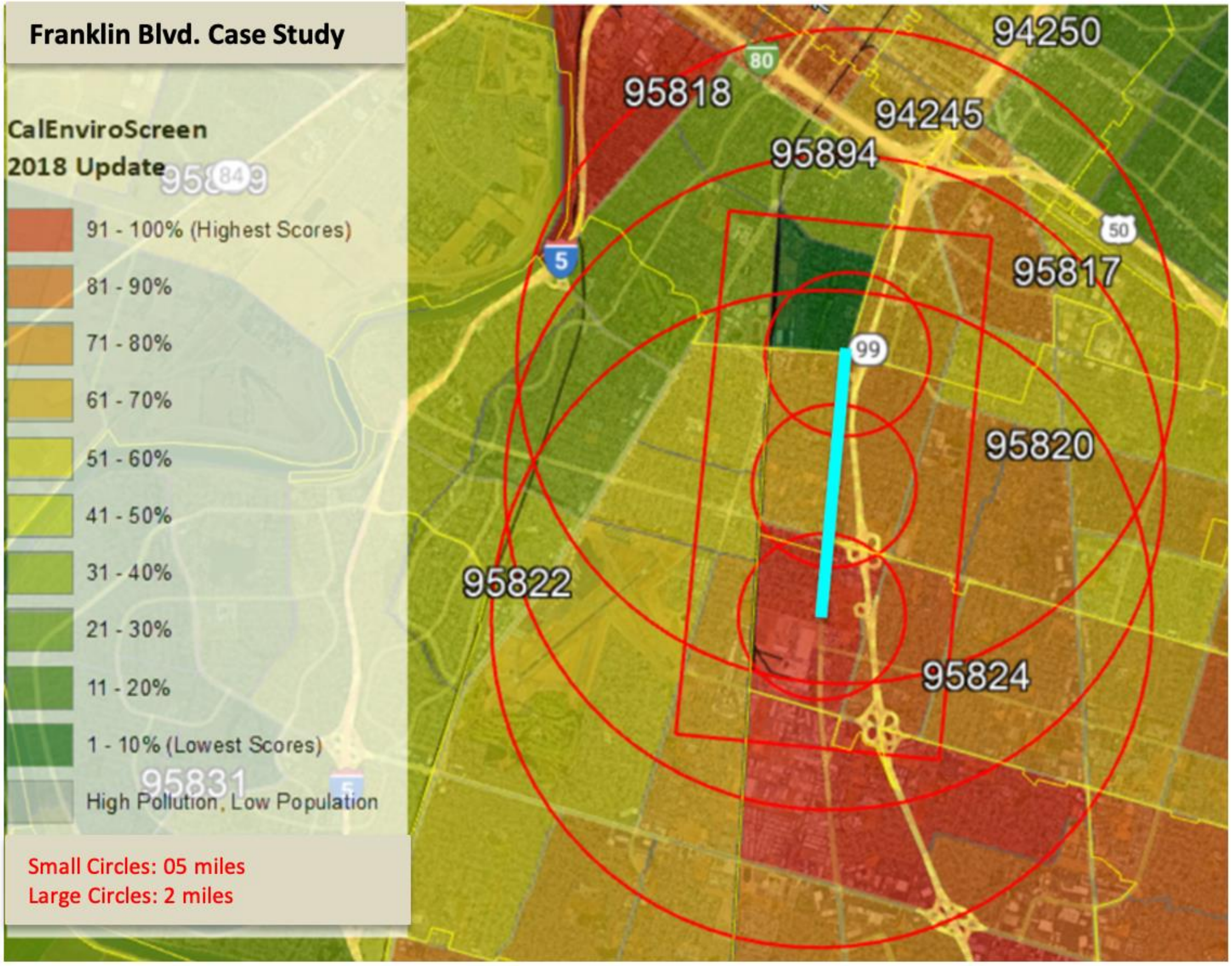


Figure 4-27. CalEnviroScreen Map showing the Franklin Boulevard Case Study. *Notes: blue line indicates the complete street. Small red circles indicate 0.5 mile walking distance from complete street. Large red circles indicate 2.0 bicycling distance from complete street.*

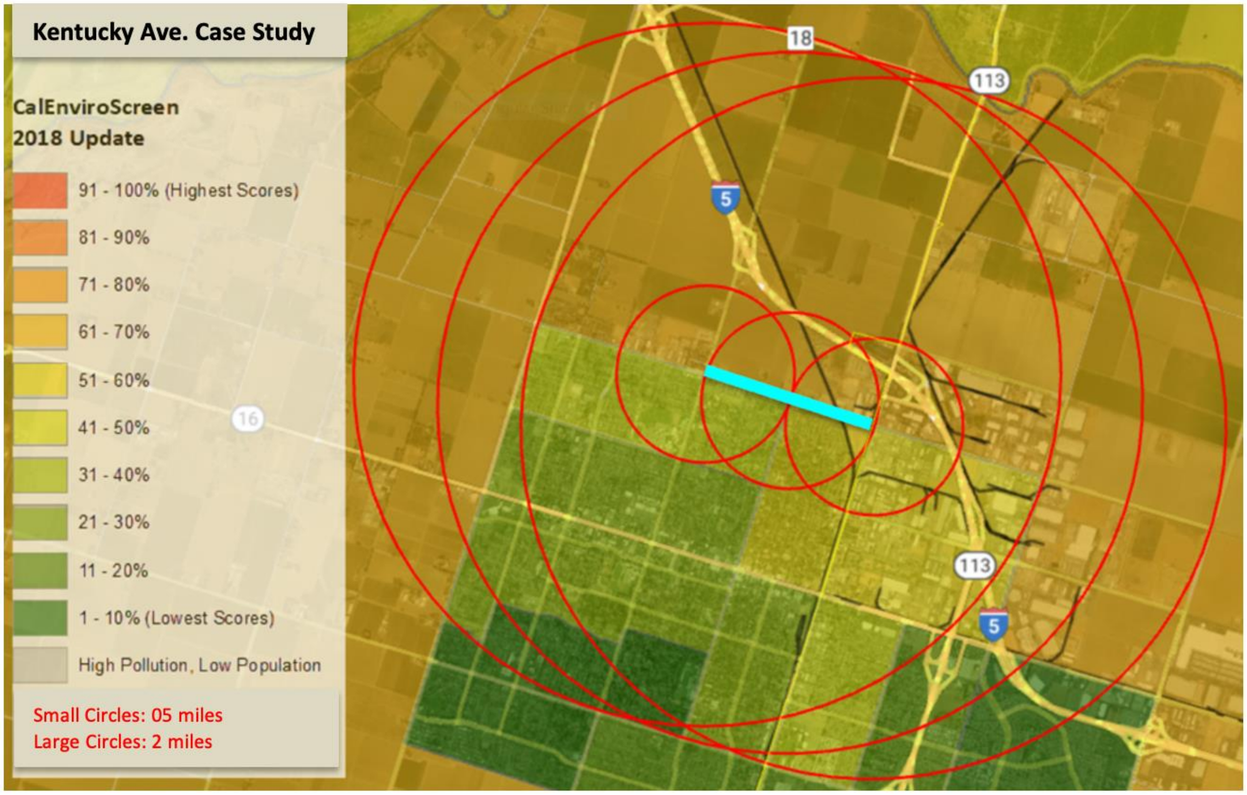


Figure 4-28. CalEnviroScreen Map showing the Kentucky Avenue Case Study. *Notes: blue line indicates the complete street. Small red circles indicate 0.5 mile walking distance from complete street. Large red circles indicate 2.0 bicycling distance from complete street.*

Table 4-73. Summary table of population weighted CalEnviroScreen percentile ranking for neighborhoods near complete streets.

Complete Street	**Population within 0.5 miles**	**Population within 2.0 miles**	**Population weighted CalEnviroScore percentile rankings within 0.5 miles***	**Population weighted CalEnviroScore percentile rankings within 2 miles***
San Fernando Street	18,418	163,708	63 (61-66)	64 (62-67)
Franklin Boulevard	11,261	79,988	61 (58-63)	63 (61-66)
Kentucky Avenue	16,521	20,767	55 (52-56)	47 (45-50)

**Note: Middle of range shown, numbers in parentheses are ranges from CalEnviroScreen*

4.2.5. Case Studies Summary SLCA Results

Summary results for the San Fernando Street, Franklin Boulevard, and Kentucky Avenue case studies are shown in in Table 4-74, Table 4-75, and Table 4-76, respectively.

4.2.5.1. Accessibility

Accessibility is divided into Access to Community Destinations, Access to Schools, and Access to Jobs are reported separately in the complete streets LCA framework. Access to Schools was separated from other destinations in the development of the original complete streets LCA framework based on feedback from a Complete Streets America panel that also included advocates for safe routes to schools. The panel said that schools were different from other destinations because they involved a unique vulnerable population and more focused set of destinations. Access to Jobs was separated because the methods for calculating it are somewhat different from calculations for other community destinations, and the difficulties of estimating numbers of jobs compared with determining numbers of community destinations.

Access indicators need to be interpreted with care. There are three issues to be concerned with for access indicators, as identified in the report on the development of the complete streets LCA framework (Harvey, 2018). The following is a condensed version of the discussion of those three concerns in that report.

> First, if the performance measure is written to produce the best value for the indicator (the highest value for accessibility) then a project in a neighborhood with a high level of previous investment in community destinations and greater density of them will produce a high value when a complete street accesses them. Alternatively, if the performance measure is written in terms of the improvement

(change) in the indicator rather than the highest final value, then a disadvantaged project that may have a smaller number of community destinations that were more dispersed and that become accessible with the installation of the complete street may have a larger change in value. For this reason, the interpretation of access variable in the case studies considers both final accessibility value and change in value.

Second, many performance indicators for transportation projects calculate accessibility in terms of the number of connections or improvement of connections to community destinations that a project will produce. What is missing from these performance indicators is the consideration of the number of community destinations that are in the neighborhood. A neighborhood with a greater density of community destinations will likely have a better accessibility indicator value than one where there has been underinvestment in community destinations because of the different densities, which has little to do with the complete street. The density of community destinations must be considered with interpreting access indicators.

The mapping of community destinations and supporting infrastructure of different types in the neighborhood, as was done for the case studies, is a first step. If the mapping shows a low density of community destinations, it may be an indicator of lack of public investment in community destinations and their maintenance. In these cases, investment in access is not the only issue, and there is a need for investment in creating and maintaining more destinations as well as including active transportation access. In other words, creation of destinations and active transportation options to reach them need to be bundled together.

> A third consideration when identifying accessibility and connectivity performance measures is connectivity between neighborhoods by active transportation and/or active transportation combined with transit between adjacent neighborhoods. This type of network connectivity facilitates people coming into the neighborhood to create more economic opportunity for its businesses and facilitates people in the neighborhood being able to access community destinations in adjacent neighborhoods. The existing patterns of inter-neighborhood connections in many urban areas are often the result of historical transportation and housing planning decisions that resulted in segregation and limited connectivity between neighborhoods defined by race, ethnicity and/or income level. These were routinely created and enforced by race/ethnic/religious exclusions that were written into housing development covenants, sometimes by mortgage lending practices, sometimes by violence or the threat of it, and sometimes by elimination of connections by not building easy-to-use transportation connections or by placement of difficult-to-cross transportation facilities. Identifying and eliminating these inter-neighborhood barriers as part of the planning of complete streets is an important consideration.

These concerns are the background for the interpretation of the access indicators for the three case studies.

4.2.5.1.a. Access to Community Destinations

Community destinations are defined as those physical sites that provide access to the resources essential for neighborhood health and safety, social cohesion, and economic productivity.

Access to these locations can also be thought of as access to the social goods needed for opportunity and mobility in the urban environment. Community destinations counted within the radii of walking and biking distances used in this study are grocery stores, pharmacies, hospitals and clinics, banks, post offices, libraries, coffee shops, restaurants, gas stations, police stations, places of worship, and museums.

Access to community destinations by any mode is determined by the number of community destinations, and access by complete street is determined by the number of destinations accessible by complete street. Increases in the access to community destinations by complete street indicator occur when destinations are within the walking and biking radii of the complete street, and when the number of community destinations is high. The indicator value will show less increase if the complete street does not provide access to many destinations. As noted previously, a low density of community destinations can cause a low value for this indicator. If there are people living near by and a low density of destinations this suggests that an investment in community destinations is likely warranted. If there are few people living near the complete street then the low density of destinations is an indication that the complete street might not be as useful compared to a more densely populated area. The intra-neighborhood accessibility increases if the complete street is part of a planned set of streets that create an interconnecting network, as opposed to a complete street that is not a link in a current or planned network (which was identified for each case study in Section 4.1).

The results shown in Table 4-74, Table 4-75, and Table 4-76 indicate that all of the complete streets increased access to community destinations by a complete street because there was no complete street previously. The number of San Fernando Street community destinations decreased from before to after the complete street for 7 of the 12 types of destinations.

Because the Access to Community Destinations performance indicator is dependent on the number of community destinations in the neighborhood, projects with different densities of destinations should not be compared. Interpretation of results within and between projects requires consideration of destination densities. Destinations were counted from before and after the complete streets project. Some analysis of changes in destination densities from before and after complete street construction was done for this study. Destination densities can change because of the complete street if the complete street design contributes to loss of destinations. However, most changes in the number of destinations within walking or biking distance of the complete street are caused by factors that have nothing to do with the complete street. Interpretation of access indicators needs to consider these changes should be done in practice.

4.2.5.1.b. Access to Schools

Access to schools is important for safety, and to improve livability and public health for children. Safety is the primary concern for active transportation access, but public health effects from physical activity, and potentially shorter travel times to schools allowing for more sleep for children and teens can also be beneficial, including consideration of sleep time for children and young adults (Voulgaries et al., 2019). Access to schools by a complete street increased from zero to all the destinations within the respective radii for walking and bicycling. Complete streets built near more schools will increase the value of this indicator.

A better assessment of the effects of the complete streets regarding changes in travel modes to school and perceived safety was obtained from use of the survey instrument for school principals developed in this project. As noted, the reopening of schools during the Covid pandemic is the likely reason that the survey had a very low response rate.

4.2.5.1.c. Access to Jobs

Access to jobs is a measure of the access of locations of employment to pedestrian, bicycle, and transit infrastructure and services. Easier accessibility to jobs reduces the need for driving to work and can make businesses more attractive for local employees. Connectivity by active transportation and/or active transportation combined with transit between a neighborhood and adjacent neighborhoods is also an important consideration. This type of connectivity facilitates people coming into a neighborhood to create more economic opportunities for its businesses and facilitates access to jobs for people in disadvantaged neighborhoods.

Access to jobs by a complete street increased from zero to all the destinations within the respective radii for walking and bicycling. Like access to community destinations, this access indicator is dependent on the number of community destinations in the neighborhood, particularly those offering employment.

4.2.5.2. Jobs

4.2.5.2.a. Job Creation

The purpose of this indicator is to identify whether the complete streets project will create jobs. All construction work will generate temporary construction jobs. The most value comes from new permanent jobs from new places of employment being attracted to the location, and from helping to retain permanent jobs by making the location a more attractive place to work.

As noted in the methodology part of this chapter, job creation was not directly measured, but was instead estimated using the Garrett-Peltier model. That model is tied to spending on the construction, which is a very indirect estimate of job creation for a specific project. Complete streets can be expected to attract new places of employment and retain existing businesses, if designed to support those employers. Despite the estimated positive results from the model shown for all three case studies by the job creation indicator seen in the summary tables, the results should be used with caution because they are generated from a regression model. A better approach would be to identify new businesses and associated jobs created by them after construction of the complete streets. However, whether the complete street was the direct cause would be difficult to identify without interviewing decision-makes at the employment locations, and after enough time for those locations to become established.

Job retention by making existing businesses, often likely to be owned by local residents in disadvantaged neighborhoods, is as important or potentially more important than new job creation. Job retention has no metric at this time, and was not able to be considered in these case studies.

4.2.5.3. Mobility/Connectivity

4.2.5.3.a. Connectivity Indices

One of the important roles of complete streets is to improve the ability of people in neighborhoods to reach destinations quickly and safely by walking or biking, or active transportation combined with transit. This includes the need to not have gaps in the route where active transportation is not safe and direct. The purpose of this index is to identify the ability to travel to different locations in the neighborhood by walking or bicycling, including consideration of the richness of within- and between-neighborhood transit points in a neighborhood.

The density of routes between neighborhoods and complete streets should be considered when interpreting this indicator. The indicator should look at the improvement in connectivity as opposed to the final value for connectivity because a neighborhood that has a high density of destinations will always have a higher connectivity. The changes in intersection density per linear mile were similar for San Fernando Street and Franklin Boulevard, approximately 13 to 15%, while the change in connectivity for Kentucky Avenue was approximately 25%.

Higher connectivity was found in the Franklin Boulevard case study which is along a dense business district. San Fernando Street had the next highest connectivity, followed by Kentucky Avenue which is has very few destinations on one side of the street.

4.2.5.3.b. Connectivity to Transit

This performance measure is important as it demonstrates the connectivity between neighborhood streets and larger corridors that are important connection points in the city transportation grid. For example, in San Jose, San Fernando Street, one of the main downtown streets, connects downtown San Jose to Diridon Station, which is the central passenger rail depot for San Jose and a transit hub for Santa Clara County and the Silicon Valley. Historical transportation and housing planning decisions have often resulted in the current patterns of poor inter-neighborhood connections in many urban areas. Limited connectivity contributes to segregation between neighborhoods by race, ethnicity, and income level (Hernandez, 2021).

San Fernando Street and Franklin Boulevard had the highest connectivity to transit after completion (or planned completion) of the complete street, and Franklin Boulevard had the greatest percent increase in connectivity percent, approximately 160% compared with approximately 95% for San Fernando Street. Kentucky Avenue had the lowest final connectivity to transit and had a 33% increase in connectivity to transit. As can be seen in Figure 4-25, Kentucky Avenue has one bus station approximately 0.5 miles from one end of the complete street, and the transit center is on the other side of the city outside the farthest active transportation/transit travel zone.

4.2.5.4. Safety and Public Health

4.2.5.4.a. Delay

Delay is an indicator of time it takes to complete a walking or bicycling trip. The desirable direction for delay from construction of complete streets is a topic of debate. Intersections can increase safety if they are signalized and the signals are set up to be accessible to pedestrians and bicyclists and timed for their crossing. Improved safety leads to a more useable environment, which ultimately has the effect of improving economic productivity when this investment happens on a business corridor. Delay's effect may be negative and discourage people from using the street or the biking/walking facilities if a lot of time is spent on waiting at intersections. Therefore, when the delay is considered as a performance measure, the context of the complete street and the type of intersections and their effect on safety should also be considered. Delay may be caused by a lack of destinations and lack of connectivity, especially in disadvantaged neighborhoods, resulting in longer travel times.

There is an increase in the number of intersections in San Fernando Street, Franklin Boulevard, and Kentucky Avenue after the construction of the complete street projects, which increases the delay indicator. The results tables show the highest delay time after completion of the complete street for Franklin Boulevard, followed by San Fernando Street, and then Kentucky Avenue. The greatest increase in delay was on Kentucky Avenue (49%), followed by San Fernando Street (27%), and Franklin Boulevard (11%).

4.2.5.4.b. Level of Service

Level of service is a quality of service indicator that measures the way users might perceive a service condition (e.g., safety, travel time, delay, comfort, speed). Safety includes consideration of risk of collisions with vehicles for bicycles and pedestrians, risk of collisions between bicycles and pedestrians (particularly dangerous for seniors, children and people in wheelchairs), risk from obstacles (particularly dangerous for bicycles and people in wheelchairs), and ability to cross vehicle routes considering traffic gaps and signal timings. Safety also includes consideration of crime, including violent crime and robbery particularly important for children, seniors, women traveling alone and people in wheelchairs, and theft, particularly important for bicycles left at transit stations. in part determine the level of security perceived by travelers.

Some other active transportation and transit factors that affect the perception of LOS including safety are lighting, sight distances on routes and in the vegetation on the sides of routes (hiding places), level of maintenance, litter, noise, and adjacent heavy traffic (summaries available in Saelens and Handy, 2008; Cunningham and Michael, 2004; Humpel et al., 2002; Owen et al., 2004).

Bicycle Level of Service (BLOS) and Pedestrian Level of Service (PLOS) methodologies were not designed to analyze all types of bike lanes and could not accurately reflect the improvements in bike safety, especially for the Franklin Boulevard and Kentucky Avenue case studies. Therefore, Bicycle Level of Traffic Stress (LTS), which can be applied to all these scenarios, is the recommended approach for all complete street projects.

The BLOS and PLOS for San Fernando Street did not change with the complete street, while they generally improved for Franklin Boulevard with some anomalies between methodologies. For Kentucky Avenue the BLOS improved or stayed the same depending on the methodology, while the PLOS improved.

The Bicycle Level of Traffic Stress improved for the San Fernando Street and Kentucky Avenue complete streets and improved dramatically for the Franklin Boulevard complete street.

Crashes increased somewhat for the San Fernando Street case, but may just reflect typical variability in a small geographical area over a short period of crash data collection. There was insufficient data to assess the other two complete streets.

4.2.5.4.c. Bicycle and Pedestrian Miles Traveled

These parallel indicators are the measurements of miles traveled in a specific location for a particular period by walking and bicycle. Creating bike lanes and pedestrian lanes by complete street design can be an important factor to make active transportation more viable in disadvantaged neighborhoods which can result in large improvement in PMT and BMT performance measures, if density of destinations of opportunity, transit connections and safety issues are addressed.

Bicycle miles traveled (BMT) and Pedestrian Miles Traveled (PMT) increased dramatically for downtown San Jose, which includes the San Fernando Street case, and increases are expected from modeling for the yet to be built Franklin Boulevard complete street. There was insufficient data to evaluate Kentucky Avenue.

4.2.5.4.d. Critiques of BMT and PMT

There is a debate regarding how PMT and BMT should be interpreted for complete street projects. On the one hand, these performance measures recognize increasing pedestrian and bicyclist trips if the distances to destinations are reasonable. On the other hand, long distances that people must travel by walking and bicycling to reach destinations will also show increasing BMT and PMT, which could also be an indication that there are few destinations in the neighborhood or poor connectivity (few direct routes). For example, in disadvantaged neighborhoods high PMT and BMT can be an indication that community destinations are sparse and widely spaced and people do not have access to vehicles and forced to walk or bicycle long distances, which has a negative social effect.

There are two ways to increase PMT and BMT. The first is to encourage people to walk instead of drive (positive desired direction for sustainability) by making driving more difficult and/or making walking and bicycling easier such as with a complete street and greater connectivity. The second is to increase the number of community destinations near housing or the density of housing near community destinations. Both of these strategies can be used together. It is suggested that the measure be modified to consider “trips” or “trip segments”, and include consideration of transit connected to complete streets as a means of increasing PMT and BMT trip segments and overcoming longer distances between destinations and housing.

Several questions should be answered in this regard, including:

- How multi-modal trips should be handled in terms of a trip counter
- How walking trips to transit and walking from the transit station to the final destination should be considered and counted
- How those walking trips and walking-transit trips should be distinguished

Research to determine the most effective combinations of PMT, BMT and PMT-transit and BMT-transit trip segments results in the greatest reduction in VMT and increase in bicycle and pedestrian trips would be valuable. One suggestion is to keep BMT/PMT and add bicycle/pedestrian trip numbers, which helps the framework not rewarding bad land use planning that results in few and far between community destinations that are far from housing.

The SLCA framework for complete streets and the consideration of multiple social indicators provides the opportunity for developing and testing improved social indicators.

4.2.6. Discussion and Interpretation

Three case studies were considered in different parts of California to test the complete street framework, including the San Fernando Street complete street project located in San Jose, Franklin Boulevard complete street project located in Sacramento, and Kentucky Avenue complete street project located in Woodland, California. These case studies are located in more and less advantaged neighborhoods. The case studies include projects in urban areas and rural areas to compare the rural project with the urban projects.

The framework is based on five categories of concerns and 17 performance measures or indicators. Physical activity and green land consumption indicators were not considered in the this chapter because the data for these performance measures were unavailable. The main challenges in this study for the SLCA were data collection and interpretation difficulty for some of the indicators. Determining appropriate data sources took some time but was then easier once the data sources had been identified. Data for the pre-construction values was more difficult for those projects already built, San Fernando Street and Kentucky Avenue. It is intended that the framework will primarily be used prior to construction for the evaluation of proposed projects for design and location, which will eliminate the need for finding the historical data that was needed for this research project. Predicting post-construction conditions for a complete street that has not yet been built, such as the Franklin Boulevard case study, is also inherently difficult. This is considered in Section 4.4.3 for keeping or removing indicators from the framework. Every complete street project is unique, and this study discusses potential pitfalls in interpretation of some of the indicators, particularly when comparing one complete street project to another. Recommendations for avoiding those pitfalls when interpreting indicators in included in the discussion of the results from the case studies. Some of the models were appropriate for large areas and were not helpful to quantify or were not even quantifiable for the project-level complete street projects, such as green land consumption. These indicators are recommended for removal from the framework in Section 4.4.

The complete street LCA framework was purposefully for the interpretation of each individual indicator to support decision-making for location, design and potentially for prioritization of complete streets. Each indicator was selected to address a specific potential benefit of the complete street project within its unique context. The intention is that decision-makers then use the individual indicator results and consider them in the context of the goals of each complete street project to support their decisions. The author's view is that aggregating and weighting of the indicator scores to produce a single final SLCA score is inappropriate because each of the potential benefits should be considered against stated goals for the project, and because weighting of indicator results to produce a single value would need to be developed for each project based on the weighting of the unique goals for each project. Changes in the location and design of the project will change each indicator value differently. Also, communication between planners, designers and with stakeholders requires discussion of specific performance outcomes addressed by each indicator. Therefore, the desired direction for sustainability, and observed trend, and desired trend for each category and each indicator is provided, instead of calculating only one final score.

The results summary of all the performance measures quantified for the three case studies are presented in Table 4-74, Table 4-75, and Table 4-76.

Table 4-74. Summary Results SLCA for San Fernando Street Case Study

Selected Category	Selected Performance Measures (Indicator)	Desired direction for sustainability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normalized) difference (%)	Desired trend (Increase / Decrease /Direction)[1]	Observed trend (Increase / Decrease /Direction)[1]
Accessibility	Access to Community Destinations (0.5-mi)	Positive	94,170	0	70,076	70,076	Number of People having accessibility to Destination		**Inc**	**Inc**
	Access to Community Destinations (2-mi)	Positive	192,931	0	175,834	175,834				
	Access to Community Destinations (3-mi)	Positive	321,630	0	319,246	319,246				
	Access to Community Destinations (4.5-mi)	Positive	488,180	0	468,867	468,867				
	Access to school (0.5-mi)	Positive	402	0	402	402	Number of Students		**Inc**	**Inc**
	Access to school (2-mi)	Positive	2,895	0	2,895	2,895				
Jobs	Access to Jobs (0.5-mi)	Positive	21,053	0	19,546	19,546	Number of Employees having accessibility to Jobs		**Inc**	**Inc**
	Access to Jobs (2-mi)	Positive	27,209	0	26,692	26,692				
	Access to Jobs (3-mi)	Positive	50,022	0	52,485	52,485				

Selected Category	Selected Performance Measures (Indicator)	Desired direction for sustainability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase / Decrease /Direction)[1]	Observed trend (Increase / Decrease /Direction)[1]
	Access to Jobs (4.5-mi)	Positive	76,530	0	78,241	78,241				
	Job Creation (Direct Jobs)	Positive	0		38		Number of Job Created		**Inc**	**Inc**
	Job Creation (Indirect Jobs)	Positive	0		19					
	Job Creation (Induced Jobs)	Positive	0		19					
	Job Creation (Total)	Positive	0		76					

Selected Category	Selected Performance Measures (Indicator)	Desired direction for sustainability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase / Decrease /Direction)[1]	Observed trend (Increase / Decrease /Direction)[1]
Mobility / Connectivity	Connectivity Index (Intersection Density)	Positive	83		95	12	$mile^{-2}$	14.5%	**Inc**	**Inc**
	Connectivity Index (intersection per Linear Mile)	Positive	64		73	9	$mile^{-3}$	14.1%		
	Active Transportation to Local and Regional Transit Connectivity Index (Mileage of Bike/ Ped. Lane)	Positive	19.4		38	18.6	Mile	95.9%	**Inc**	**Inc**
	Active Transportation to Local and Regional Transit Connectivity Index (Bike/Ped. Facility Density)	Positive	5.8		11.2	5.4	$mile^{-1}$	93.1%		

Selected Category	**Selected Performance Measures (Indicator)**	**Desired direction for sustainability**	**Accessible by conv. street before the construction of the CS**	**Accessible by CS before construction of CS**	**Accessible by complete street after construction of CS**	**Accessible by complete street difference between before and after building the CS**	**Unit per capita**	**Relative (normal-ized) difference (%)**	**Desired trend (Increase / Decrease /Direction)[1]**	**Observed trend (Increase / Decrease /Direction)[1]**
	Pedestrian and Bicyclist Delay	Positive and Negative	677 sec (11 min)		871 sec (14 min)	194 sec (3 min)	Second /minutes	27.3%	**Dec/Inc**	**Inc**
	Level of Service (Urban or Auto)	Negative	C		C				**Dec**	**None**
Safety / Public Health	Level of Service (Bicycle Level of Service)-NCHRP	Positive	D		D				**Dec (Towards A)**	**None**
	Level of Service (Bicycle Level of Service)-HCM	Positive	C		C				**Dec (Towards A)**	**None**
	Level of Service (Pedestrian level of Service)-NCHRP	Positive	4.14		4.14				**Dec**	**None**
	Level of Service (Pedestrian level of Service)-HCM	Positive	B		B				**Dec (Towards A)**	**None**

Selected Category	**Selected Performance Measures (Indicator)**	**Desired direction for sustainability**	**Accessible by conv. street before the construction of the CS**	**Accessible by CS before construction of CS**	**Accessible by complete street after construction of CS**	**Accessible by complete street difference between before and after building the CS**	**Unit per capita**	**Relative (normal-ized) difference (%)**	**Desired trend (Increase / Decrease /Direction)[1]**	**Observed trend (Increase / Decrease /Direction)[1]**
	Level of Service (Transit level of Service)	Positive			F				**Dec (Towards A)**	**None**
	Bicycle Level of Traffic Stress (LTS)	Negative	2.5 (Moderately Low)		1 (Very Low)	1.5			**Dec**	**Dec**
	Crashes	Negative	79		92	13	Number of Crashes	16.5%	**Dec**	**Inc**
	Pedestrian Miles Traveled (0.5-mile) [2]	Positive and Negative	7,799		31,135	23,336	Ped* miles/day	299%	**Inc**	**Inc**
	Pedestrian Miles Traveled (2-mile)[2]	Positive and Negative	31,194		124,540	93,346	Ped* miles/day	299%	**Inc**	**Inc**
	Bicycle Miles Traveled (0.5-mile) [2]	Positive and Negative	2,279		6,101	3,822	Bike* miles/day	168%	**Inc**	**Inc**
	Bicycle Miles Traveled (2-mile) [2]	Positive and Negative	8,916		24,404	15,488	Bike* miles/day	174%	**Inc**	**Inc**
Livability	Street Trees	Positive	136		127	-9	Number of trees	-6.6%	**Inc**	**Dec**

[1] *Inc = increased, Dec = decreased, None = No change*

[2] *For entire downtown San Jose, not just San Fernando Street*

Table 4-75. Summary Results SLCA for Franklin Boulevard Case Study

Selected Category	Selected Performance Measures (Indicator)	Desired direction for Sustain-ability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase/ Decrease/ Direction)[1]	Observed trend (Increase/ Decrease/Direction)[1]
Accessibility	Access to Community Destinations (0.5-mi)	Positive	24,468	0	27,159	27,159	Number of People having accessibility to Destinations		**Inc**	**Inc**
	Access to Community Destinations (2-mi)	Positive	138,534	0	153,773	153,773				
	Access to Community Destinations (Polygon Transit Buffer)	Positive	44,772	0	49,697	49,697				
	Access to school (0.5-mi)	Positive	762	0	762	762	Number of Students		**Inc**	**Inc**
	Access to school (2-mi)	Positive	7,666	0	7,666	7,666				
Jobs	Access to Jobs (0.5-mi)	Positive	1,857	0	3,008	3,008	Number of Employees having accessibility to Jobs		**Inc**	**Inc**
	Access to Jobs (2-mi)	Positive	13,469	0	21,820	21,820				
	Access to Jobs (Polygon Transit Buffer)	Positive	3,671	0	5,947	5,947				

Selected Category	Selected Performance Measures (Indicator)	Desired direction for Sustain-ability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase/ Decrease/ Direction)[1]	Observed trend (Increase/ Decrease/Direction)[1]
	Job Creation (Direct Jobs)	Positive	0		35	35	Number of Created Jobs		**Inc**	**Inc**
	Job Creation (Indirect Jobs)	Positive	0		18	18				
	Job Creation (Induced Jobs)	Positive	0		17	17				
	Job Creation (Total)	Positive	0		70	70				

Selected Category	Selected Performance Measures (Indicator)	Desired direction for Sustain-ability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase/ Decrease/ Direction)[1]	Observed trend (Increase/ Decrease/Direction)[1]
Mobility / Connectivity	Connectivity Index (Intersection Density)	Positive	145		164	19	mile^{-2}	13%	**Inc**	**Inc**
	Connectivity Index (intersection per Linear Mile)	Positive	45		51	6	mile^{-3}	13%		
	Active Transportation to Local and Regional Transit Connectivity Index (Mileage of Bike/ Ped. Lane)	Positive	15.6		40.2	24.6	Mile	157.7%	**Inc**	**Inc**
	Active Transportation to Local and Regional Transit Connectivity Index (Bike/Ped. Facility Density)	Positive	3		7.8	4.8	mile^{-1}	160.0%		

Selected Category	**Selected Performance Measures (Indicator)**	**Desired direction for Sustain-ability**	**Accessible by conv. street before the construction of the CS**	**Accessible by CS before construction of CS**	**Accessible by complete street after construction of CS**	**Accessible by complete street difference between before and after building the CS**	**Unit per capita**	**Relative (normal-ized) difference (%)**	**Desired trend (Increase/ Decrease/ Direction)[1]**	**Observed trend (Increase/ Decrease/Direction)[1]**
	Pedestrian and Bicyclist Delay	Positive and Negative	3645 sec (61 min)		4062 sec (68 min)	417 sec (7 min)	Second /minutes	11.5%	**Inc/Dec**	**Inc**
	Level of Service (Urban or Auto)	Negative	B		C				**Dec**	**Inc**
Safety / Public Health	Level of Service (Bicycle Level of Service)-NCHRP	Positive	D		D				**Dec (Towards A)**	**None**
	Level of Service (Bicycle Level of Service)-HCM	Positive	D		A				**Dec (Towards A)**	**Dec**
	Level of Service (Pedestrian level of Service)-NCHRP	Positive	2.54		0.15				**Dec**	**Dec**
	Level of Service (Pedestrian level of Service)-HCM	Positive	D		B				**Dec (Towards A)**	**Dec**

Selected Category	**Selected Performance Measures (Indicator)**	**Desired direction for Sustain-ability**	**Accessible by conv. street before the construction of the CS**	**Accessible by CS before construction of CS**	**Accessible by complete street after construction of CS**	**Accessible by complete street difference between before and after building the CS**	**Unit per capita**	**Relative (normal-ized) difference (%)**	**Desired trend (Increase/ Decrease/ Direction)[1]**	**Observed trend (Increase/ Decrease/Direction)[1]**
	Level of Service (Transit level of Service)	Positive	F		F				**Dec (Towards A)**	**None**
	Bicycle Level of Traffic Stress (LTS)	Negative	4 (High)		1 (Very low)	3			**Dec**	**Dec**
	Crashes (bike/ped)	Negative	18				Number of Crashes		**Dec**	**No data**
	Pedestrian Miles Traveled (0.5-mile)	Positive and Negative	1,433		1,211	28	Ped* miles/day	545%	**Inc/Dec**	**Inc**
	Pedestrian Miles Traveled (2-mile)	Positive and Negative	5,732		4,844	110	Ped* miles/day	545%	**Inc/Dec**	**Inc**
	Bicycle Miles Traveled (0.5-mile)	Positive and Negative	261		176	2	bicycle* miles/day	207%	**Inc/Dec**	**Inc**
	Bicycle Miles Traveled (2-mile)	Positive and Negative	1,044		704	6	bicycle* miles/day	207%	**Inc/Dec**	**Inc**
Livability	Street Trees	Positive	49		349	300	Number of trees	612%	**Inc**	**Inc**

[1] *Inc = increased, Dec = decreased, None = No change*

Table 4-76. Summary Results SLCA for Kentucky Avenue Case Study

Selected Category	Selected Performance Measures (Indicator)	Desired direction for Sustainability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase/ Decrease/ Direction)[1]	Observed trend (Increase / Decrease/ Direction)[1]
Accessibility	Access to Community Destinations (0.5-mi)	Positive	7,926	0	7,926	7,926	Number of People having accessibility to Destinations		**Inc**	**Inc**
	Access to Community Destinations (2-mi)	Positive	74,945	0	71,258	71,258				
	Access to Community Destinations (Polygon Transit Buffer)	Positive	20,268	0	20,426	20,426				
	Access to school (0.5-mi)	Positive	1,285	0	1,285	1,285	Number of Students		**Inc**	**Inc**
	Access to school (2-mi)	Positive	5,361	0	5,361	5,361				
Jobs	Access to Jobs (0.5-mi)	Positive	505	0	505	505	Number of Employees having accessibility to Jobs		**Inc**	**Inc**
	Access to Jobs (2-mi)	Positive	5,618	0	5,442	5,442				
	Access to Jobs (Polygon Transit Buffer)	Positive	1,696	0	1,717	1,717				

Selected Category	**Selected Performance Measures (Indicator)**	**Desired direction for Sustainability**	**Accessible by conv. street before the construction of the CS**	**Accessible by CS before construction of CS**	**Accessible by complete street after construction of CS**	**Accessible by complete street difference between before and after building the CS**	**Unit per capita**	**Relative (normal-ized) difference (%)**	**Desired trend (Increase/ Decrease/ Direction)[1]**	**Observed trend (Increase / Decrease/ Direction)[1]**
	Job Creation (Direct Jobs)	Positive	0		48	48	Number of Created Jobs		**Inc**	**Inc**
	Job Creation (Indirect Jobs)	Positive	0		24	24				
	Job Creation (Induced Jobs)	Positive	0		24	24				
	Job Creation (Total)	Positive	0		96	96				

Selected Category	Selected Performance Measures (Indicator)	Desired direction for Sustainability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase/ Decrease/ Direction)^{1}	Observed trend (Increase / Decrease/ Direction)^{1}
Mobility / Connectivity	Connectivity Index (Intersection Density)	Positive	53		66	13	mile^{-2}	25%	**Inc**	**Inc**
	Connectivity Index (intersection per Linear Mile)	Positive	26		33	7	mile^{-3}	27%		
	Active Transportation to Local and Regional Transit Connectivity Index (Mileage of Bike/ Ped. Lane)	Positive	10.2		13.6	3.4	Mile	33.3%	**Inc**	**Inc**
	Active Transportation to Local and Regional Transit Connectivity Index (Bike/Ped. Facility Density)	Positive	5.1		6.8	1.7	mile^{-1}	33.3%		

Selected Category	**Selected Performance Measures (Indicator)**	**Desired direction for Sustainability**	**Accessible by conv. street before the construction of the CS**	**Accessible by CS before construction of CS**	**Accessible by complete street after construction of CS**	**Accessible by complete street difference between before and after building the CS**	**Unit per capita**	**Relative (normal-ized) difference (%)**	**Desired trend (Increase/ Decrease/ Direction)[1]**	**Observed trend (Increase / Decrease/ Direction)[1]**
	Pedestrian and Bicyclist Delay	Positive and Negative	476 sec (8 min)		711 sec (12 min)	235 sec (4 min)	Second /minutes	49.4%	**Inc/Dec**	**Inc**
	Level of Service (Urban or Auto)	Negative	A		No data					**No data**
Safety / Public Health	Level of Service (Bicycle Level of Service)-NCHRP	Positive	F		F				**Dec (Towards A)**	**None**
	Level of Service (Bicycle Level of Service)-HCM	Positive	D		C				**Dec (Towards A)**	**Dec**
	Level of Service (Pedestrian level of Service)-NCHRP	Positive	3.52		1.79				**Dec**	**Dec**
	Level of Service (Pedestrian level of Service)-HCM	Positive	D		A				**Dec (Towards A)**	**Dec**

Selected Category	Selected Performance Measures (Indicator)	Desired direction for Sustainability	Accessible by conv. street before the construction of the CS	Accessible by CS before construction of CS	Accessible by complete street after construction of CS	Accessible by complete street difference between before and after building the CS	Unit per capita	Relative (normal-ized) difference (%)	Desired trend (Increase/ Decrease/ Direction)[1]	Observed trend (Increase / Decrease/ Direction)[1]
	Level of Service (Transit level of Service)	Positive	F		F				**Dec (Towards A)**	**None**
	Bicycle Level of Traffic Stress (LTS)	Negative	4 (High)		3 (Moder-ately High)	3			**Dec**	**Dec**
	Crashes (bike/ped)	Negative	1		0		Number of Crashes		**Dec**	**Dec**
	Pedestrian Miles Traveled (0.5-mile)	Positive and Negative	NO DATA		NO DATA		Ped* miles/day		**Inc/Dec**	**None**
	Pedestrian Miles Traveled (2-mile)	Positive and Negative	NO DATA		NO DATA		Ped* miles/day		**Inc/Dec**	**None**
	Bicycle Miles Traveled (0.5-mile)	Positive and Negative	1,301		1,390	89	bicycle* miles/day	7%	**Inc/Dec**	**Inc**
	Bicycle Miles Traveled (2-mile)	Positive and Negative	5,205		5,560	355	bicycle* miles/day	7%	**Inc/Dec**	**Inc**
Livability	Street Trees	Positive	35		119	84	Number of trees	240.0%	**Inc**	**Inc**

[1] *Inc = increased, Dec = decreased, None = No change*

4.3. Environmental Life Cycle Assessment

This section evaluates the environmental part of the socio-economic and environmental LCA framework developed for complete streets by Harvey et al. (2018). The framework is used to quantify the environmental impacts of complete streets and compare them with the existing vehicle-centric configuration streets. Complete streets that have not yet been constructed are evaluated using the city/county design documents for that project.

Some results of the complete street framework application are assessed in a sensitivity analysis of the three case studies before (conventional street) and after (complete street) the construction of the complete streets. Changes in vehicle miles traveled and speed are also considered before and after building the complete streets in all three case studies.

4.3.1. Environmental LCA Modeling and Assumptions

The scope of the LCA study in this section is limited to material production, transportation of raw materials from the extraction site to a processing plant and from there to the construction site, construction activities (cradle-to-laid), and vehicle use in the use stage. The use stage scope includes changes in vehicle miles traveled (VMT) and vehicle speed and their effects on selected emissions from the well-to-pump (production) and pump-to-wheel (combustion) perspectives. The evaluation does not include the end-of-life of the built infrastructure, or any other effects on vehicles, or the use of alternative modes of transportation instead of motorized vehicles. Only passenger cars and light-duty trucks (SUVs) that burn gasoline are considered, and this study does not assume any heavier freight vehicles. The assumption of no heavy vehicles will underestimate the thickness of the pavement needed and the vehicle emissions. Truck count data were not available.

The analysis period was assumed to be 30 years. The reduction in VMT for each case study was used to offset the extra emissions due to the material and construction for complete street (CS-) options compared to conventional (Conv-) options in the sensitivity analysis. The functional unit is one block of the complete street for each of the three case studies.

The Sacramento County Office of Engineering Improvement Standard (Sacramento County 2009) was used to determine the pavement layer thicknesses. Pavement width and block length were determined using Google Maps™ and Google Earth™. Kentucky Avenue was visited by one of the author to record the street features needed for the analysis. The summary of the layer type and road dimensions for all the cases is presented in Table 4-77.

Table 4-77. Street Dimensions for the three case study streets

Case Study	**Aggregate Base Thickness [cm (in)]***	**Asphalt Concrete Thickness [cm (in)]***	**Complete Street Pavement Width [m (ft)]**	**Block Length [m (ft)]**
San Fernando Street	33 (13)	9 (3.5)	13 (42)	81 (265)
Franklin Boulevard	33 (13)	9 (3.5)	13 (42)	104 (340)
W. Kentucky Avenue	25 (10)	9 (3.5)	10 (32)	270 (886)
E. Kentucky Avenue	33 (13)	9 (3.5)	13 (42)	270 (886)

**Assumed based on assumption of no heavy trucks*

In the current study, the GaBi software, which is a commercial LCA software developed by thinkstep, Inc. (now owned by Sphera), was used to develop models for each case. The impact indicators are from TRACI 2.1, developed by the US Environmental Protection Agency (US EPA; Bare 2012), for the life cycle impact assessment (LCIA).

A detailed study was performed to develop pavement construction material and energy models that are specific to California conditions and they can be found in the UCPRC LCI report (Saboori et al., 2021). These inventories were used to perform the eLCA for the three case studies. The materials and energy models used based on Saboori et al. (2021) for this study are in APPENDIX E in the archived data for this project. Some other items commonly used in complete streets, such as paint and plantings, were taken from the complete street LCA framework study developed by Harvey et al. (Harvey et al., 2018).

Three main impact categories are of particular importance and interest in California: global warming potential (GWP), photochemical ozone creation potential or also called smog formation, and the effects of particulate matter that are smaller that 2.5 microns on human health. These three TRACI impact indicators were considered in this study. Primary energy demand (PED) from non-renewable and renewable sources LCIs from GaBi were used to quantify the energy indicator for each case study. Feedstock energy or Primary Energy Demand (Non-Fuel) is the energy stored in the construction materials that are not consumed (such as asphalt; ISO 2006, Butt et al., 2019; Ostovar et al., 2020) and is also quantified for the three case studies. All the indicators considered here are summarized as:

- Global Warming Potential (GWP): in kg of CO2e.
- Photochemical Ozone Creation Potential: in POCP: in kg of O3e in TRACI (a measure of smog formation or SFP).
- Human Health (PM2.5): in kg of PM2.5 (particulate matters smaller than or equal to 2.5 micrometers in diameter).
- Total Primary Energy Demand: used as fuel from renewable and non-renewable resources (net calorific value excluding feedstock energy): in MJ.
- Feedstock Energy is Primary Energy Demand used as a material from nonrenewable resources (also called PED [non-fuel]): in MJ.

According to the LCA framework for complete streets, a typical list of all the complete street elements is shown in Table 4-78 (Harvey et al., 2018). Tables shown in APPENDIX E , which are extracted from the complete street LCA framework (Harvey et al., 2018), show the LCI and LCIA of the materials and surface treatments needed to calculate the LCI and LCIA of the complete street elements (Table 4-78). The LCIA is summarized in APPENDIX E .

Table 4-78. Complete Street Elements

Complete Street Element (a Single Item)	Service Life (yrs)	Material Used
Buffered Cycle Track	3	Paint (area)
Coloring Lanes	3	Paint (area)
Curb Extension	15	PCC[1] on AB[2]
Curb Type 5	15	PCC
Island	15	PCC on AB
Planted Furniture Zone	5	Planting
Raised Bicycle Buffer	10	HMA[3] (overlay)
Raised Cycle Track	10	HMA (overlay)
Raised Middle Lane	10	HMA (overlay)
Raising the Intersection to Sidewalk Grade	10	HMA (overlay)
Shelter/Transit station	15	PCC on AB
Striping	3	Paint (linear)
Textured/Pervious Pavement	10	Permeable HMA
Widening Sidewalk	15	PCC on AB

[1] PCC = Portland cement concrete
[2] AB = Agrregate base
[3] HMA = Hot mix asphalt

Service life was assumed for each element of conventional and complete streets separately (shown later) to determine the number of times each element needs to be treated/replaced during the 30-year analysis period with a typical maintenance, rehabilitation, or reconstruction treatment. According to the framework, it was assumed that the entire conventional street and complete street infrastructure would be replaced at the end of their service life.

4.3.2. Results and Discussion

4.3.2.1. San Fernando Street Case Study

The input used to calculate the environmental impacts for San Fernando Street are presented in Table 4-79. Table 4-80 and

Table 4-82 show the needed information to calculate the itemized impacts during the 30 years analysis period for conventional options and complete street options, respectively. Table

4-81 and Table 4-83 represent the impact categories of the San Fernando Street case study during the material, transportation, and construction stages (absolute values) before and after building the complete street, respectively.

Table 4-79. Input needed for San Fernando Complete Street Case study

Case Study	Block Length (m)	Complete Street Width (m)	Daily Traffic (#Cars/ Day)	% Change in Emission Rates	Min. AB[2] Thickness (cm)	Min. HMA[3] Thickness (cm)	Vehicle Speed on the Street (km/h)
San Fernando Street	81	12.80	9957	0.0%	33	8.89	40

[1] VMT = Vehicle miles traveled

[2] AB = Aggregate base

[3] HMA = Hot mix asphalt

Table 4-80. Input required for the Conventional Options to Calculate the Itemized Impacts for Materials, Transportation, and Construction Stages- San Fernando Street

Treatment (during the analysis period)	Functional Unit	Service Life (yrs)	Thick-ness (cm)	# of Treatment Applications	Traveled Way Width (m)	# per block	Note
HMA[1] (overlay)	1 Block	10.0	8.9	3	3.70	3	Street Top Layer
Aggregate, Crushed	1 Block	15.0	33.0	2	3.70	3	Street AB[3]
PCC[2]	1 Block	20.0	15.2	2	0.91	2	Curb & Gutter Surface
Aggregate, Crushed	1 Block	15.0	15.2	2	0.91	2	Curb & Gutter AB
Planting	1 Block	5.0	NA	6	1.83	2	Landscape
PCC	1 Block	20.0	9.2	2	1.52	2	Sidewalk Surface
Aggregate, Crushed	1 Block	15.0	15.2	2	1.52	2	Sidewalk AB

[1] HMA = Hot mix asphalt

[2] PCC = Portland cement concrete

[3] AB = Aggregate base

Table 4-81. Absolute Values of Impact Categories for the Conventional Options for Materials, Transportation, and Construction Stages- San Fernando Street

Treatment (during the analysis period)	Note	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Share of this item in Total GWP[4]
HMA[1] (overlay)	Street Top Layer	1 Block	3.33E+04	4.21E+03	2.13E+01	3.80E+05	1.21E+06	40.6%
Aggregate, Crushed	Street AB[3]	1 Block	1.77E+04	3.14E+03	6.75E+00	2.73E+05	0.00E+00	21.6%
PCC[2]	Curb & Gutter Surface	1 Block	1.38E+04	1.28E+03	7.57E+00	1.07E+05	0.00E+00	16.9%
Aggregate, Crushed	Curb & Gutter AB	1 Block	1.17E+03	2.07E+02	4.45E-01	1.80E+04	0.00E+00	1.4%
Planting	Landscape	1 Block	1.91E+01	1.07E+01	6.56E-02	7.71E+02	0.00E+00	0.0%
PCC	Sidewalk Surface	1 Block	1.39E+04	1.29E+03	7.63E+00	1.08E+05	0.00E+00	17.0%
Aggregate, Crushed	Sidewalk AB	1 Block	1.95E+03	3.45E+02	7.42E-01	3.00E+04	0.00E+00	2.4%
Total		**1 Block**	**8.19E+04**	**1.05E+04**	**4.45E+01**	**9.17E+05**	**1.21E+06**	

[1] *HMA = Hot mix asphalt*

[2] *PCC = Portland cement concrete*

Table 4-82. Inputs needed for the Complete Street Options to Calculate the Itemized Impacts for Materials, Transportation, and Construction Stages- San Fernando Street

CS Element	Material	Service Life (yrs)	# per Block	Length (m)	Width (m)	Area of the Element (m^2)	% of area that is replacing conventional treatment
Coloring Lanes	Paint (area)	3	2	81	2.44	197	0%
Shelter/Transit station	PCC[1] on AB[2]	15	1	15	3.00	45	100%
Planted Furniture Zone	Planting	5	1	61	3.00	182	100%
Curb Type 5	PCC	15	1		NA	NA	0%
Coloring Lanes	Paint (area)	3	2			0	0%
Raised Bicycle Buffer	HMA[3] (overlay)	10	2	81	NA	NA	0%
Buffered Cycle Track	HMA (overlay)	3	2	81	1.52	123	100%

[1] *PCC = Portland cement concrete*

[2] *AB = Aggregate base*

[3] *HMA = Hot mix asphalt*

Table 4-83 shows the breakdown of total GWP between the conventional elements and complete street elements. According to this table, 95% of the total GWP in the material, transportation, and construction stages belongs to the conventional elements, including the pavement, curbs, and gutters, etc., and only 5% of the total GWP belongs to the complete street elements.

Table 4-83. Absolute Values of Impact Categories for the Complete Street (After the CS Construction) for Materials, Transportation, and Construction Stages- San Fernando Street

CS Element	**Material**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	**Share of this item in Total GWP**
Complete Street Options							
Coloring Lanes	Paint (area)	6.77E-03	8.33E-02	6.19E-07	1.09E-02	0.00E+00	4.7%
Shelter/Transit station	PCC[1] on AB[2]	3.75E+03	3.77E+02	1.99E+00	3.17E+04	0.00E+00	
Planted Furniture Zone	Planting	1.18E+01	2.45E+00	1.50E-02	1.76E+02	0.00E+00	
Curb Type 5	PCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Coloring Lanes	Paint (area)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Raised Bicycle Buffer	HMA[3] (overlay)	2.26E+02	2.86E+01	1.45E-01	2.59E+03	8.22E+03	
Buffered Cycle Track	HMA (overlay)	1.27E-03	1.56E-02	1.16E-07	2.05E-03	0.00E+00	
Total (Complete Street Impacts)		*3.99E+03*	*4.08E+02*	*2.15E+00*	*3.45E+04*	*8.22E+03*	
Conventional Options							
Treatment (during the analysis period)	**Note**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	95.3%
HMA (overlay)	Street Top Layer	3.33E+04	4.21E+03	2.13E+01	3.80E+05	1.21E+06	
Aggregate, Crushed	Street AB[3]	1.77E+04	3.14E+03	6.75E+00	2.73E+05	0.00E+00	
PCC	Curb & Gutter Surface	1.38E+04	1.28E+03	7.57E+00	1.07E+05	0.00E+00	
Aggregate, Crushed	Curb & Gutter AB	1.17E+03	2.07E+02	4.45E-01	1.80E+04	0.00E+00	
Planting	Landscape	1.91E+01	1.07E+01	6.56E-02	7.71E+02	0.00E+00	
PCC	Sidewalk Surface	1.39E+04	1.29E+03	7.63E+00	1.08E+05	0.00E+00	

CS Element	Material	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Share of this item in Total GWP
Aggregate, Crushed	Sidewalk AB	1.95E+03	3.45E+02	7.42E-01	3.00E+04	0.00E+00	
Total (Conventional Street Impacts)		*8.08E+04*	*1.03E+04*	*4.39E+01*	*8.97E+05*	*1.16E+06*	

[1] PCC = Portland cement concrete

[2] AB = Aggregate base

[3] HMA = Hot mix asphalt

Table 4-84 summarizes the absolute values of impact categories before (conventional street) and after (complete street) constructing the complete street for materials, transportation, and construction stages. Table 4-85 depicts the absolute change and the percentage change in each impact category when changing from the conventional street to the complete street.

Table 4-84. Summary of the Absolute Values of Impact Categories Before (Conventional Street) and After (Complete Street) the Construction of San Fernando Complete Street for Materials, Transportation, and Construction Stages.

Item	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Total Impacts of the Conventional Street	1 Block	8.19E+04	1.05E+04	4.45E+01	9.17E+05	1.21E+06
Impacts of the Complete Street Elements of Complete Street	*1 Block*	*3.99E+03*	*4.08E+02*	*2.15E+00*	*3.45E+04*	*8.22E+03*
Impacts of the Conventional Elements of Complete Street	*1 Block*	*8.08E+04*	*1.03E+04*	*4.39E+01*	*8.97E+05*	*1.16E+06*
Total Impacts of the Complete Street	1 Block	8.48E+04	1.07E+04	4.61E+01	9.32E+05	1.16E+06

Table 4-85. Absolute and Percent changes in Material and Construction Stages Impact Indicators for San Fernando Street due to complete street implementation compared to the conventional options over the analysis period of 30 years

Item	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Absolute Change (CS-Conv)	1 Block	2.89E+03	1.99E+02	1.53E+00	1.53E+04	-4.44E+04
% Change [(CS-Conv)/Conv]	1 Block	3.5%	1.9%	3.4%	1.7%	-3.7%

The changes between the complete street and the conventional street are due to different quantities used for different materials, primarily asphalt, concrete, and aggregate base resulting from the reduction in total pavement surface area in the complete street design. An increase of up to 4% was seen in all the impact categories except for the PED (non-fuel) indicator, where almost a 4% reduction was observed. A small increase of no more than 4% impacts indicates that converting a conventional street to a complete street may not be an environmental impact-intensive process compared to the benefits one attains from the complete streets. Reduction in PED (non-fuel) is the only category that demonstrates decreased impacts when transferring to complete street options, and occurs because less asphalt is used. As mentioned, PED (Non-Fuel) has no environmental impact and is a measure of using a non-renewable resource (oil). Also, note that an increase or decrease in the environmental impacts when converting from conventional streets to complete streets is project-specific. Every project is unique and may or may not have all features of the complete street, depending on the design. Therefore, each complete street project needs to be studied separately.

4.3.2.2. Franklin Boulevard Case Study

The input used to quantify the environmental impacts of the Franklin Boulevard complete street case study is presented in Table 4-86. Table 4-87 and Table 4-89 show the needed information to calculate the itemized impacts during the 30 years analysis period for conventional options and complete street options, respectively. Table 4-88 and Table 4-90 present the impact categories of the Franklin Boulevard case study from the material, transportation, and construction stages (absolute values) before and after building the complete street, respectively.

Table 4-86. Inputs needed for Franklin Boulevard Complete Street Case study

Case Study	Block Length (m)	Complete Street Pavement Width (m)	Daily Traffic (#Cars/Day)	% Change in Emission Rates	Min. AB[2] Thickness (cm)	Min. HMA[3] Thickness (cm)	Vehicle Speed on the Street (km/h)
Franklin Boulevard	104	12.80	16,200	0.0%	33	8.89	56

[1] VMT = Vehicle miles traveled

[2] AB = Aggregate base

[3] HMA = Hot mix asphalt

Table 4-87. Input Needed for the Conventional Options to Calculate the Itemized Impacts for Materials, Transportation, and Construction Stages- Franklin Boulevard

Treatment (during the analysis period)	Functional Unit	Service Life [yrs]	Thick-ness (cm)	# of Treatment Application	Salvage (% of Service Life)	Traveled Way Width (m)	# per block	Note
HMA[1] (overlay)	1 Block	10.0	8.9	3	0%	3.70	3	Street Top Layer
Aggregate, Crushed	1 Block	15.0	33.0	2	0%	3.70	3	Street AB
PCC[2]	1 Block	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface
Aggregate, Crushed	1 Block	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB
Planting	1 Block	5.0	NA	6	0%	1.83	2	Landscape
PCC	1 Block	20.0	9.2	2	50%	1.52	2	Sidewalk Surface
Aggregate, Crushed	1 Block	15.0	15.2	2	0%	1.52	2	Sidewalk AB

[1] HMA = Hot mix asphalt

[2] PCC = Portland cement concrete

Table 4-88. Absolute Values of Impact Categories for the Conventional Options for Materials, Transportation, and Construction Stages- Franklin Boulevard

Treatment (during the analysis period)	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Share of this item in Total GWP
HMA[1] (overlay)	1 Block	4.27E+04	5.40E+03	2.73E+01	4.88E+05	1.55E+06	40.6%
Aggregate, Crushed	1 Block	2.27E+04	4.03E+03	8.67E+00	3.50E+05	0.00E+00	21.6%
PCC[2]	1 Block	1.78E+04	1.64E+03	9.72E+00	1.37E+05	0.00E+00	16.9%
Aggregate, Crushed	1 Block	1.50E+03	2.65E+02	5.71E-01	2.31E+04	0.00E+00	1.4%
Planting	1 Block	2.45E+01	1.38E+01	8.41E-02	9.90E+02	0.00E+00	0.0%

Treatment (during the analysis period)	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Share of this item in Total GWP
PCC	1 Block	1.79E+04	1.65E+03	9.79E+00	1.38E+05	0.00E+00	17.0%
Aggregate, Crushed	1 Block	2.50E+03	4.42E+02	9.52E-01	3.85E+04	0.00E+00	2.4%
Total	**1 Block**	**1.05E+05**	**1.34E+04**	**5.71E+01**	**1.18E+06**	**1.55E+06**	

[1] *HMA = Hot mix asphalt*

[2] *PCC = Portland cement concrete*

Table 4-89. Inputs needed for the Complete Street Options to Calculate the Itemized Impacts for Materials, Transportation, and Construction Stages- Franklin Boulevard

CS Element	Material	Service Life (yrs)	# per Block	Length (m)	Width (m)	Area of the Element (m2)	% of area that is replacing conventional treatment
Coloring Lanes	Paint (area)	3	2	104	2.13	221	0%
Shelter/Transit station	PCC[1] on AB[2]	15	1	15	3.00	45	100%
Planted Furniture Zone	Planting	5	1	84	2.00	167	100%
Curb Type 5	PCC	15	1		NA	NA	0%
Coloring Lanes	Paint (area)	3	2			0	0%
Raised Bicycle Buffer	HMA[3] (overlay)	10	2	104	NA	NA	0%
Buffered Cycle Track	HMA (overlay)	3	2	104	0.61	63	100%

[1] *PCC = Portland cement concrete*

[2] *AB = Aggregate base*

[3] *HMA = Hot mix asphalt*

Table 4-90 shows the breakdown of total GWP between the conventional elements and complete street elements. According to this table, 96% of the total GWP in the material, transportation, and construction stages belongs to the conventional elements, including the pavement, curbs, gutters, etc. On the other hand, only 4% of the total GWP belongs to the complete street elements.

Table 4-90. Absolute Values of Impact Categories for the Complete Street (After the CS Construction) for Materials, Transportation, and Construction Stages- Franklin Boulevard

CS Element	Material	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Share of this item in Total GWP
Complete Street Options							
Coloring Lanes	Paint (area)	7.60E-03	9.35E-02	6.95E-07	1.23E-02	0.00E+00	3.8%
Shelter/Transit station	PCC on AB	3.75E+03	3.77E+02	1.99E+00	3.17E+04	0.00E+00	
Planted Furniture Zone	Planting	1.08E+01	2.25E+00	1.37E-02	1.62E+02	0.00E+00	
Curb Type 5	PCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Coloring Lanes	Paint (area)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Raised Bicycle Buffer	HMA (overlay)	2.90E+02	3.67E+01	1.86E-01	3.32E+03	1.05E+04	
Buffered Cycle Track	HMA (overlay)	6.51E-04	8.01E-03	5.95E-08	1.05E-03	0.00E+00	
Total (for 1 Block)		*4.05E+03*	*4.16E+02*	*2.19E+00*	*3.52E+04*	*1.05E+04*	
Conventional Options							
Treatment (during the analysis period)	**Note**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	96.2%
HMA (overlay)	Street Top Layer	4.27E+04	5.40E+03	2.73E+01	4.88E+05	1.55E+06	
Aggregate, Crushed	Street AB	2.27E+04	4.03E+03	8.67E+00	3.50E+05	0.00E+00	
PCC	Curb & Gutter Surface	1.78E+04	1.64E+03	9.72E+00	1.37E+05	0.00E+00	
Aggregate, Crushed	Curb & Gutter AB	1.50E+03	2.65E+02	5.71E-01	2.31E+04	0.00E+00	
Planting	Landscape	2.45E+01	1.38E+01	8.41E-02	9.90E+02	0.00E+00	
PCC	Sidewalk Surface	1.79E+04	1.65E+03	9.79E+00	1.38E+05	0.00E+00	
Aggregate, Crushed	Sidewalk AB	2.50E+03	4.42E+02	9.52E-01	3.85E+04	0.00E+00	
Total (for 1 Block)		*1.04E+05*	*1.32E+04*	*5.65E+01*	*1.16E+06*	*1.50E+06*	

Table 4-91 summerizes the absolute values of impact categories before (conventional street) and after (complete street) constructing the complete street for materials, transportation, and construction stages. Table 4-92 depicts the absolute and percentage changes in each impact category when transferring from the conventional street to the complete street.

Table 4-91. Summary of the Absolute Values of Impact Categories Before (Conventional Street) and After (Complete Street) the Construction of Franklin Complete Street for Materials, Transportation, and Construction Stages.

Item	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Total Impacts of the Conventional Street	1 Block	1.05E+05	1.34E+04	5.71E+01	1.18E+06	1.55E+06
Impacts of the CS Elements of Complete street	*1 Block*	*4.05E+03*	*4.16E+02*	*2.19E+00*	*3.52E+04*	*1.05E+04*
Impacts of the Conventional Elements of Complete street	*1 Block*	*1.04E+05*	*1.32E+04*	*5.65E+01*	*1.16E+06*	*1.50E+06*
Total Impacts of the Complete Street	1 Block	1.08E+05	1.36E+04	5.87E+01	1.19E+06	1.51E+06

Table 4-92. Absolute and Percent changes in Material and Construction Stages in Franklin Boulevard due to complete street implementation compared to the conventional options over the analysis period of 30 years

Item	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Absolute Change (CS-Conv)	1 Block	2.95E+03	2.07E+02	1.57E+00	1.61E+04	-4.20E+04
% Change [(CS-Conv)/Conv]	1 Block	2.8%	1.5%	2.7%	1.4%	-2.7%

These changes between the complete street and the conventional street are due to different quantities used for different materials, primarily asphalt, concrete, and aggregate base resulting from the reduction in total pavement surface area in the complete street design. The changes in all the impact indicators are less than 3%, indicating that the conversion to a complete street leads to small changes in the amounts and types of materials used in a complete street compared to a conventional street. PED (Non-Fuel) is the only category that demonstrates decreased impacts when transferring to complete street options. This decrease is mostly because complete street elements replaced the asphalt pavement elements, with high PED (Non-Fuel) values, with other items. As mentioned, PED (Non-Fuel) has no environmental impact and measures the use of a non-renewable resource (oil).

4.3.2.3. Kentucky Avenue Case study

As discussed in the previous sections regarding the Kentucky Avenue case study, this complete street project widened Kentucky Avenue from two to four lanes from East Street to College Street and reconstructed the roadway as a complete street from East Street to West Street, including East Street to College Street and College Street to West Street.

The input used to calculate the environmental impacts for the Kentucky Avenue are presented in Table 4-93, Table 4-94, and Table 4-96 show the needed information to calculate the itemized impacts during the 30 years analysis period for the conventional options and complete street options, respectively. Table 4-95 and Table 4-97 present the impact categories of the Kentucky Avenue case study from the material, transportation, and construction stages (absolute values) before and after building the complete street, respectively.

Table 4-93. Input needed for Kentucky Avenue Complete Street Case study

Case Study	**Block Length (m)**	**Complete Street Pavement Width (m)**	**Daily Traffic (#Cars/Day)**	**% Change in Emission Rates**	**Min AB[2] Thickness (cm)**	**Min HMA[3] Thickness (cm)**	**Vehicle Speed on the Street (km/h)**
West Kentucky Avenue	270	9.75	11635	0.0%	25.4	8.9	64.38
East Kentucky Avenue	270	12.80	11635	0.0%	33.0	7.62	64.38

[1] *VMT = Vehicle miles traveled*

[2] *AB = Aggregate base*

[3] *HMA = Hot mix asphalt*

Table 4-94. Input required for the Conventional Options to Calculate the Itemized Impacts for Materials, Transportation, and Construction Stages- Kentucky Avenue

	Treatment (during the analysis period)	Func-tional Unit	Service Life (yrs)	Thick-ness (cm)	# of Treat-ment Applica-tion	Salvage (% of Service Life)	Traveled Way Width (m)	# per block	Note
West Kentucky	HMA[1] (overlay)	1 Block	10.0	8.9	3	0%	3.70	3	Street Top Layer
	Aggregate, Crushed	1 Block	15.0	25.4	2	0%	3.70	3	Street AB[3]
	PCC[2]	1 Block	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface
	Aggregate, Crushed	1 Block	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB
	Planting	1 Block	5.0	NA	6	0%	1.83	2	Landscape
	PCC	1 Block	20.0	9.2	2	50%	1.52	2	Sidewalk Surface
	Aggregate, Crushed	1 Block	15.0	15.2	2	0%	1.52	2	Sidewalk AB
	Total	**1 Block**							
East Kentucky	HMA (overlay)	1 Block	10.0	7.6	3	0%	3.70	3	Street Top Layer
	Aggregate, Crushed	1 Block	15.0	33.0	2	0%	3.70	3	Street AB
	PCC	1 Block	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface
	Aggregate, Crushed	1 Block	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB
	Planting	1 Block	5.0	NA	6	0%	1.83	2	Landscape
	PCC	1 Block	20.0	9.2	2	50%	1.52	2	Sidewalk Surface
	Aggregate, Crushed	1 Block	15.0	15.2	2	0%	1.52	2	Sidewalk AB
	Total	**1 Block**							

[1] *HMA = Hot mix asphalt*

[2] *PCC = Portland cement concrete*

[3] *AB = Aggregate base*

Table 4-95. Absolute Values of Impact Categories for the Conventional Options for Materials, Transportation, and Construction Stages- Kentucky Avenue

	Treatment (during the analysis period)	**Functional Unit**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	**Share of this item in Total GWP[3]**
West Kentucky	HMA[1] (overlay)	1 Block	8.47E+04	1.07E+04	5.43E+01	9.68E+05	3.08E+06	38.0%
	Aggregate, Crushed	1 Block	3.47E+04	6.15E+03	1.32E+01	5.35E+05	0.00E+00	15.6%
	PCC[2]	1 Block	4.63E+04	4.28E+03	2.53E+01	3.57E+05	0.00E+00	20.8%
	Aggregate, Crushed	1 Block	3.90E+03	6.91E+02	1.49E+00	6.02E+04	0.00E+00	1.8%
	Planting	1 Block	6.39E+01	3.59E+01	2.19E-01	2.58E+03	0.00E+00	0.0%
	PCC	1 Block	4.66E+04	4.31E+03	2.55E+01	3.60E+05	0.00E+00	20.9%
	Aggregate, Crushed	1 Block	6.51E+03	1.15E+03	2.48E+00	1.00E+05	0.00E+00	2.9%
	Total	**1 Block**	**2.23E+05**	**2.73E+04**	**1.23E+02**	**2.38E+06**	**3.08E+06**	
East Kentucky	HMA (overlay)	1 Block	9.53E+04	1.21E+04	6.11E+01	1.09E+06	3.46E+06	38.1%
	Aggregate, Crushed	1 Block	5.14E+04	9.09E+03	1.96E+01	7.92E+05	0.00E+00	20.5%
	PCC	1 Block	4.63E+04	4.28E+03	2.53E+01	3.57E+05	0.00E+00	18.5%
	Aggregate, Crushed	1 Block	3.90E+03	6.91E+02	1.49E+00	6.02E+04	0.00E+00	1.6%
	Planting	1 Block	6.39E+01	3.59E+01	2.19E-01	2.58E+03	0.00E+00	0.0%
	PCC	1 Block	4.66E+04	4.31E+03	2.55E+01	3.60E+05	0.00E+00	18.6%
	Aggregate, Crushed	1 Block	6.51E+03	1.15E+03	2.48E+00	1.00E+05	0.00E+00	2.6%
	Total	**1 Block**	**2.50E+05**	**3.16E+04**	**1.36E+02**	**2.76E+06**	**3.46E+06**	

[1] HMA = Hot mix asphalt

[2] PCC = Portland cement concrete

Table 4-96. Inputs needed for the Complete Street Options to Calculate the Itemized Impacts for Materials, Transportation, and Construction Stages- Kentucky Avenue

	CS Element	Material	Service Life (yrs)	# per Block	Length (m)	Width (m)	Area of the Element (m2)	% of area that is replacing conventional treatment	Total Mass/ Area/ Length/ Count over that of the CS element in the CS tab
West Kentucky	Coloring Lanes	Paint (area)	3	1	270	2.13	576	0%	576
	Curb Extension	PCC[1] on AB[2]	15	3	8	2.44	20	100%	59
	Raising the Intersection to Sidewalk Grade	HMA (overlay)	10	1	10	3.00	29	0%	29
	Raised Bicycle Buffer	HMA (overlay)	10	2	8	NA	NA	0%	16
	Buffered Cycle Track	HMA[3] (overlay)	3	2	270	0.30	82	100%	165
	Total (for 1 Block)								
East Kentucky	Coloring Lanes	Paint (area)	3	2	270	2.13	576	0%	1152
	Planted Furniture Zone	Planting	5	1	250	2.00	500	100%	500
	Raised Bicycle Buffer	HMA (overlay)	10	2	270	NA	NA	0%	540
	Buffered Cycle Track	HMA (overlay)	3	2	270	0.30	82	100%	165
	Total (for 1 Block)								

[1] *PCC = Portland cement concrete*

[2] *AB = Aggregate base*

[3] *HMA = Hot mix asphalt*

Table 4-97 shows the breakdown of total GWP between the conventional elements and complete street elements for West Kentucky Avenue and East Kentucky Avenue. According to this table, 97% of the total GWP in the material, transportation, and construction stages comes from the conventional elements pavement, curbs, gutters, etc., in West Kentucky Avenue. At the same time, the share of the conventional part of East Kentucky Avenue is almost the whole GWP in the material and construction stage.

Table 4-97. Absolute Values of Impact Categories for the Complete Street (After the CS Construction) for Materials, Transportation, and Construction Stages- Kentucky Avenue

	CS Element	Material	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Share of this item in Total GWP
			Complete Street Option					
West Kentucky	Coloring Lanes	Paint (area)	9.90E-03	1.22E-01	9.05E-07	1.60E-02	0.00E+00	2.6%
	Curb Extension	PCC[1] on AB[2]	4.88E+03	4.91E+02	2.59E+00	4.13E+04	0.00E+00	
	Raising the Intersection to Sidewalk Grade	HMA[3] (overlay)	1.08E+03	1.36E+02	6.89E-01	1.23E+04	3.91E+04	
	Raised Bicycle Buffer	HMA (overlay)	2.24E+01	2.83E+00	1.44E-02	2.56E+02	8.14E+02	
	Buffered Cycle Track	HMA (overlay)	8.48E-04	1.04E-02	7.76E-08	1.37E-03	0.00E+00	
	Total (for 1 Block)		*5.98E+03*	*6.30E+02*	*3.30E+00*	*5.38E+04*	*3.99E+04*	
East Kentucky	Coloring Lanes	Paint (area)	1.98E-02	2.44E-01	1.81E-06	3.20E-02	0.00E+00	0.3%
	Planted Furniture Zone	Planting	3.24E+01	6.73E+00	4.11E-02	4.83E+02	0.00E+00	
	Raised Bicycle Buffer	HMA (overlay)	7.56E+02	9.57E+01	4.85E-01	8.64E+03	2.75E+04	
	Buffered Cycle Track	HMA (overlay)	8.48E-04	1.04E-02	7.76E-08	1.37E-03	0.00E+00	
	Total Complete Street Impact (for 1 Block)		*7.88E+02*	*1.03E+02*	*5.26E-01*	*9.13E+03*	*2.75E+04*	
			Conventional Option					
	Treatment (during the analysis period)	**Note**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	
West Kentucky	HMA (overlay)	Street Top Layer	8.47E+04	1.07E+04	5.43E+01	9.68E+05	3.08E+06	97.4%
	Aggregate, Crushed	Street AB[3]	3.47E+04	6.15E+03	1.32E+01	5.35E+05	0.00E+00	
	PCC	Curb & Gutter Surface	4.63E+04	4.28E+03	2.53E+01	3.57E+05	0.00E+00	
	Aggregate, Crushed	Curb & Gutter AB	3.90E+03	6.91E+02	1.49E+00	6.02E+04	0.00E+00	
	Planting	Landscape	6.39E+01	3.59E+01	2.19E-01	2.58E+03	0.00E+00	
	PCC	Sidewalk Surface	4.66E+04	4.31E+03	2.55E+01	3.60E+05	0.00E+00	

	CS Element	**Material**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	**Share of this item in Total GWP**
	Aggregate, Crushed	Sidewalk AB	6.51E+03	1.15E+03	2.48E+00	1.00E+05	0.00E+00	
	Total		*2.21E+05*	*2.70E+04*	*1.22E+02*	*2.36E+06*	*3.01E+06*	
East Kentucky	HMA (overlay)	Street Top Layer	1.11E+05	1.41E+04	7.12E+01	1.27E+06	4.04E+06	99.7%
	Aggregate, Crushed	Street AB	5.92E+04	1.05E+04	2.26E+01	9.13E+05	0.00E+00	
	PCC	Curb & Gutter Surface	4.63E+04	4.28E+03	2.53E+01	3.57E+05	0.00E+00	
	Aggregate, Crushed	Curb & Gutter AB	3.90E+03	6.91E+02	1.49E+00	6.02E+04	0.00E+00	
	Planting	Landscape	6.39E+01	3.59E+01	2.19E-01	2.58E+03	0.00E+00	
	PCC	Sidewalk Surface	4.66E+04	4.31E+03	2.55E+01	3.60E+05	0.00E+00	
	Aggregate, Crushed	Sidewalk AB	6.51E+03	1.15E+03	2.48E+00	1.00E+05	0.00E+00	
	Total Conventional Street Impact	*1 Block*	*2.74E+05*	*3.50E+04*	*1.49E+02*	*3.06E+06*	*4.04E+06*	

[1] *PCC = Portland cement concrete*

[2] *AB = Aggregate base*

[3] *HMA = Hot mix asphalt*

Table 4-98 summarizes the absolute values of impact categories before (conventional street) and after (complete street) the construction of complete street for materials, transportation, and construction stages for West Kentucky Avenue and East Kentucky Avenue. Table 4-99 shows the absolute change and the percentage change in each impact category when transferring from the conventional street to the complete street for West and East Kentucky Avenue.

Table 4-98. Summary of the Absolute Values of Impact Categories Before (Conventional Street) and After (Complete Street) the Construction of Kentucky Avenue Complete Street for Materials, Transportation, and Construction Stages

	Item	**Functional Unit**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**
West Kentucky	**Total Impacts of the Conventional Street**	*1 Block*	*2.23E+05*	*2.73E+04*	*1.23E+02*	*2.38E+06*	*3.08E+06*
	Impacts of the CS Elements of Complete street	*1 Block*	*5.98E+03*	*6.30E+02*	*3.30E+00*	*5.38E+04*	*3.99E+04*
	Impacts of the Conventional Elements Elements of Complete street	*1 Block*	*2.21E+05*	*2.70E+04*	*1.22E+02*	*2.36E+06*	*3.01E+06*
	Total Impacts of the Complete Street	1 Block	2.27E+05	2.77E+04	1.25E+02	2.41E+06	3.05E+06
East Kentucky	**Total Impacts of the Conventional Street**	*1 Block*	*2.50E+05*	*3.16E+04*	*1.36E+02*	*2.76E+06*	*3.46E+06*
	Impacts of the CS Elements of Complete street	*1 Block*	*7.88E+02*	*1.03E+02*	*5.26E-01*	*9.13E+03*	*2.75E+04*
	Impacts of the Conventional Elements Elements of Complete street	*1 Block*	*2.58E+05*	*3.30E+04*	*1.39E+02*	*2.88E+06*	*3.46E+06*
	Total Impacts of the Complete Street	1 Block	*2.59E+05*	*3.31E+04*	*1.39E+02*	*2.89E+06*	*3.49E+06*

Table 4-99. Absolute and Percent in Material and Construction Stages Change changes in Kentucky Avenue due to complete street implementation compared to the conventional options over the analysis period of 30 years

	Item	**Functional Unit**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**
West Kentucky	Absolute Change (CS-Conv)	1 Block	4.23E+03	3.45E+02	2.28E+00	2.80E+04	-2.85E+04
	% Change [(CS-Conv)/Conv]	1 Block	1.9%	1.3%	1.9%	1.2%	-0.9%
East Kentucky	Absolute Change (CS-Conv)	1 Block	8.66E+03	1.50E+03	3.53E+00	1.30E+05	2.75E+04
	% Change [(CS-Conv)/Conv]	1 Block	3.5%	4.7%	2.6%	4.7%	0.8%

These changes between the complete street and the conventional street are due to differences in the quantities used for different types of materials, primarily asphalt, concrete, and aggregate base resulting from the reduction in total pavement surface area in the complete street design. Changes in all the impact indicators are less than 2% for West Kentucky Avenue, and less than 5% for East Kentucky Avenue. These small changes indicate that converting a conventional street to a complete street may not be an environmental impact-intensive process compared to the benefits one attains from the complete streets. Reduction in PED (non-fuel) is the only category in West Kentucky Avenue that demonstrates a decrease in impacts when transferring to complete street options, which is mostly because complete street elements replaced the asphalt pavement elements, with high PED (Non-Fuel) values, with other items. As mentioned, PED (Non-Fuel) has no environmental impact and is a measure of using a non-renewable resource (oil).

4.3.2.4. Summary of Conventional and Complete Street Elements Infrastructure Delivery Contributions to GHG

The contributions of the conventional street elements and the additional complete streets elements to the total GHG emissions for each case study are summarized in Figure 4-29. In all cases, the contribution of the complete streets elements is less than 5% of the total emissions.

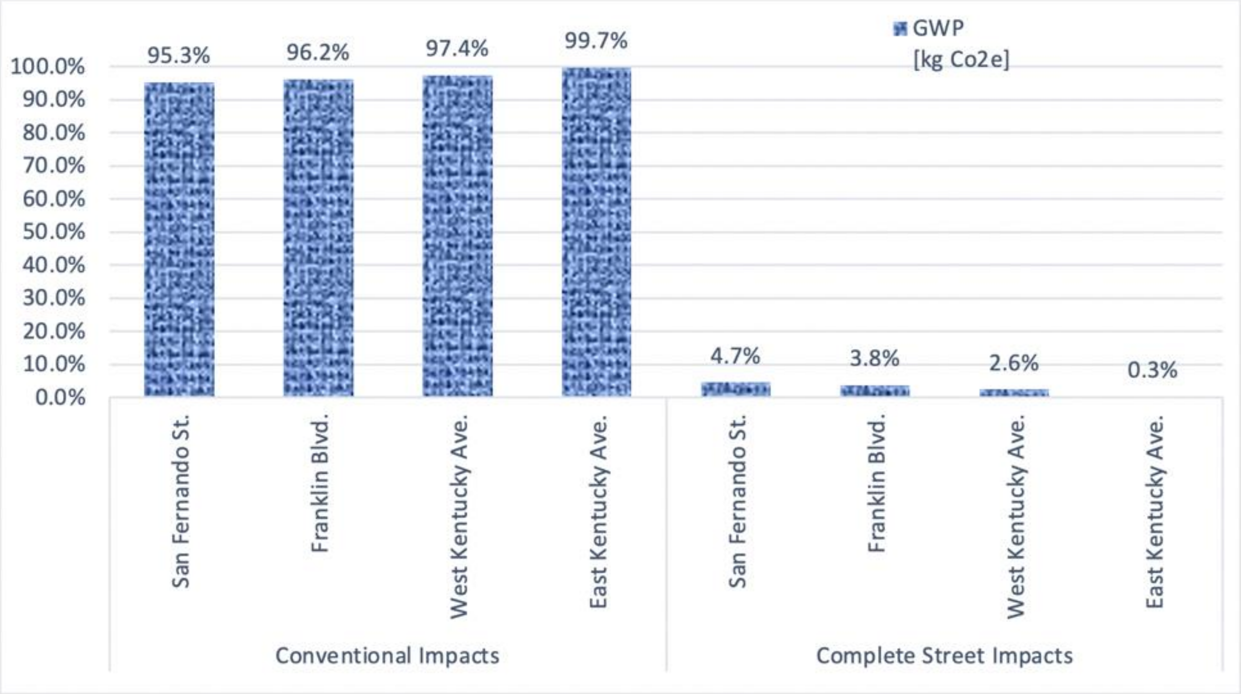


Figure 4-29. Breakdown of materials and construction GWP of complete streets between their conventional elements and complete street elements

4.3.2.5. Change in Vehicle Miles Travelled (VMT) and Traffic Speed

One of the primary goals of the complete street design guidelines is to reduce VMT by facilitating active transportation, including walking and bicycling modes. Reducing traffic speeds with complete streets features can improve active transportation safety and potentially to transfers of motorized vehicle mode to the active mode of transportation; however, reduced speeds can negatively impact vehicle fuel efficiencies. The analysis in this section was performed to quantify the environmental impacts due to change in the VMT and speed change before and after the construction of complete streets, combined with the LCA results from materials, transportation, and construction stages. The relative sensitivities of materials, transportation, and construction stages, speed change, and VMT change on the model outputs are analyzed in this section.

Following the LCA framework for complete streets (Harvey et al., 2018), the environmental impacts of fuel combustion in vehicles during the use stage were used to evaluate the emissions due to changes in VMT before and after the construction of the complete streets. There are associated information and related assumptions for each case study, mostly based on the framework, including the environmental impacts of fuel consumption calculated in two separate stages: a) gasoline production (well-to-pump) and b) tailpipe emissions (pump-to-wheel).

Gasoline production encompasses all the upstream impacts, including crude oil extraction, transportation to the refinery plant, processes performed at the refinery, and transportation to the filling station. These data were collected from the GaBi software (GaBi 2019).

The combustion of fuel by the vehicle results in tailpipe emissions. Following the framework's assumptions, the EMFAC web database developed by the California Air Resources Board was used in this stage (EMFAC Web Database). Then, the emission rates of light-duty autos (passenger cars) and light-duty truck type 1 (sports utility vehicles [SUV] and pick-ups) vehicles in Sacramento County in 2018 were extracted and used for the case studies. 60% of the vehicles were assumed to be passenger cars, and 40% were assumed to be light-duty trucks. Changes in VMT of freight vehicles and buses were not considered in this study. Only constant speeds were considered in the modeling, and changes in the drive cycles were not included because EMFAC does not have detailed drive cycle data. Two design speeds were considered before and after the construction of the complete streets.

Table 4-100 shows the traffic volume and speed for each case study. Changes in VMT were calculated using the California Air Resource Board VMT reduction tool (CARB, 2016).

Table 4-100. Inputs for Calculating the Vehicle Fuel Consumptions for San Fernando Street, Franklin Boulevard, and Kentucky Avenue Case Studies

Case Study	Daily Traffic (#Cars/Day)	Estimated % Change in VMT after Complete Street is built	Conventional Design Speed (mph)	Complete Street Design Speed (mph)
San Fernando Street	9,957	-1.1%	25	25
Franklin Boulevard	16,200	-1.4%	35	30
Kentucky Avenue	11,635	-2.2%	40	35

Table 4-101 summarizes the LCIA results during the use stage for the three case studies evaluating the traffic emissions a) before building the complete streets (conventional design or Conv), b) after construction of the complete streets (complete street design (ΔVMT)) considering only VMT changes, and c) after construction of the complete streets (complete street design (ΔVMT + Speed Change)) considering both VMT changes and speed changes.

Table 4-101. LCIA results during the use stage evaluating the traffic emissions in the conventional situation, complete street situation (considering change in VMT), and complete street situation (considering change in VMT and speed) for the three case studies

Item	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]
San Fernando Street				
Traffic (Conv[a])	2.46E+06	1.26E+02	2.54E+04	3.16E+07
Traffic (CS[b]+ΔVMT[c])	2.43E+06	1.25E+02	2.51E+04	3.13E+07
Traffic (CS+ΔVMT+Speed Change)	2.43E+06	1.25E+02	2.51E+04	3.13E+07
Franklin Boulevard				
Traffic (Conv)	4.28E+06	2.31E+02	4.65E+04	5.79E+07
Traffic (CS+ΔVMT)	4.22E+06	2.28E+02	4.59E+04	5.71E+07
Traffic (CS+ΔVMT+Speed Change)	4.64E+06	2.44E+02	4.91E+04	6.11E+07
Kentucky Avenue				
Traffic (Conv)	7.81E+06	4.08E+02	8.19E+04	1.02E+08
Traffic (CS+ΔVMT)	7.64E+06	3.98E+02	8.01E+04	9.97E+07
Traffic (CS+ΔVMT+Speed Change)	7.83E+06	4.23E+02	8.51E+04	1.06E+08

[a] *Conv: Conventional design (before the construction of the complete street)*

[b] *CS: Complete street design (After the construction of the complete street)*

[c] *ΔVMT: Change in the VMT (After the construction of the CS – Before the construction of the CS)*

Figure 4-30 to Figure 4-33 present the changes in LCIA results during different stages, including the change in material, transportation, and construction, and use stage (the change in VMT and change in both VMT and speed). Based on the results shown in Figure 4-30 through Figure 4-33 reductions in traffic speed can significantly impact the well-to-wheel emissions of the traffic during the use stage. Reducing design speeds from 56 to 48 km/h (35 to 30 mph) on Franklin Boulevard and 64 to 56 km/h (40 to 35 mph) on Kentucky Avenue increase well-to-wheel impacts for the complete street versus conventional options across their VMT changes. Franklin Boulevard shows a sharp increase in the GWP when both speed and VMT are changed (Figure 4-30). Because, within the speed range of residential parts of this street, any speed reduction results in dramatic decreases in fuel efficiency and increases in tailpipe emissions, and the resulting increased emissions cannot be offset by a 1% to 2% reduction in VMT of this case study.

Changes in speed and VMT on Franklin Boulevard leads to a large increased in emissions and on Kentucky Avenue to a slight increase in all the impact categories. However, a small decrease in the impacts was observed for the San Fernando complete street project as no speed change on the San Fernando Street was made. In contrast, a reduction across all impact categories was seen for all the three case studies when VMT was changed but the speed was not. It is important to note that heavy vehicles such as freight trucks are not included in the analysis as these streets are not truck traffic intensive.

According to Figure 4-30 through Figure 4-33 changes in the material and construction stages are negligible compared to the use phase for all three case studies. The results from these three case studies indicate that the effects on environmental impacts due to a complete street implementation should be analyzed separately and on a project-by-project basis. They also indicate that additional reductions in VMT of around 5% that might be expected as complete street networks begin to connect and increase the viability of active transportation trips could result in overall decreases in emissions.

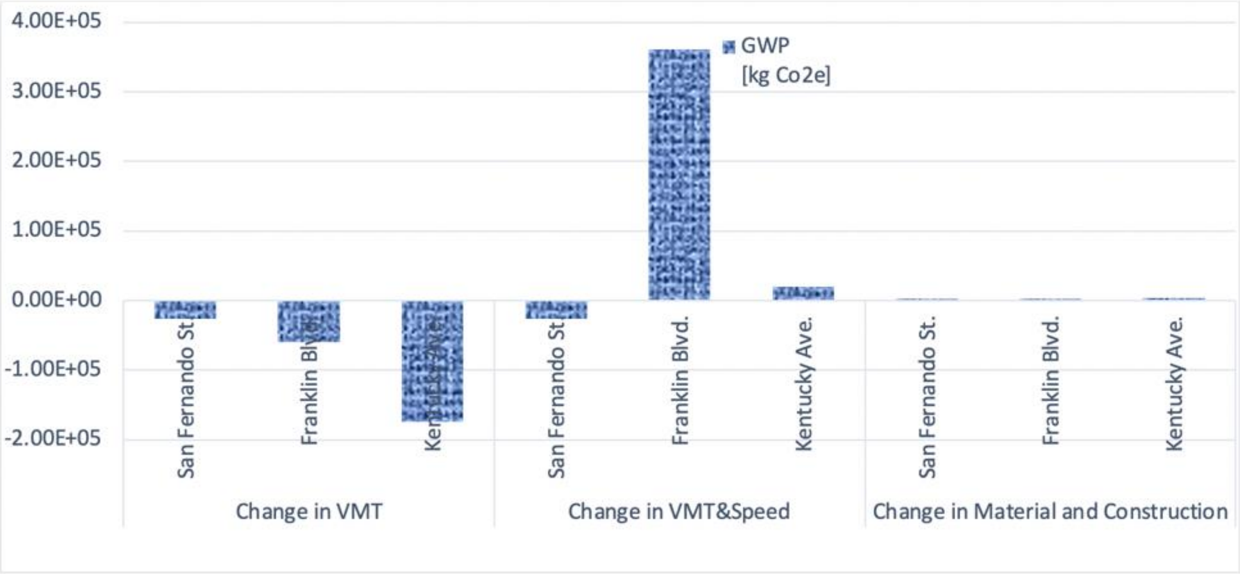


Figure 4-30. The difference in Well-to-Wheel and Material and Construction GWP [kg CO2e] Impacts (CS-Conv) during the Analysis Period (30 years) for the three case studies

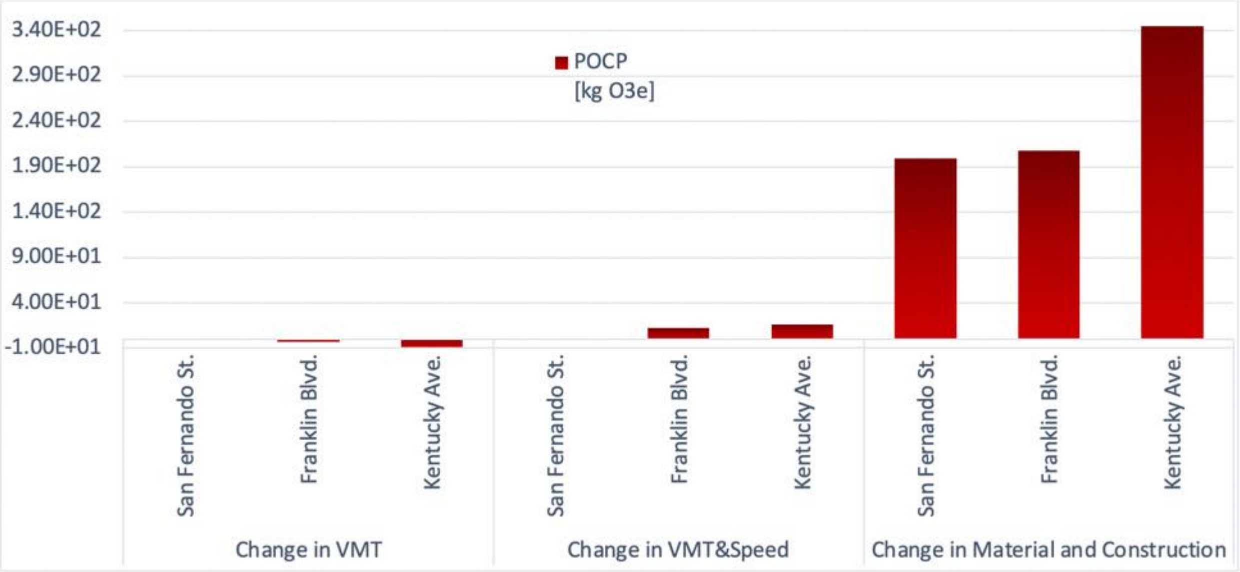


Figure 4-31. The difference in Well-to-Wheel and Material and Construction POCP [kg O3e] Impacts (CS-Conv) during the Analysis Period (30 years) for the three case studies

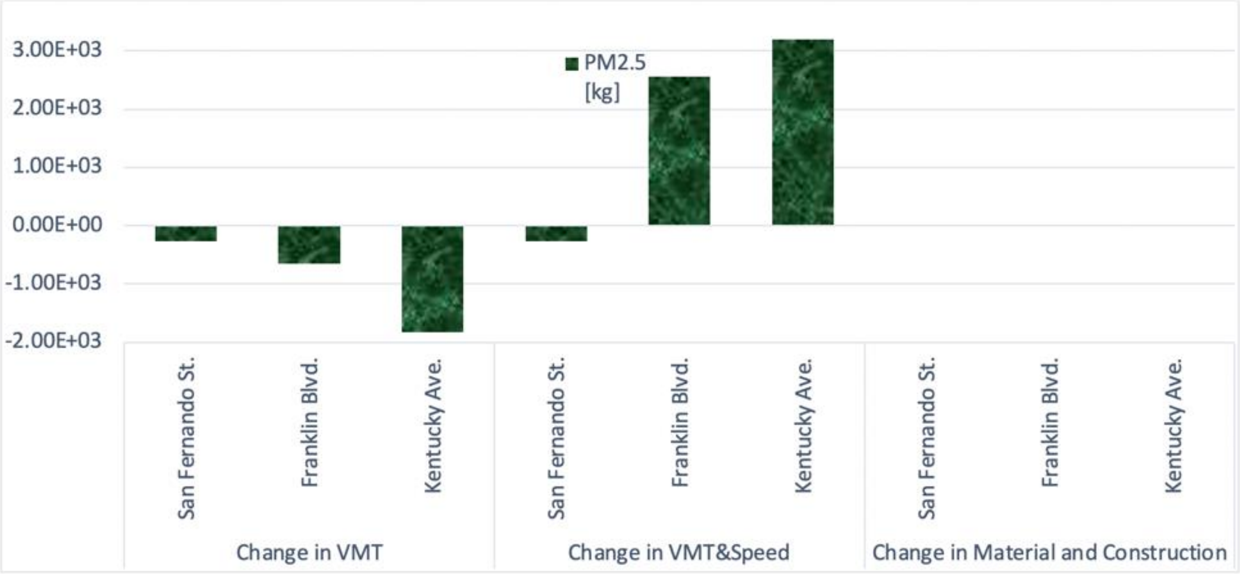


Figure 4-32. The difference in Well-to-Wheel and Material and Construction PM2.5 [kg] Impacts (CS-Conv) during the Analysis Period (30 years) for the three case studies

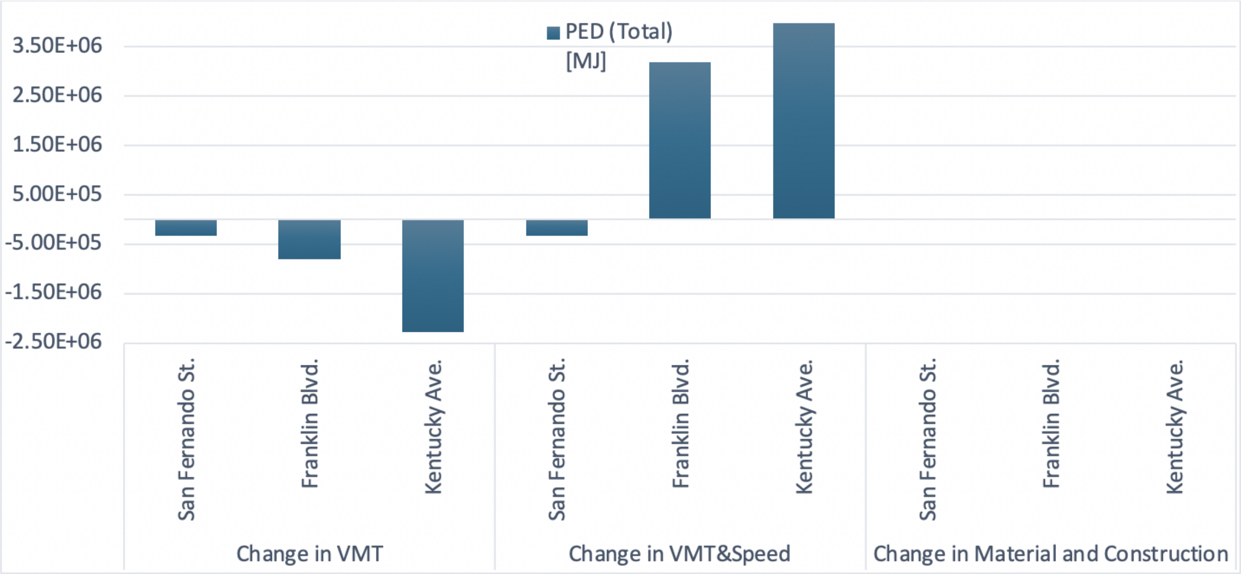


Figure 4-33. The difference in Well-to-Wheel and Material and Construction PED [MJ] Impacts (CS-Conv) during the Analysis Period (30 years) for the three case studies

4.4. Summary of Results and Recommendations for Complete Streets LCA Framework

4.4.1. Summary

The goal of this chapter and its predecessor was to develop the methodology to quantitatively help answer this question: is a complete street a solution for a proposed project in the public street right-of-way to improve the functionality of shared spaces? If built or proposed but not yet built, how will the complete street deliver the intended performance with regard to safety, accessibility to all users, convenience, economic benefits, and environmental benefits and comfort as it was designed for that location and in that street network?” This question is important when determining how best to achieve these goals for a given neighborhood, what features to design into the proposed project, and where to locate projects.

Results of three case studies are presented in this chapter from quantifying the socio-economic and environmental impacts of complete streets and comparing them with the existing conventional streets, focusing primarily on the social performance indicators and also including environmental indicators. The results are compared with the conventional existing streets that were configured to be vehicle-centric. To test the framework, the three case studies were solicited in urban, suburban, and rural areas. The case studies also include more and less advantaged neighborhoods. Case study evaluation was based on the project design for those that had not yet been started or completed. Where the case study project had been completed, the project was evaluated based on performance before and after project completion.

The primary purpose of the case studies was to evaluate the efficacy of the performance measures proposed in the previous chapter with regard to reasonableness of the results and the practicalities and difficulties of using them with the intent to provide a recommended final set of indicators. The indicators were also tested for use in areas with more and less advantaged areas in terms of density of community destinations, access to transit, and population density. The second purpose was to evaluate complete streets in different contexts and see what kinds of benefits the indicators identified, and where the indicators did not identify benefits. The benefits were also considered with respect to social and environmental vulnerability and existing environmental, social and health burdens by inclusion of use of a social vulnerability indexing tool, in this case CalEnviroScreen. The third purpose was to advance the use of quantitative tools to help measure the success of a complete streets project to improve neighborhood quality of life by improving the ability to use active transportation and active transportation with transit as part of mobility to safely reach destinations of interest.

4.4.2. Conclusions

4.4.2.1. Evaluation of Social and Economic Performance Indicators

The social and economic performance indicators included in the social LCA (SLCA) framework that was used in this project provide insight into specific and different potential benefits of a given complete streets project. The SLCA framework is based on five categories of concerns and 17 performance measures or indicators. They span the range of benefits typically expressed as being desirable for a neighborhood, and potentially coming from a complete street. The case studies reinforced the observation when assembling the framework that all the performance indicators should be considered as a set, rather than being converted into a simple score. According to the UNEP SLCA guidelines, aggregating and weighting can be used in the final steps of LCA, leading to a final SLCA score. However, due to the context-specific and qualitative nature of social aspects of the complete streets, and the desire for different benefits from different projects, indicating only one SLCA final score does not portray the complete picture and may also be misleading.

The case studies also reconfirmed the idea of the original framework that the observed or estimated change direction for each indicator, the desired direction of change for each category and each indicator, and the size of the change are all important when considering the multiple effects of constructing a complete street. Examining the likely changes in these indicators from the complete street projects provided a more holistic view of the project and its likely benefits and disbenefits, or likely ineffectiveness in creating change, than would otherwise be possible. Although other benefits, such as a “sense of place” and neighborhood pride are not measurable, the majority of the expressed purposes for building a complete street can be evaluated. In particular, even if all complete streets projects provide benefits, the relative size of the changes in beneficial outcomes is now possible.

The performance indicators also provide a quantitative sense of locations where the complete street is likely not providing some benefits and/or where the design or location for the complete streets might be changed to do a better job of providing a particular type of benefit. Examples include the results from the survey of principals (although only two surveys were returned) that indicated the need for additional complete streets within the active transportation buffers for the Franklin Boulevard and Kentucky Avenue projects to provide additional benefits for safe access to their schools. They also show where the complete street by itself will provide impressive results for a given type of benefit. Examples include improved pedestrian level of service for Kentucky Avenue, and improvement of the bicycle level of stress and connectivity to transit for Franklin Boulevard and San Fernando Street.

The main challenges in this social LCA (SLCA) study was data collection and the inherent context-specific and qualitative nature of social aspects of each complete street project. Finding historical data for the complete streets that were already built, such as for the San Fernando Street and Kentucky Avenue case studies, was difficult or impossible for some indicators. For the complete street that has not yet been built, such as the Franklin Boulevard case study, it was hard to predict the outcome of the complete street project and what will data look like in the future. As with any work involving complex data gathering and calculations there is a steep learning curve, with more effort required earlier in the process, and greater productivity as experience is gained. It is expected that as quantitative measures become more commonplace for evaluating projects, efforts to improve data sources and methods for using the data will reduce the effort. Each indicator was rated by the data collectors for difficulty. It can be seen from the results of finding and interpreting the results of these case studies that further improvement of the Social LCA framework for complete streets to make it more efficient and practical should involve the following steps:

- The performance indicators should be reviewed for difficulty of data collection, difficulty of interpretation, and usefulness in providing data to support decision-making regarding where to locate and how to design complete streets
- The performance indicator review should include consideration of improvement of indicators for both data collection and interpretation
- The recommended indicators should be reduced to a minimum set sufficient to provide sufficient information to support decision-making to reduce the cost and time needed to complete an evaluation

The evaluations of performance measures have been interpreted and discussed for each case study separately. The results summary of all the performance measures quantified for the three case studies were presented in Table 4-74, Table 4-75, and Table 4-76. The following are the initial results of following the process bulleted above.

Access to schools is a very important indicator for most neighborhoods; however, there are interpretation issues with the Access to Schools indicator. Results from the two survey results from school principals indicated that this measure may not do a good job of capturing the impacts or lack of impacts of a complete street on travel to school because of particular travel-to-school patterns and challenges and/or the lack of a more built-out complete streets network. The results from the survey were illuminating and the use of this or a similar survey as part of evaluation of Access to School is recommended.

The Job Creation indicator was difficult to interpret. It uses a model that has uncertainty as to its ability to predict permanent and part-time jobs stimulated by the complete street. Since only a top-down model was found to be practical, and its results not particularly applicable for estimating the creation of permanent jobs, rather than jobs related to the design and construction of the complete street, it is recommended that this indicator be dropped. Instead, if job creation is an important priority for building complete streets, it is recommended that attention be paid to building complete streets in locations where planning and investment for the creation of new businesses or other types of permanent job creation will also occur. In addition, more research should be conducted on the synergistic interactions of complete streets and that kind of planning and investment for potential development of better job creation indicators.

Job retention is also important, potentially more important than job creation because existing businesses may be closely associated with employing and serving existing neighborhood residents. Retention of talented and young people to work in neighborhoods can potentially be aided by infrastructure investments such as complete streets. The framework currently has no indicator for this important consideration.

There was a debate regarding the interpretation of the Bike/Pedestrian Delay indicator. Construction of a complete street can increase delay through changes in stop light timing, addition of stops signs, and other measures in the design that slow vehicle traffic, which is important for active transportation safety (particularly bicycle safety where there are on-street bicycle lanes), but which may also slow active transportation travel. Increases in delay that slow active transportation travel may reduce the desire of people using active transportation to quickly get to their destinations.

On the other hand, one of the purposes of a complete street is to provide active transportation access to multiple attractions (businesses, recreational activities, social interaction) along the complete street, which often be increased by slower travel. Complete streets are often part of strategies to change streets from high-speed traffic conveyors through neighborhoods to welcoming places that attract shoppers and residents by allowing them to easily cross the street and interact with small clusters of businesses or “nodes”. This is expected to lead to increased shopping and revenue, and job and business retention. Increasing transit stops along the complete street allows lower-income people, who predominantly are those without cars, to access these nodes for activity and employment.

Interpretation of the delay indicator likely needs consideration of whether the complete street is intended as a safe connector between locations or a safe and attractive way to produce social and economic activity at the location of the complete street through better access by active transportation.

Adding bicycle and pedestrian trip numbers in addition to BMT and PMT was suggested in this study to help the framework test and interpret whether BMT and PMT are indicating more active transportation or instead indicating long distances between sparse community destinations. The pedestrian level of service (PLOS) and bicycle level of service (BLOS) indicators are not recommended for continued inclusion because of the difficulty of using them, and the uncertainty of interpreting them. Better versions of PLOS and BLOS should be investigated for inclusion.

The current study did not consider physical activity and green land consumption indicators because collecting data for these performance measures was not doable due to the unavailability of data for the specific complete streets case studies.

4.4.2.2. Consideration of Complete Streets Indicators in Advantaged and Disadvantaged Neighborhoods

The three case studies were also used to evaluate each of the performance indicators as they were being used to evaluate complete streets in more and less advantaged neighborhoods. Disadvantaged neighborhoods are those that have had less public and private investment, reflected by fewer community destinations, fewer schools, fewer jobs, and greater physical and social isolation from opportunities because of less physical connectivity. A complete street can have value in both affluent and segregated spaces. The lack of investment, destinations supporting opportunity and well-being, and connectivity is commonly due to past intentional segregation based on race as well as income.

Complete streets can benefit all kinds of neighborhoods, which is reflected in the final values for the indicators. Locations with many destinations of opportunity can be benefited by connecting them with complete street projects that help the neighborhood and build out the network of complete streets.

Disadvantaged neighborhoods (also called priority population areas) and/or more rural or rural/urban interface areas with a lower density destination will not show final indicator values as high as more advantaged neighborhoods or neighborhoods with denser populations. These neighborhoods may show a greater change in the calculated indicator if they have little current access to complete streets compared with an advantaged neighborhood that already has some complete streets. Considering further investment to create more destinations in populated areas, particularly the higher density of destinations on the complete street and both near housing, should be considered simultaneously with the complete street.

Urban/rural fringe areas may particularly benefit from placing complete streets to connect to schools, even where there is a sparse density of other destinations.

There are concerns about using and interpreting the Pedestrian Miles Traveled (PMT) and Bicycle Miles Traveled (BMT) indicators. Higher values for these two indicators are generally considered to be indications of benefits. The concern is that high PMT and BMT numbers can be caused by a lack of schools, healthcare, stores, parks, jobs, and other destinations of interest within accessible walking, bicycling, or active transportation plus transit distances in or near a disadvantaged neighborhood. High PMT and BMT numbers might indicate the need for greater investment in destinations contributing to the quality of life rather than a positive active transportation environment. The inclusion of a Pedestrian Trips and Bicycle Trips indicator along with PMT and BMT would provide a better indication of which is the case for a given project.

Quantifying complete streets social benefits using the SLCA framework facilitates these types of analysis and interpretation when planning and designing complete streets projects and complete streets networks. The use of the social vulnerability and current impact burdens with the SLCA framework provided additional important information for planning complete streets and networks. For these case studies, the CalEnviroScreen tool was used along with the performance indicators to help identify projects that particularly help neighborhoods where people are disadvantaged and bearing the burdens of inadequate existing transportation or existing transportation systems that damage their quality of life. In terms of serving disadvantaged neighborhoods, Franklin Boulevard had the highest CalEnviroScreen percentile score, indicating that it provided the most benefit to disadvantaged neighborhoods, followed by San Fernando Street and then Kentucky Avenue. Using the CalEnviroScreen tool with the SLCA performance measures provides a very strong methodology for identifying which complete streets will provide the most benefit to the most disadvantaged communities. CalEnviroScreen is a reliable source for this type of data that doesn't require aggregating use of census data. Others outside of California can replicate this model using data from the Center for Disease Control and Prevention's Social Vulnerability Index (CDC SVI).

4.4.2.3. Environmental LCA

As was the case for the initial evaluation of the Complete Streets LCA Framework, the environmental impacts coming from the materials, materials transportation, and construction phases of building or reconstructing a conventional versus a complete street are very small. The coming of new LCA tools to easily calculate environmental impacts for materials, transportation, and construction will make the evaluation of design alternatives to reduce environmental impacts relatively easy.

The primary environmental impacts come from the use stage. Any changes in vehicle travel (vehicle miles traveled, VMT) will have a relatively large impact on environmental impacts as long as the vehicle fleet remains primarily dependent on internal combustion engines. The effects of a reduction in vehicle speeds from complete street design features are somewhat more complex than they appear in the analysis. Reductions in speed at speeds below 45 miles per hour may increase fuel use and emissions for longer blocks. This is an area that needs a more detailed drive cycle study.

The effects of adding street trees were not considered in the environmental LCA. The extent of available modeling is not known but should be investigated in future studies.

4.4.3. Recommendations

4.4.3.1. Recommended and Not Recommended Performance Indicators for the SLCA Framework

One or more performance measures were chosen from each category that was not too difficult in terms of data collection, methodology, and interpretation. The selected performance measures have lower scores (better ranks) and are easier to interpret compared to the unselected ones. Table 4-102 shows the degree of difficulty of data collection and use of the methodology for each performance measure in the initial framework, and the final recommended and not recommended performance measures, according to the three case studies. The reasons for difficulty in data collection, methodology, or interpretation for each performance measure were explained in each case study's section and are summarized in Table 4-102.

4.4.3.2. Use of Social Vulnerability Data with the SLCA Framework Performance Indicators

The use of the CalEnviroScreen tool with the SLCA Framework for Complete Streets, or other data such as the federal Social Vulnerability Index, is recommended to provide quantitative assessment indicators for the social and health vulnerability and existing environmental burdens of neighborhoods in which complete streets projects are proposed to be built. This information helps identify neighborhoods that may have a previous poor investment in community destinations (public and private) and transportation infrastructure, and that may particularly benefit from better access using lower-cost active transportation, particularly when it is used to connect with transit. This kind of data can also be used to help track that neighborhood that have previously been disadvantaged because of segregation, discrimination and lack of public investment are receiving complete streets and other investments that can reduce social and health vulnerability and environmental burdens.

4.4.4. Overall Conclusions

The purpose of this section was successfully achieved by testing the complete streets LCA framework developed in a previous chapter by using it to quantify the environmental and social impacts of complete streets through three case studies. The results were used to evaluate the efficacy of the proposed performance measures regarding the reasonableness of the results and the practicalities and difficulties of using them to provide a recommended final set of indicators. A new part of the framework is the use of social vulnerability information to help inform the process of quantitively assessing the benefits of complete streets. The results and recommendations from the project will be used to further refine the social and environmental LCA framework to provide more useful quantitative decision support information and to make it easier to use. Table 4-102 shows the recommended and not recommended performance measures based on experience from the three case studies.

Table 4-102. Recommended (R) and Not Recommended (NR) Performance Measures Based on Experience from the Three Case Studies

Category	**Performance Measure**	**Data Difficulty (1-5)**	**Methodology / Calculation Difficulty (1-5)**	**Analysis or Interpretation Issue (Yes or No)**	**Comments**	**Recommended (R) or Not Recommended (NR)**
Accessibility	Access to Community Destinations	4	1	No	• Data collection was time-consuming due to number of destinations. • Collecting data before the construction of the complete street for San Fernando St. and Kentucky Ave. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was difficult. • Interpretation of change of access should be for access by complete streets and should consider change of community destinations which may not be related to complete street.	R
	Access to school	5	3	Yes/ Interpretation	• Data collection was very difficult due to dependency on the school principals' responses. Use of the school survey developed for this project is recommended.	R
Jobs	Access to Jobs	4	1	No	• Data collection was time-consuming due to number of jobs. • Collecting data before the construction of the complete street for San Fernando St. and Kentucky Ave. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was difficult. • Interpretation of change of access should be for access by complete streets and should consider estimated change of jobs which may not be related to complete street.	R
	Job Creation	5	3	Yes/ Interpretation	• Collecting data for only the complete street project was very difficult, national model was used. • Collecting data for temporary and permanent jobs and distinguishing them was difficult, national model was used.	NR

Category	**Performance Measure**	**Data Difficulty (1-5)**	**Methodology / Calculation Difficulty (1-5)**	**Analysis or Interpretation Issue (Yes or No)**	**Comments**	**Recommended (R) or Not Recommended (NR)**
Mobility/ Connectivity	Active Transportation to Local and Regional Transit Connectivity Index*	3	1	No	• Collecting data before the construction of the complete street for San Fernando St. and Kentucky Ave. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was difficult.	R
	Connectivity Index	3	1	No	• Collecting data before the construction of the complete street for San Fernando St. and Kentucky Ave. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was difficult.	R
	Bike/Pedestrian Delay	3	1	Yes/ Interpretation	• Collecting data before the construction of the complete street for San Fernando St. and Kentucky Ave. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was difficult. • There is a debate regarding the positive and negative influences of delay on the functionality of the complete street. The goal of the complete street (through travel or destination travel) needs to be identified to interpret results.	R
Safety/ Public Health	Level of Service (Bicycle Level of Service)	5	4	No	• Data collection for a large number of parameters, equations, and methodologies was very tricky. • Collecting data before the construction of the complete street for San Fernando St. and Kentucky Ave. was difficult. • BLOS methodologies were not designed to analyze all types of bike lanes. So, they could not accurately reflect the improvements in bike safety, especially in Franklin Blvd. and Kentucky Ave. case studies. • Consider other types of BLOS calculations in future.	NR
	Level of Service (Pedestrian level of Service)	5	4	No	• Data collection for a large number of parameters, equations, and methodologies was very tricky.	NR

Category	Performance Measure	Data Difficulty (1-5)	Methodology / Calculation Difficulty (1-5)	Analysis or Interpretation Issue (Yes or No)	Comments	Recommended (R) or Not Recommended (NR)
					• Collecting data before the construction of the complete street for San Fernando St. was very difficult. • Consider other types of PLOS calculations in future.	
	Level of Service (Urban level of Service)	5	4	No	• Data collection for a large number of parameters, equations, and methodologies was very tricky. • Collecting data before the construction of the complete street for San Fernando St. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was not doable.	NR
	Level of Service (Transit level of Service)	5	4	No	• Data collection for a large number of parameters, equations, and methodologies was very tricky. • Collecting data before the construction of the complete street for San Fernando St. was not doable and for Kentucky Ave. was difficult. • Collecting data for after the construction of the Franklin Blvd. complete street was difficult.	NR
	Level of Service (Bicycle Level of Stress)	1	1	No	• No problems for this indicator	R
	Crashes	3	3	No	• No problems for this indicator	R
	Physical Activity and Health	5	5	No	• Collecting data considering only the complete street project was not doable.	NR
	Pedestrian Miles Traveled (PMT)	4	3	Yes/ Interpretation	• Collecting data considering only the complete street project was difficult. • There is a debate regarding how PMT should be interpreted because high PMT can imply greater use of active transportation or sparse density of destinations. • The recommendation is to keep PMT and add pedestrian trip numbers.	R
	Bicycle Miles Traveled (BMT)	4	3	Yes/ Interpretation	• Collecting data considering only the complete street project was difficult.	R

Category	Performance Measure	Data Difficulty (1-5)	Methodology / Calculation Difficulty (1-5)	Analysis or Interpretation Issue (Yes or No)	Comments	Recommended (R) or Not Recommended (NR)
					• There is a debate regarding how BMT should be interpreted because high BMT can imply greater use of active transportation or sparse density of destinations. • The recommendation is to keep BMT and add bicycle trip numbers.	
Livability	Green Land Consumption	5	5	No	• Collecting data considering only the complete street project was not doable.	NR
	Street Trees	1	1	No	• No problems for this indicator • Indicator should be improved by considering environmental LCA indicator effects of trees, and additional social indicators such as human thermal comfort.	R

[1: Very easy 2: Easy 3: Moderate 4: Difficult 5: Very difficult]

CHAPTER 5. A STRATEGY FOR INTEGRATING SUSTAINABILITY MEASURES IN THE PLANNING PHASE OF TRANSPORTATION INFRASTRUCTURE IN CALIFORNIA USING LCA METHODOLOGY

This chapter proposes a strategy for integrating sustainability measures in the planning phase of transportation infrastructure in California using LCA methodology (Chapter 5).

The objective of the proposed future study is to develop an up-to-date and representative (regional) LCI database for generic road infrastructure elements in California to quantify their environmental impacts during the planning and initial design phases.

The goal of sustainability principles is to bring key environmental, social, and economic factors into the decision-making process. Transport infrastructure planning and delivery is a long and complex process implemented at different levels. Transportation infrastructure is crucial to the economy and every aspect of our social lives, and environmental impacts during the life cycle stages of transport infrastructure are substantial. The first step for managing the environmental impacts of such a system is to quantify them. While the increased efforts to quantify sustainability effects can be observed in recent years, quantification of the full-system and life cycle quantification following LCA principles in the planning process is in the early stages of development. This chapter aims to identify ideas for when and how considerations of life cycle impacts following LCA principles can be integrated into the transport infrastructure planning process, what decisions should be taken, and which data should be used.

Life Cycle Assessment (LCA) should be conducted to improve the ability to quantify the system, the life cycle effects of decisions, and changes in systems, without the high level of design details which usually are needed in LCA for quantifying the system precisely. The proposed methodology focuses on the conceptual and early design stages in which the choices should be made regarding rehabilitation, reconstruction, retrofit, or repurposing of a road corridor and its basic scope and dimension, and the corresponding choice of road elements. This chapter considers the use of LCA during the planning phase of transport infrastructure at the state-level and local government-level in California to fill the gaps in the quantification of environmental impacts.

5.1. Introduction

5.1.1. Background

Principles of sustainability are being embraced by an increasing number of agencies, companies, organizations, institutes, and governing bodies in conducting business and managing their activities (Harvey et al., 2016). Sustainability principles aim to bring key environmental, social, and economic factors into the decision-making process (Van Dam et al., 2015). Environmental impacts such as greenhouse gas (GHG) emissions, and resource and energy use during the life cycle stages of transport infrastructure are substantial. The increased efforts to quantify sustainability effects can be observed in recent years (Van Dam et al. 2015, and Harvey et al. 2016). Quantification of environmental impacts should be integrated into the planning process for transport infrastructure to become more sustainable (Karlsson et al., 2017).

The United States, with the 4.11 million lane-miles of roads, contains 2.75 million lane-miles of paved roads. Each year, this network supports three trillion vehicle miles, which leads to 70% of the U.S. annual petroleum consumption of more than 213 billion gallons (Bureau of Transportation Statistics website and Davis et al., 2017). Over the next decade, $54 billion is invested in Senate Bill 1 (SB1) legislative package to fix California’s transportation system, which is the Road Repair and Accountability Act of 2017. SB 1 increases funding by an average of $5.4 billion annually for California’s transportation system, split between state and local investments.

These new investments are expected to substantially increase the quantities of materials and construction used for pavement infrastructure in the state. These numbers, which show the huge cost of the network, also depict the importance of the impacts of the transportation network on the environment in terms of material consumption and emissions to air and society, and therefore, the need for quantification of such impacts.

Life Cycle Assessment can provide quantitative information for decision-makers to evaluate the direct and indirect impacts of transportation systems (Chester et al., 2012). LCA is a holistic, recognized, and standardized approach for quantifying all emissions, resource consumption, and related environmental and health impacts which are linked to a service, asset or product (Du, 2015). It is important to explore solutions leading to minimum life cycle environmental impacts (Miliutenko, 2016). Although LCA has a broad application in various industries, its implementation in a planning process is rare and needs more investigation (Van Dam et al., 2015; Harvey et al. 2018; Kim et al., 2022; Du, 2015).

5.2. Main concepts of conceptual design phase of road infrastructure planning

Planning is the process of deciding how a community uses its land and other resources including analyzing the environmental and socioeconomic impacts of development and infrastructure projects. “Planning decisions usually require local political approval and reflect the desires and interests of the community”. The process for making planning decisions is defined by local and state laws (OPR, 2005). Road infrastructure planning is a long-lasting and complex process that is implemented at different levels (Miliutenko, 2016). This chapter focuses on using LCA during the planning phase of transport infrastructure in the U.S. to fill the gaps in quantifying environmental impacts.

LCA can be applicable at different steps of the planning process depending on the decision for the stage of development of the road infrastructure. For instance, a location to build a specific road should be decided in the early planning stage, while a type of road or material alternative, as well as design alternative, should be selected in the later planning stages (Butt et al., 2015) (Figure 5-1). Early stages of planning have the greatest opportunity to reduce GHG emissions in the lifetime of infrastructure projects (Miliutenko, 2016). In addition, early planning has the highest effect on impacts since the major scoping decisions are made at this stage. It should be noted that very few new roads are built in the U.S. and especially in California. Some money is spent on widening to add new lanes, however, the vast majority is on preservation and maintenance, and rehabilitation and reconstruction, which do require planning.

Network Level	**Objectives, Targets, Prioritizing between projects**	**Policies, Guidelines, Standards, Identifying issues to be generally considered**
Project Level	**Identifying options, Screening evaluation**	**Optimizing design, Selection of materials**
Decision Level **Decision Stage**	**Early Planning Stage**	**Late Planning/ Design Stage**

Figure 5-1. Decision situations that call for a life cycle perspective. (Butt et al., 2015)

5.2.1. Planning in Europe

In Europe, the level of planning is from national to local, and each country has its own specific process with different names for each stage that are not always comparable. The three main levels of decisions distinguished by four European countries (i.e., Sweden, Norway, Denmark, and the Netherlands) include: 1) choice of transport modality at the national level, 2) choice of road corridor and construction type of a specific project, and 3) choice of specific construction design as shown in Figure 5-2 (Miliutenko et al., 2014, Miliutenko, 2016)

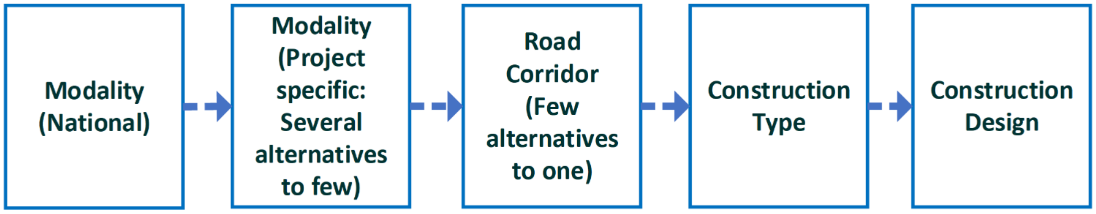


Figure 5-2. Figure 3. Choice of specific construction design (Miliutenko, 2016)

The main concepts of road infrastructure planning in the US, and environmental studies in the planning phase are considered in this chapter. European countries (i.e., Sweden, Norway, Denmark, and the Netherlands) have a few studies which have integrated the life cycle assessment into the planning phase, while in the U.S., no study shows this combination (Miliutenko et al., 2012, Miliutenko, 2016, and Karlsson et al., 2017). In the U.S., there are several documents that show the processes of infrastructure planning considering environmental issues but without conducting LCA.

5.2.2. Planning in the US

To review the planning processes of transport infrastructure, the current study focuses on the state level and local government levels in California. Planning processes have been developed by state and local organizations in California. Project Development Procedure Manual (PDPM, 2017), General Plan Guideline (GPG, 2017), Governor’s Office of Planning and Research (OPR, 2005), and California Environment Quality Act (CEQA, 2018) are the main references reviewed in this study. “California Environmental Quality Act (CEQA) is a statute that requires state and local agencies to identify the significant environmental impacts of their actions and to avoid or mitigate those impacts, if feasible." It passed in 1970 after the National Environmental Policy Act (NEPA) was passed by the federal government of the U.S. CEQA requires local and state governments to consider a project's potential for environmental effects before a project decision-making process. (GPG, 2017, CEQA, 2018, and Caltrans, 2018) A software program called the Infrastructure Carbon Estimator (ICE) developed by the Federal Highway Administration (FHWA) is being used at the state level for identifying environmental impacts by many states. ICE uses national averages and information.

Regarding the Caltrans Project Development Procedures Manual (PDPM, 2018), the type or mode of facility proposed to meet transportation needs is defined in the planning concept (e.g., highway, transit, rail, or combination). The issues such as the number of lanes, location, and length of a project, high-occupancy vehicle lanes, general interchange, and intersection spacing are addressed in the planning scope for highway facilities. Working on a partnership basis with local land use authorities to accomplish early identification of transportation corridors and rehabilitation and reconstruction of those corridors is part of Caltrans policies. (PDPM, 2018)

5.2.2.1. Environmental studies and tools in the conceptual design planning phase

5.2.2.1.a. State-level

In California, the California Department of Transportation (Caltrans) system planning process is implemented with input from other local, regional and sub-regional plans. Caltrans system planning documents are affected by changes in local plans and policies (PDPM, 2018). In both the system planning and the project initiation stages, the preliminary environmental evaluation is performed which identifies environmental issues and anticipated adverse effects. The project scoping stage is the phase in the Project Initiation Document (PID), which is the first formal step for a specific transportation problem to develop a solution. The PID is an engineering or technical document including the conceptual scope, cost, and schedule for transportation projects (PDPM, 2018).

The Infrastructure Carbon Estimator (ICE) is a spreadsheet tool that was developed by the FHWA to estimate the life cycle energy and greenhouse gas emissions from the construction and maintenance of transportation facilities. ICE needs limited data inputs to inform planning and pre-engineering analysis. (ICE Manual, 2014)

ICE uses a nationwide database of construction bid documents from DOTs, and consultation with transportation engineers and LCA experts. The goal of ICE is to estimate the total energy and emission impact of current regional transportation system maintenance, determine possible alternative plans or projects that would result in fewer construction emissions, and distinguish the most effective strategies for reducing energy use and greenhouse gas emissions. ICE does not consider detailed data derived from engineering documents and construction plans. So, it leads ICE to be used in conjunction with transportation planning processes. ICE is not a suitable tool to inform engineering analysis and pavement selection.

Several shortcomings and challenges with which ICE is faced include limited research data sources from a small sample of projects, outdated research data that are decades old, and data without more recent changes in construction methods, materials, and equipment which are the basis of existing estimation methods (ICE presentation, 2018, and ICE Manual, 2014).

ICE uses state-specific data just for a few of its purposes, and mostly uses nationwide datasets. Another gap in ICE is the lack of considering the “end-of-life” (EOL) phase. Energy use and greenhouse gas emissions are the only two impacts that ICE considers while it does not consider other environmental impacts such as air pollution. ICE allows consideration of multiple GHG reduction strategies in infrastructure that are incompatible with each other and cannot be used simultaneously in reality, resulting in unrealistic mitigation. Single "average" values for different types of the same materials for different purposes, which can have significantly different impacts, is another ICE deficiency.

5.2.2.1.b. Local- level

The state Office of Planning and Research (OPR) is responsible for providing general plan guidelines. The California Environmental Quality Act (CEQA) needs local and state governments to meet its requirements when preparing the general plan. Most local governments and jurisdictions have selected to have a General Plan every 20 years. (OPR, 2005).

The general plan is a blueprint of a community for future development, which describes development goals and policies of a community. A general plan is also "the foundation for land use decisions made by the planning commission, city council, or board of supervisors" (OPR, 2005).

CalEEMod (California Emission Estimator Model) and SB 375 are part of the planning processes. CalEEMod, which is released by the California Air Pollution Control Officers Association (CAPCOA) in collaboration with the California Air Districts, is a model that provides a uniform platform to quantify direct emissions from construction and operation activities, as well as indirect GHG emissions from energy use, water use, and solid waste disposal to use at this step for estimating environmental impacts.

SB 375, or the "Sustainable Communities and Climate Protection Act" of 2008, which is a California law targeting GHG emissions from passenger vehicles, is led by planners. Using the regional transportation planning process to reach GHG emission reductions, as one of the significant components of SB 375, gives California Environmental Quality Act (CEQA) authority to encourage projects consistent with a regional plan in achieving GHG reductions. It also gives uthority to organize the regional housing requiring allocation process with the regional transportation process. (ILG, 2018).

5.3. Identifying strategies for using LCA at the conceptual design stage and early design stage of road improvement, and Future Needs

This section’s objective is to propose and investigate the applicability of LCA in transport infrastructure during the planning phase. In the current study, the conceptual design stage and early design stage, which are part of the planning process and design process of transport infrastructure, are defined, respectively.

The “conceptual design stage” is defined as an early stage of the transport infrastructure planning phase when an initial project estimate is developed based on the historical costs of similar projects. The information in the conceptual design stage and during the preparation of the initial plan is required to decide if, how, and when to fund a particular project. Individual projects are often part of much larger plans for transportation corridors at the state level and often part of general plans for land use requiring transportation improvements at the local level. The applicability of LCA or similar methodologies in quantifying the environmental impacts in the conceptual design stage should depend on the availability of sufficient data and information.

At the “early design stage” in which alternatives within the selected funded project should be considered chosen, fewer details compared to the later design stage and more details compared to the conceptual design stage should be considered (e.g., offering a range instead of a single average value for the dimension of chosen roads or instead of one assumed mix design for all concrete structures such as bridges, pavement, culverts, and minor concrete). Using LCA improves the ability to quantify the full-system life cycle effects of decisions and system changes.

Generic alternative designs for transport infrastructure should be defined, followed by developing their life cycle inventory (LCI) data. A library of typical designs for different functionalities (e.g., vehicle-only high speed for different levels of freight, other types of roads, roads that are for both active transportation and vehicles) would be based on past designs and incorporate current typical structures with current typical materials and construction. Next, an up-to-date and representative (regional) LCI database should be developed for those elements for which data inventories do not yet exist in California.

Then, a representative LCA model should be developed that addresses the transport infrastructure’s environmental sustainability aspect and helps practitioners make informative decisions during the applicable stage. It should be mentioned that sensitivity analysis (e.g., variance around the estimate) is very important due to the lack of details and potential errors in quantities. Environmental impacts of road transport infrastructure as well as traffic change impacts (separately and together) should be considered. The traffic data should be used as input for this study, and the traffic behavior should be out of the scope of this study. In other words, the proposed approach should take traffic projections from traffic planning processes, and they should not be developed separately for the conceptual stage LCA. However, their impacts on the approach can be calculated explicitly using well-to-wheel instead of pump-to-wheel approaches often used in planning processes.

The conceptual design stage gives practitioners a general idea for a rough estimation at the level of 10% design development while the early design stage covers more details (30% design completion). Reconstruction, retrofit, rehabilitation, and repurposing of existing infrastructure should be investigated in addition to the corresponding choice of road elements (e.g., changes or addition or removal of pavement, bridges, rails, drainage and culverts). In these early stages, generic alternative designs should be developed for each infrastructure type (e.g., roads, bridges, rails, and culverts) for different contexts. The early design stage covers more inventories to cover a wider range of cases identified by project details available in the early design stage compared to the conceptual design stage.

5.3.1. State- level planning process

Project development starts with project planning that identifies project purposes and underlying needs. Projects from the planning documents are selected for further feasibility studies to be conducted by Project Development Teams (PDTs), the steering committee for the project, to develop the Project Initiation Document (PID). The PID describes the key issues and assumptions on the scope, schedule, and estimated cost of the project that is to be used as a candidate for programming. Project programming is the process in which specific funds, State Transportation Improvement Program (STIP) or State Highway Operation and Protection Program (SHOPP), for a project are specified. Once a project is programmed, value analysis is conducted to identify all reasonable and feasible alternatives to minimize costs impacts while maximizing public benefits. A Draft Project Report (DPR), which presents project’s ultimate scope, schedule, and cost studies, should be prepared. The approved DED and DPR are circulated for public comment. The PDT selects the preferred alternative that appropriately responds to the public comments (Caltrans, 2017; and Caltrans, 2018).

Preparation of Plans, Specifications, and Estimate (PS&E) begins after the DPR and DED are approved, during which project information is reviewed and the scope of the selected alternative is refined. A complete set of project plans that allow a competent contractor to bid and build the project is prepared at the PS&E stage. Acquisition of right-of-way and obtaining approvals and permits from other agencies usually occur after project approval. The final project design incorporates comments from a District-wide engineering, safety, and environmental review. Plans, specifications, and estimates are finalized, and then the finalized PS&E bid package and bidding instructions are advertised to potential contractors. The bid proposal, which meets the project's requirements, is selected. The construction phase of the project begins after the contracts are in place. The project is complete after the final contract estimate, as-built plans are completed, claims are resolved, and mitigation is addressed (Caltrans, 2017; and Caltrans, 2018).

During the planning process proposed by Caltrans, the step considered in the conceptual design stage of infrastructure planning is the project scoping (Figure 5-3). The preliminary environmental evaluation is performed at this step, which is the first formal step for a specific transportation problem to develop a solution. Therefore, project scoping is the step of the planning process that has the potential for applying LCA. Caltrans administratively requires a PID to be completed before a project can be programmed for funding in the SHOPP. After a project is programmed, a more refined estimate should be completed based on selected project scopes and designs (early design stage) (PID presentation, 2012; Caltrans, 2017; and Caltrans, 2018).

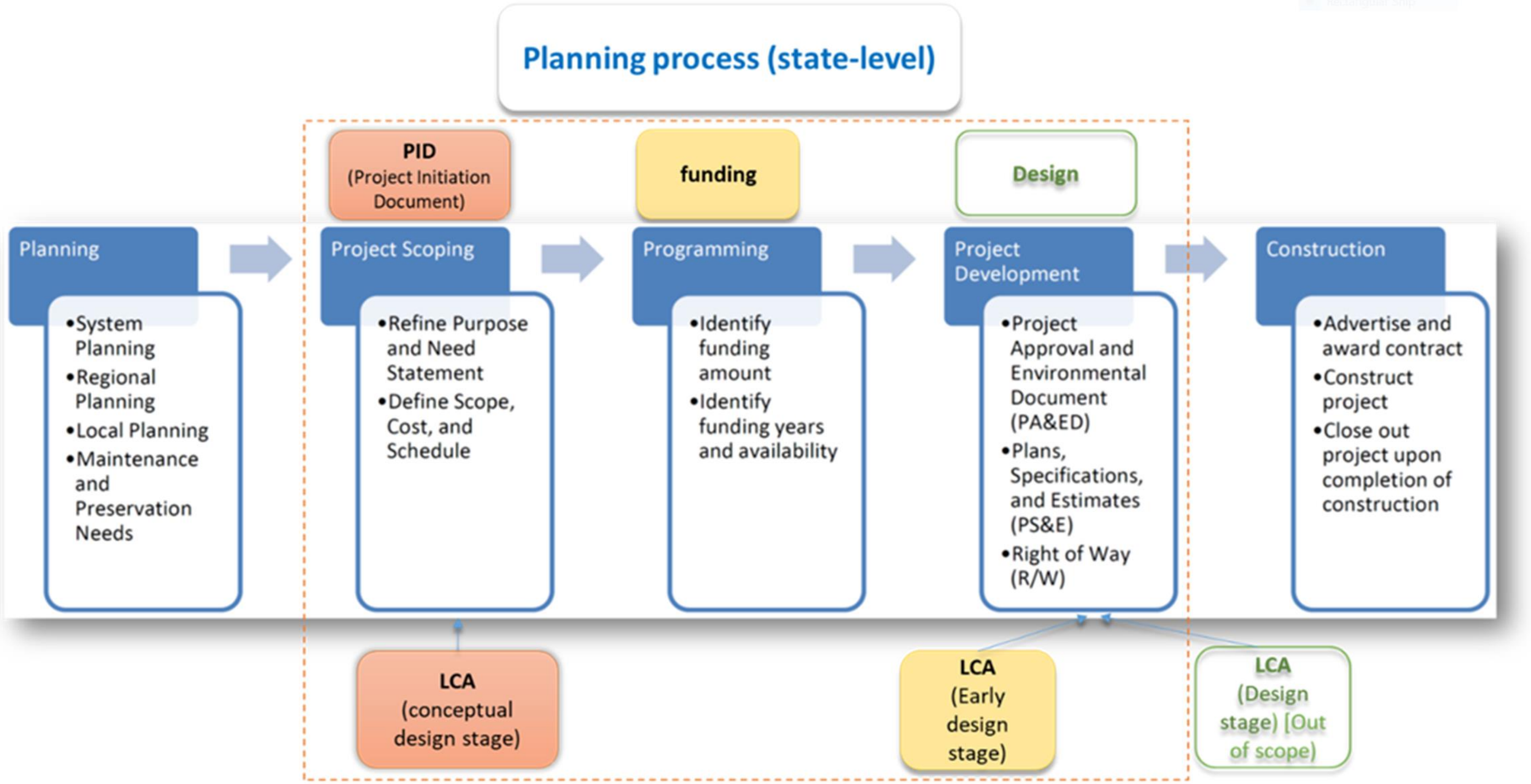


Figure 5-3. Proposed Planning Process (State-level) (Caltrans, 2018)

5.3.2. Local-level planning process

According to the general plan, during the local government-level infrastructure planning process, land use is considered in relevance to transportation infrastructure (Figure 5-4). Then, land-use alternatives are developed, and preferred alternatives are selected. The general plan also identifies all Capital Improvement Plan (CIP) led by transportation engineers. LCA is conducted to evaluate CIP projects since policymakers are usually not provided the detailed and quantified environmental impacts in terms of transportation infrastructure of their land use decisions at this stage. Therefore, conducting LCA for transportation infrastructure planning when land use plans are handed off to the transportation engineers is proposed to improve information at this conceptual design stage.

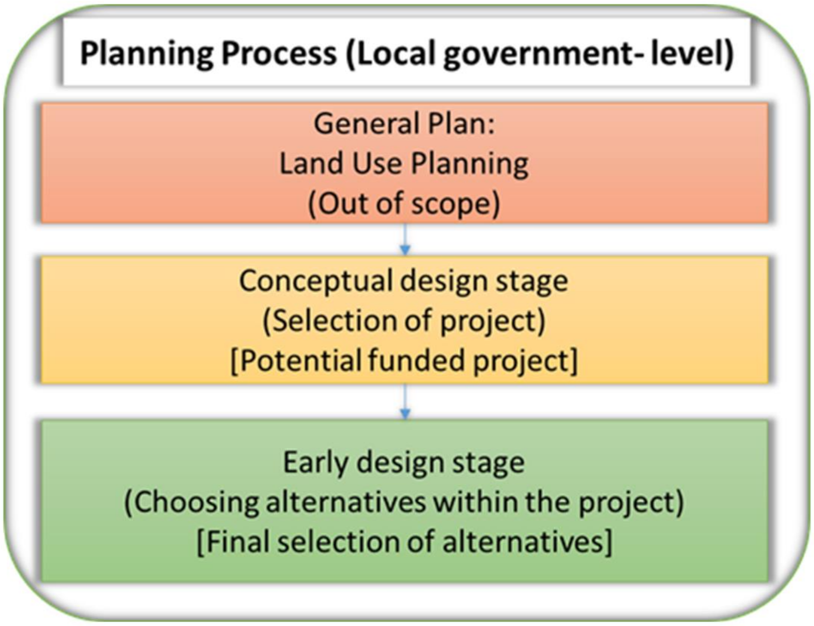


Figure 5-4. Proposed Planning Process (Local agency- level)

According to local government infrastructure planning, projects that consider possible alternatives between a pool of projects should be selected. The potential funded project should be investigated at this step, followed by selecting appropriate alternatives within the nominated project conducting LCA (early design stage). The choice of new roads, extra lanes, and bike routes are examples of project selection.

5.3.3. Example of considering Conceptual design stage and early design stage

The conceptual design stage gives practitioners has approximately 10% of the design details completed, while the early design stage has approximately 30% of the design details completed. Reconstruction, retrofit, rehabilitation, and repurposing of existing in-frastructure will be investigated in addition to the corresponding choice of road elements (e.g., changes or addition or removal of pavement, bridges, rails, drainage and culverts). In these proposed stages, generic alternative designs will be developed for each infrastructure type (e.g., roads, bridges, rails, and culverts) for different contexts. The early design stage covers more inventories to cover a wider range of cases identified by project details availa-ble in the early design stage compared to the conceptual design stage.

For instance, in California, deciding on bridge designs (e.g., steel vs. concrete structure) and bridge type (e.g., concrete box girder, steel box girder, concrete I girder, steel I girder, etc.), and the main sources of the used material (e.g., concrete, steel, etc.) will be considered in the conceptual design stage. Then, those three to four main material sources, and an approximately 80%-90% complete estimate of material quantities will be considered, and the remaining 10-20% of materials will be calculated based on them. Next, initial design of major bridge elements is done (e.g., girder, column, foundation, etc.). In the early design stage, a range of the most im-portant elements used in the considered bridge types will be collected as generic data. Generic data examples include data collection for a range of span length, a range of grid depth, and a range of deck width. “Caltrans comparative bridge costs” (Caltrans 2019), “Caltrans construction statistics” (Caltrans 2021), “Caltrans bridge design aids” (Caltrans 2005; Caltrans 2012), and “Caltrans structures design general plan sheet” (Caltrans 2010) are some of the references that can be used for California generic data collection for bridges.

All bridge materials are subject to EPDs (environmental production declaration), and EPD is potentially the source of some local inventories. It should be noted that an EPD is a transparent, objective report communicating what a product is made of and how it impacts the environment across the cradle-to-gate portion of the full life cycle in current practice (ISO 2006c).

5.4. Summary and Future Needs

5.4.1. LCI database and LCA model for transport infrastructure

The approaches for implementing LCA in the conceptual design stage and early design stage of planning include identifying questions to achieve environmental goals, defining system boundaries, functional unit and required approaches for sensitivity analysis, identifying input of the system and how they change the system, and identifying appropriate environmental LCI data and life cycle impact assessment, using appropriate typical designs (generic design). The elements for which data inventories do not yet exist include bridges, drainage, and culverts.

Literature reviews, surveying of the local contractors, local government, and Caltrans’ data and interviews, databases such as GaBi, ecoinvent, observations, and questionnaires should be used to collect the data. UCPRC LCI, which is a comprehensive pavement dataset developed and calibrated for California, and the same inventories in eLCAP should be used, and additional data should be developed in later versions of the eLCAP. A representative (regional) LCI database for those elements for which data inventories do not yet exist (e.g., bridges, drainage, and culverts) should also be developed in California.

The next steps of the proposed study should develop generic alternative designs for each infrastructure type, such as roads, bridges, rails, and culverts for different contexts. This step should be started with an early design level of detail, and inventories for that level of detail should be found. At the conceptual design stage, the numbers of each type used to arrive at a less detailed typical inventory weighted by how many of the more detailed types used in the past should be weighted. Then, appropriate data should be used to estimate the impacts of those generic design alternatives. At this step, the data sources used for modeling each item should be selected and conducted by comparing the available options. Next, several case studies can be considered to get feedback from those involved in the conceptual and early design phases at California's state and local levels.

This chapter aimed to give a brief background and literature survey to identify past efforts on this topic, including the main concepts of road infrastructure planning in Europe and the U.S., focusing on the state and local level in California. It also reviewed environmental studies in the planning phase. Then, it proposed the planning process and strategies for using LCA at the conceptual design phase and early design stage of road improvement, followed by proposing the generic data consideration in each of the proposed stages. Several case studies should be considered to apply the proposed strategies and get feedback from those involved in the conceptual and early design phases at California's state and local levels. The life cycle impact assessment calculations should be reanalyzed based on interviews with the planners to address the gaps, update the proposed process, and review its practicality.

CHAPTER 6. SUMMARY AND RECOMMENDED FUTURE WORK

This dissertation focused on the development of up-to-date and representative frameworks, models, and databases for transportation infrastructure in California to quantify the environmental and socioeconomic impacts needed to support data-driven and integrated decision-making.

This study was proposed to ponder the environmental impacts of management decisions according to the life cycle of the transportation infrastructure. It includes the development of a Social LCA framework for complete streets as a transport infrastructure considering appropriate socio-economic performance measures and relevant and reliable data sources. Several case studies were conducted to test the framework by using it to quantify the environmental and socio-economic impacts of those case studies and compare them with leaving the street in its vehicle-centric configuration. This dissertation also proposed a strategy for integrating sustainability measures in the early stage of the planning phase of transportation infrastructure in California to fill the currently existing gaps in practice.

6.1. Knowledge Gaps, Research Objectives, and Contributions to the Knowledge

6.1.1. Knowledge Gaps

Transport infrastructure and roadways provide positive and negative impacts on public health and safety, mobility, and livability.

- Even though transport and road infrastructure have significant social impacts, evaluating and quantifying these aspects of transport infrastructure in still in its infancy.
- Environmental LCA quantifies the energy, resource use, and emissions to air, water, and land for a product or a system. A reliable and representative LCI database to quantify the

environmental consequences of decisions in transportation infrastructure is always a gap and always needs to be updated.

One of the main approaches to complete streets (CS), as a design concept for streets and intersections, was to reach social and environmental benefits.

- The quantitative analysis of the potential benefits is lacking in the CS concept.
- LCA is an appropriate tool to quantify the analysis, and Social LCA quantifies the social and sociological aspects related to a system. However, a gap in transport infrastructure LCA impact indicators is a shortage of socio-economic performance measures to complement the existing environmental indicators.
- There was no established framework, models, and database for quantifying the social impacts and environmental impacts of complete street measures and comparing them with conventional design methods to allow quantification of the efficacy of complete streets in meeting the sustainability of urban streets.

The early stages of planning and conceptual design present the most significant opportunity to reduce GHG emissions in the lifetime of infrastructure projects. The early stage of planning has also the highest effect on impacts since the major scoping decisions are made at this stage.

- There was currently no available methodology for the integration of sustainability measures in the earliest stages of a development project (planning and conceptual phases) to optimize transportation infrastructure management.
- There were few studies considering LCA in the planning phase, and there is still a shortage of work regarding the appropriate use of LCA in the conceptual design and early stage of the planning phase in transport infrastructure projects at the state-level and local-government-level in the U.S, and California.

6.1.2. Research Objectives

Therefore, according to the gaps identified above, the main objectives of this dissertation were defined to develop frameworks, models, and datasets needed to fill each gap.

6.1.3. Summary of Contributions to Knowledge

The contributions to the knowledge completed by the work described in this thesis were:

- An up-to-date and representative (regional) LCI database was developed for transportation infrastructure in California for quantification of their environmental impacts, by filling gaps in current LCIs for crude oil and asphalt binder, warm mix asphalt additives, and bonded concrete overlay on asphalt, and considering case studies to evaluate the environmental life cycle impact for them.
- A Social LCA framework was developed for complete streets as a transport infrastructure considering appropriate socio-economic performance measures and relevant and reliable data sources.
- Several case studies were conducted to test the framework by using it to quantify the environmental and socio-economic impacts of those case studies and compare them with leaving the street in its vehicle-centric configuration.
- A strategy was proposed for integrating sustainability measures in the planning and conceptual design phases of transportation infrastructure in California to fill the currently existing gaps in practice.
- Identifying a framework for an up-to-date and representative (regional) LCI database for generic road infrastructure elements in California was recommended to quantify the environmental impacts during the planning and initial design phases

The following sections summarize the work done, and recommendations for future work.

6.2. Life Cycle Inventory Database and Life Cycle Assessment Model in Transportation Infrastructure Management in California

6.2.1. Summary

Environmental LCA quantifies the energy, resource use, and emissions to air, water, and land for a product or a system. A reliable LCI database to quantify the environmental consequences of decisions in transportation infrastructure is always a gap and always needs to be updated.

The main goal of this chapter was to develop an up-to-date and representative (regional) LCI database for transportation infrastructure to quantify their environmental impacts and an appropriate LCA model in transportation infrastructure management in California for those elements for which data inventories do not yet exist. Literature reviews, surveying of the local contractors, local government, and Caltrans' data and interviews, databases such as GaBi and ecoinvent, and observations were used to collect the data. UCPRC LCI, which is a comprehensive pavement dataset developed and calibrated for California, was also used, including a comprehensive list of materials, sources of energy, transport modes, and pavement surface treatments. The three developed LCIs and the three case studies that are covered in this dissertation study, were:

1. Asphalt binder,
2. Warm mix asphalt technologies and
3. Bonded concrete overlay of asphalt (BCOA).

6.2.2. Recommendations for Future Work

The LCI database and models needs to be reviewed and updated continually due to the continuous improvements in material production technologies, construction practices, and energy sources used for electricity generation, running plants, and data collection improvement, and new materials and elements for which data inventories do not yet exist in California such as roads, bridges, rails, and culverts. An important factor helps improve the quality of the data is to collect primary data instead of secondary data from local material production plants and contractors.

6.3. Complete Streets, Socio-Economic Performance Measures, and Social Life Cycle Assessment Framework

6.3.1. Summary

Life cycle assessment is a holistic approach to quantifying the environmental sustainability of a product, project, process, or system, and has increasingly been used to assess the environmental sustainability of the built environment. Environmental LCAs quantify the energy, resource use, and emissions to air, water and land for a product or a system. LCA takes a systems approach, with system boundaries depending on the goal of the assessment study, and applies it over the life cycle to account for long-term impacts rather than only initial outcomes. One gap identified in current LCA impact indicators is the lack of socio-economic indicators to complement the existing environmental indicators. To address the gaps in performance metrics, this dissertation developed a framework for LCA of complete streets projects, including the development of socio-economic impact indicators that also consider equity. A "consequential" approach was used where the physical, economic and social processes that go into a system are modeled, and changes in the behavior of the system were quantified.

The results of this study used available information regarding social goals and performance metrics, and reviewed them for applicability to goals that were identified from discussions with stakeholders, redundancy, and expected difficulty of data collection.

The tasks completed in this chapter and results of the research project include:

- Review of the literature for background on complete streets, complete streets guidelines and LCA of complete streets
    - The literature showed no previous application of Social LCA to evaluate complete streets projects
- Considering social indicators and equity
- Current processes did not address social impact performance well
- There were no commonly used indicators for social impacts
- Focus on the neighborhood as a scaling unit
- Focus on neighborhood needed that could be helped by a complete street was an approach that help improve the equity of social impacts as opposed to the complete street itself being the focus
- Adaption of social and economic indicators and performance measures
    - Different systems of social impact indicators and performance measures were compared, and a set was identified covering the categories in the different systems, and more importantly addressing many of the concerns identified from the data collection
    - An approach for evaluating how the indicators and measures could be considered for equity of comparison was developed
    - The approach was applied to the initial set of indicators and measures, and used to remove some and change others

6.3.2. Recommendations for Future Work

The next step in this research and development arc is to test the full framework by using it to quantify environmental and social impacts of complete streets case studies and comparing them with leaving the street in its vehicle centric configuration. Case study evaluation should be based on project design for those that have not yet been constructed or completed. Where case study projects have been completed, projects should be evaluated based on performance before and after project completion. Case studies should be solicited in different parts of the U.S. with different neighbourhoods, including urban and rural locations, and in more and less advantaged neighborhoods so that the equity aspects of the framework can also be evaluated. More performance measures can be defined according to those specific states and neighbourhoods.

6.4. Case Studies to Demonstrate the Use of Social LCA and Environmental LCA for Complete Streets

6.4.1. Summary

The social and economic performance indicators included in the social LCA framework that was used in this study provided insight into specific and different potential benefits of a given complete streets project. The SLCA framework was based on five categories of concerns and 17 performance measures or indicators. They span the range of benefits typically expressed as being desirable for a neighborhood and potentially coming from a complete street. The main challenges in this social LCA study were data collection and the inherent context-specific and qualitative nature of social aspects of each complete street project. The evaluations of performance measures have been interpreted and discussed for each case study separately. The results summary of all the performance measures quantified for the three case studies was presented. This chapter includes evaluation of all indicators for difficulty of data collection, difficulty of calculation, difficulty of interpretation, and ability to consider change in performance as part of complete streets evaluation.

6.4.2. Recommendations for Future Work

As was the case for the initial evaluation of the Complete Streets LCA Framework developed by Harvey et al., 2018, the environmental impacts coming from the materials, materials transportation, and construction phases of building or reconstructing a conventional versus a complete street are very small. The coming of new LCA tools to easily calculate environmental impacts for materials, transportation, and construction will make the evaluation of design alternatives to reduce environmental impacts relatively easy. The primary environmental impacts come from the use stage. Any changes in vehicle travel (vehicle miles traveled, VMT) will have a relatively large impact on environmental impacts as long as the vehicle fleet remains primarily dependent on internal combustion engines. The effects of reduction in vehicle speeds from complete street design features are somewhat more complex than they appear in the analysis in this chapter. Reductions in speed at speeds below 45 miles per hour may increase fuel use and emissions for longer blocks. This is an area that needs more detailed drive cycle study.

Furthermore, the framework developed in chapter 3 did not include a method for considering environmental justice concerns in minority and low-income neighborhoods. In chapter 4, the framework was expanded focusing the CalEnviroScreen tool from the California Environmental Protection Agency to assess the exposure of neighborhoods and their vulnerability to environmental impacts in conjunction with the performance indicators. Other tools like CalEnvironScreen can be used with the framework.

6.5. Planning Phase of Transportation Infrastructure in California Using LCA Methodology and Recommended Future Work

6.5.1. Summary

There was a lack of a framework for the appropriate use of LCA in the planning phase of a transport infrastructure project in the U.S., and a challenge to find a transparent and open database that can be used freely in LCA studies for the planning phase of transport infrastructure. Regarding the importance of LCA in the planning phase of transport infrastructure, the United States needs to start developing procedures and routines on whether and where LCA is appropriate and how to conduct LCA in transport infrastructure planning. This chapter's objective was to propose a strategy for integrating sustainability measures in the planning phase of transportation infrastructure in California using LCA methodology. This chapter also discussed the importance of future studies for developing an up-to-date and representative (regional) LCI database for generic road infrastructure elements in California to quantify their environmental impacts during the planning and initial design phase.

This chapter covered a brief background and literature survey to identify past efforts on the main concepts of road infrastructure planning in Europe, and in the US (focused on national, state-level, and local-level in California). It reviewed environmental studies in the planning phase, followed by defining the planning process and strategies for using LCA at the conceptual design phase and early design stage of road improvement. The conceptual design stage and the early design stage were defined as part of the planning and design process of transportation infrastructure. The conceptual design stage gives practitioners a general idea of the design details, while the early design stage, which are both proposed in the current proposal, covers more details. The early design stage covers more inventories compared to the conceptual design stage.

To review the planning processes of transportation infrastructure, the current proposed method focused on the state and local government levels in California. According to this proposed methodology, generic alternative designs for transport infrastructure should be defined, followed by developing their life cycle inventory data.

6.5.2. Recommendations for Future Work

An up-to-date and representative (regional) LCI database should be developed for those elements for which data inventories do not yet exist in California such as roads, bridges, rails, and culverts. A representative LCA model should then be developed that addresses the transport infrastructure's environmental sustainability aspect and helps practitioners make informative decisions during the applicable stage. Environmental impacts of road transport infrastructure and traffic change impacts (separately and together) should be considered.

REFERENCES

AARP (2019). Examples of complete streets Policies and Guides. https://www.aarp.org/content/dam/aarp/livable-communities/old-learn/transportation/complete-streets-policies-examples-aarp.pdf, accessed: Dec. 29, 2019.

Abella, J.P., K Motazedi, J Guo, and J.A. Bergerson (2016). Petroleum Refinery Life Cycle Inventory Model (PRELIM). PRELIM v1.1, User guide and technical documentation. https://www.ucalgary.ca/lcaost/files/lcaost/prelim-v1-1-documentation.pdf, Accessed: Sep. 2019.

ACT LA (2018). Transit Justice. http://allianceforcommunitytransit.org/transit-justice/, accessed May 30, 2018.

Aczel, M.R. and Makuch, K.E (2017). Environmental Impact Assessments and Hydraulic Fracturing: Lessons from Two U.S. States, *Centre for Environmental Policy, Imperial College London*.

Alexander, C. Neis, H., Anninou, H., and King, I. (1987). A new theory of urban design. *The Center for Environmental Structure*, Oxford University Press, Nov. 19, 1987.

Andrews, E. S., Barthel, L. P., Tabea, B., Benoît, C., Ciroth, A., Cucuzzella, C., GENSCH, C., Hébert, J., Lesage, P., Manhart, A., and Mazeau, P. (2009) UNEP Guideline for Social Life Cycle Assessment of Products. *United Nations Environment Programme (UNEP)*, 2009. http://www.unep.fr/shared/publications/pdf/dtix1164xpa-guidelines_slca.pdf.

Appleyard, D. (1980). Livable streets: protected neighborhoods? *The ANNALS of the American Academy of Political and Social Science*, 1980, Vol. 451(1), pp. 106-117.

Arcese, G., Lucchetti, M. C., Massa, I., and Valente., C. (2018). State of the art in S-LCA: Integrating literature review and automatic text analysis. *The International Journal of Life Cycle Assessment*, Vol. 23, No. 3, pp. 294-405, 2018. https://doi.org/10.1007/s11367-016-1082-0

Arcese, G., Lucchetti, M. C., Massa, I., and Valente., C. (2018). State of the art in S-LCA: Integrating literature review and automatic text analysis. *The International Journal of Life Cycle Assessment*, Vol. 23, No. 3, pp. 294-405, 2018. https://doi.org/10.1007/s11367-016-1082-0

Astec Industriees, Inc. (2017). Astec Double Barrel Green®, Green Pac™ for Continuous, and Green Pac™ for Batch, Technical Reference for NYSDOT, Accessed Jul. 20, 2020, https://www.dot.ny.gov/divisions/engineering/technical-services/technical-services-repository/details/astec.pdf

Athena Institute, (2005). Road Rehabilitation Energy Reduction Guide for Canadian Road Builders, in collaboration with Canadian Construction Association, Natural Resources, Canada.

Bare, J. C. Feb. (2008). Traci: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology*, https://doi.org/10.1162/108819802766269539.

Benoit Norris, C., Traverso, M., Tabea, B., Valdivia, S., Vickery-Niederman, G., Franze, J., Azuero, L., Ciroth, A., Mazijin, B., and Aulisio, D. (2013) The Methodological Sheets for Sub-Categories in Social Life Cycle Assessment (S-LCA). *United Nations Environment Programme (UNEP)*.

Benoit, C., Norris, G. A., Traverso, M., Tabea, B., Valdivia, S., Vickery-Niederman, G., Franze, J., Azuero, L., Ciroth, A., Mazijin, B., and Aulisio, D. (2013) The Methodological Sheets for Sub-Categories in Social Life Cycle Assessment (S-LCA). *United Nations Environment Programme (UNEP)*. https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf.

Benoit, C., Norris, G. A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., and Beck., T. (2010) The guidelines for social life cycle assessment of products: Just in time! *The International Journal of Life Cycle Assessment*, Vol. 15, No. 2, pp. 156–163.

Benoit, C., Norris, G. A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., and Beck., T. (2010) The guidelines for social life cycle assessment of products: Just in time! *The International Journal of Life Cycle Assessment*, Vol. 15, No. 2, pp. 156–163, 2010, https://link.springer.com/content/pdf/10.1007/s11367-009-0147-8.pdf, accessed Jan. 2020.

Brancaccio, D., Conlon, R. Talent Retention as a Community Development Strategy for Low-Income Neighborhoods. https://www.abundantcommunity.com/talent-retention-as-a-community-development-strategy-for-low-income-neighborhoods/ , accessed 8 June 2022

Bureau of Transportation Statistics website. (2017). available at: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_06.html, accessed: Nov. 7, 2017.

Bureau of Transportation Statistics website. (2021). available at: https://www.bls.gov/iag/tgs/iag23.html, accessed Mar. 2021.

Butt, A. A., Harvey, J. T., Reger, D., Saboori, A., Ostovar, M., and Bejarano, M. (2019). Life Cycle Assessment of Airfield Pavements and Other Airside Features: Framework, Guidelines, and Case Studies Research Report, *Federal Aviation Administration, Performing Organization Report No*.: DOT/FAA/TC-19/2.

Butt, A. A., Harvey, J.T., Saboori, A., Ostovar, M., Bejarano, M., and Garg, N. (2021). Decision Support in Selecting Airfield Pavement Design Alternatives Using Life Cycle Assessment: Case Study of Nashville Airport, *Journal of Sustainability,* Vol. 13, Iss. 1, Multidisciplinary Digital Publishing Institute.

Butt, A. A., Harvey, J.T., Saboori, A., Ostovar, M., Garg, N. (2019). Airfield Life Cycle Assessment: Benchmark Study of a Project at JFK International Airport. *Airfield and Highway Pavements 2019: Innovation and Sustainability in Highway and Airfield Pavement Technology*, ASCE, P 456-464, 2019. https://ascelibrary.org/doi/10.1061/9780784482476.045, accessed Feb. 2020.

Butt, A.A., Harvey, J.T., Reger, D., Saboori, A., Ostovar, M., and Bejarano, M. Feb. (2019). Life-Cycle Assessment of Airfield Pavements and Other Airside Features: Framework, Guidelines and Case Studies. Research Report, *Federal Aviation Administration*, Performing Organization No.: DOT/FAA/TC-19/2.

Butt, A.A., Harvey, J.T., Saboori, A., Ostovar, M., and Reger, D. (2019). Airfield Life Cycle Assessment: Benchmark Study of a Project at JFK International Airport. Airfield and Highway Pavements 2019: Innovation and Sustainability in Highway and Airfield Pavement Technology, *ASCE*, P 456-464.

Cal State University (2012) Capital Planning, Design and Construction, Section V - Measurement Devices for Campus Physical Planning, Sections 9045 – 9050, *California State University*, Jan. 2012, https://www.calstate.edu/cpdc/suam/SUAM9045-9050.pdf

CalEPA and OEHHA. (2017) CalEnviroScreen 3.0. *California Environmental Protection Agency and Science for a Healthy California*, January 2017. https://oehha.ca.gov/media/downloads/calenviroscreen/report/ces3report.pdf, accessed Jun. 2020.

California Energy Commission (CEC). (2020). California Oil Refinery History, https://www.energy.ca.gov/data-reports/energy-almanac/californias-petroleum-market/californias-oil-refineries/california-oil, Accessed May 2020.

California Energy Commission (CEC). 2020. PETROLEUM WATCH, https://www.energy.ca.gov/sites/default/files/202002/202002_Petroleum_Watch_ADA_0.pdf, Accessed May 2020.

Caltrans. (2017). Complete Streets Implementation Action Plan 2.0. *California Department of Transportation*, June 2014 - June 2017.

http://www.dot.ca.gov/hq/tpp/offices/ocp/docs/CSIAP2_rpt.pdf , accessed: Nov. 27, 2017

Caltrans (2017a) Toward an Active California State Bicycle+ Pedestrian. *Technical Report, California Department of Transportation*, May 2017. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/f0020350_activeca_final-plan-2017-05-18-a11y.pdf, accessed May 2019.

Caltrans (2017b), A Guide to Bikeway Classification, *California Department of Transportation*, July 2017, access at http://lvbikecoalition.org/wp-content/uploads/2017/12/caltrans-d4-bike-plan_bikeway-classification-brochure_072517.pdf, July 10, 2020

Caltrans (2019) ATP, Active Transportation Program (ATP) List- April 1 – June 30, 2019, *California Department of Transportation*, 2019, https://dot.ca.gov/-/media/dot-media/programs/sb1/documents/atp-attachment-1-q4-a11y.pdf

Caltrans workshop, Schmidt, C., Sauer, S., and Alm, E. (2018). Developing Corridor Planning Guidance at Caltrans, *California Department of Transportation presentation*.

Caltrans, From Problems to Projects, (2018). Office of Program and Project Planning, *California Transportation Department website*, http://www.dot.ca.gov/hq/tpp/offices/owd/academy_files/sac-2017/4-Pids.pdf, accessed: Nov. 7, 2018.

Caltrans. (2018). Planning process. *California Transportation Department website*. http://www.dot.ca.gov/hq/tpp/faqs.html, accessed: Oct. 7, 2018.

Caltrans. (2020). California Department of Transportation Authorized List for Warm Mix Asphalt Technologies, Accessed Jun. 1, 2020, https://mets.dot.ca.gov/aml/WarmMixAsphaltTechnologiesList.php?print=yes

Caltrans (2019). Comparative Bridge Costs, Division of Engineering Services, Structure Design, *California Transportation Department website:* https://dot.ca.gov/-/media/dot-media/programs/local-assistance/documents/hbp/2018/comparativebridgecosts-2018.pdf , accessed: Jul. 22, 2021

Caltrans (2021). Construction Statistics 2020, Division of Engineering Services, *California Transportation Department website:* https://transportationops.org/publications/caltrans-manuals-engineering-services-bridge-manuals, accessed: Nov. 20, 2021

Caltrans (2005). Bridge Design Aids, Chapter 11, *California Transportation Department website:* https://transportationops.org/publications/caltrans-manuals-engineering-services-bridge-manuals, accessed: Jul. 17, 2021

Caltrans (2012). Bridge Design Aids, Chapter 6, *California Transportation Department website:* https://transportationops.org/publications/caltrans-manuals-engineering-services-bridge-manuals, accessed: Jul. 16, 2021

Caltrans (2010). OSB Study Bridege 1, Structure Design General Plan, Division of Engineering Services, *California Transportation Department website:* https://transportationops.org/publications/caltrans-manuals-engineering-services-bridge-manuals, accessed: Jul. 20, 2021

CARB (2016) Greenhouse Gas Quantification Methodology for the California Transportation Commission, Active Transportation Program, *California Air Resource Board*, Oct. 2016

CECA ARKEMA Group. (2017). CECABASE rt 945, Safety Data Sheet. https://arrmaz.com/wpcontent/uploads/2017/08/Road_Science_Cecabase_RT945_USA_TDS.pdf , accessed Jul. 15, 2020

Centers for Disease Control and Prevention (CDC). (2022). Social Vulnerability Index (SVI) mapping website. https://svi.cdc.gov/map.html , accessed 2 May 2022

Change Lab Solution, Pedestrian *Friendly Code Directory: Shade Trees*, http://changelabsolutions.org/childhood-obesity/shade-trees, accessed Dec. 2019.

Cheraghian, G., Flachetto, A. C., You, Z., Chen, S., Kim, Y.S., Westerhoff, J., Moon, K.H., and Wistuba, M. (2020). Warm mix asphalt technology: An up to date review, Journal of Cleaner Production, Vol. 268, https://doi.org/10.1016/j.jclepro.2020.122128

Chester, M., Matute, J., Bunje, P., Eisensteint, W., Pincetl, S., Elizabet, Z., and Cepeda, C. (2012). Life‐Cycle Assessment for Transportation Decision‐making. *UCLA Institute of Environment and Sustainability*.

City of Sacramento (2016) Bicycle Master Plan, August 2016, http://www.cityofsacramento.org/-/media/corporate/files/public-works/transportation/bicycle-master-plan/sacramento-2016-bicycle-master-plan.pdf, accessed: July, 2020

City of Sacramento (2020a) Franklin Boulevard Complete Street Project: Our Street, Our Future. *City of Sacramento*. https://www.cityofsacramento.org/Public-Works/Engineering-Services/Projects/Current-Projects/Franklin-Complete-Street, accessed Feb. 2020.

City of Sacramento (2020b) Average Daily Traffic, *City of Sacramento*, http://www.cityofsacramento.org/public-works/transportation/traffic-data-maps/traffic-counts, accessed Feb. 2020.

City of Sacramento and Department of Public Works, City of San Jose (2020a) San Jose Better Bike Plan 2025, Oct. 2020. https://www.sanjoseca.gov/your-government/departments-offices/transportation/walking-and-biking/better-bike-plan-2025

City of Sacramento and Department of Public Works. (2018). Grant Application for the Sacramento Area Council of Governments' 2018 Regional Active Transportation Program, Franklin Boulevard Complete Street Phase 2, *Sacramento Area Council of Governments (SACOG)*, Aug. 2018, https://sacog.org/sites/main/files/file-attachments/sacramento_-_franklin_blvd_phase_2.pdf

City of San Jose (2020b) Better Bikeways, *City of San Jose*. https://www.sanjoseca.gov/your-government/departments/transportation/biking/better-bikeways, accessed Mar. 2020.

City of San Jose (2020c) Average Daily Traffic, *City of San Jose, Capital of Silicon Valley*, https://data.sanjoseca.gov/dataset/average-daily-traffic1, accessed Feb. 2020.

City of San Jose (2020d) San Jose Crash Table 2015-2019 database. https://data.sanjoseca.gov/dataset/crashes2014_2019, accessed Oct. 2020.

City of San Jose (2020e) Environmental Benefits of Street Trees, *powered by City of San Jose DOT*. https://csjdotgis.maps.arcgis.com/apps/webappviewer/index.html?id=ed392b9a2a874c0db9d0ed0ff223f64a, accessed Nov. 2020.

City of Woodland (2002) Bicycle Transportation Master Plan. https://www.cityofwoodland.org/DocumentCenter/View/1015/City-Bikeway-Master-Plan-PDF?bidId=, accessed 10 May 2022.

City of Woodland (2015) Average Daily Traffic Volume, *City of Woodland, Public Works Department*, 2015, https://www.cityofwoodland.org/DocumentCenter/View/3007/Traffic-Counts-2015.

City of Woodland Data Website (2021) *Fatal car crashes and road traffic accidents in Woodland database*, http://www.city-data.com/accidents/acc-Woodland-California.html, accessed Jun. 2021.

Complete Streets Act of 2021. 117th Congress (2021-2022). https://www.congress.gov/bill/117th-congress/house-bill/1289/text, accessed: Feb. 2022.

Complete Streets Design Manual (2010) *City of New Haven*. https://smartgrowthamerica.org/app/legacy/documents/cs/policy/cs-ct-newhaven-manual.pdf, accessed: Nov. 28, 2017.

Congressional research service. Apr. (2012). U.S. Oil Imports and Exports, Neelesh Nerurkar, Congressional research service.

Corona, B., Bozhilova-Kisheva, K. P., Olsen, S. I., and San Miguel. G. (2017) Social life cycle assessment of a concentrated solar power plant in Spain: A methodological proposal. *Journal of Industrial Ecology*, Vol 21, No. 6, pp. 1566-1577, DOI: 10.1111/jiec.12541. https://doi.org/10.1111/jiec.12541.

Corona, B., Bozhilova-Kisheva, K. P., Olsen, S. I., and San Miguel. G. (2017) Social life cycle assessment of a concentrated solar power plant in Spain: A methodological proposal. *Journal of Industrial Ecology*, Vol 21, No. 6, pp. 1566-1577, DOI: 10.1111/jiec.12541. https://doi.org/10.1111/jiec.12541.

Cosgrove, J., Van Vleck, R. and Bunster-Ossa, I.F. (2017). *Webinar: Promoting equitable change through creative placemaking & Complete Streets*. https://catsip.berkeley.edu/news/1121-webinar-promoting-equitable-change-through-creative-placemaking-complete-streets, accessed: Nov. 28, 2017.

CTC (2019) Active Transportation Program- Statewide Component, *California Transportation Commission*, 2019, https://catc.ca.gov/-/media/ctc-media/documents/013019-recos-statewide-revised-a11y.pdf

Cunningham, G., and Michael, Y. (2004) Concepts Guiding the Study of the Impact of the Built Environment on Physical Activity for Older Adults: A Review of the Literature. *Am Journal of Health Promot*. Jul-Aug 2004, Vol. 18, No. 6, pp. 435–443. DOI: 10.4278/0890-1171-18.6.435. https://www.ncbi.nlm.nih.gov/pubmed/15293929, accessed Aug. 4, 2018.

CVS (2020) Company at a glance: Facts and figures about CVS Health, *CVS Health*, https://cvshealth.com/about-cvs-health/our-company-at-a-glance, accessed Jun. 2020.

D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., Harman, T., Jamshidi, M., Jones, W., Newcomb, D., Prowell, B., Sines, R., and Yeaton, B. (2008). Warm-Mix Asphalt: European Practice, Research Report, Federal Highway Administration, DTFH61-99-C-005, https://international.fhwa.dot.gov/pubs/pl08007/pl08007.pdf

Davis, S. C., Diegel, S. W., & Boundy, R. G. (2015). Transportation energy data book. *Department of Energy*. Edition 34 (No. ORNL-6991).

Department of Industrial Ecology, Leiden University. (2016). CML-IA Characterisation Factors. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

Du, C.H., Freire, F., and Dias, L. (2014) Overview of Social Life Cycle Assessment. *life cycle in practice, At Lille,* France, 2014. https://www.researchgate.net/publication/268577177_OVERVIEW_OF_SOCIAL_LIFE_CYCLE_ASSESSMENT

Dunn, Roger and Robert Pretty. (1984) Mid-Block Pedestrian Crossings - An Examination of Delay. *In the 12th Annual Australian Road Research Board Conference,* Hobart, Tasmania, Australia, Proceedings, August 1984.

EIA (2011) Review of Emerging Resources: U.S. Shale Gas and Shale Oil Play, *U.S. Department of Energy*, Washington, DC 20585.

EIA. (2018). Analysis & Projections. U.S. Crude Oil Production to 2025: Updated Projection of Crude Types. https://www.eia.gov/analysis/petroleum/crudetypes/, Accessed September 2018.

EIA (2019) Petroleum and Other Liquids Data, U.S. Energy Information Administration (EIA), https://www.eia.gov/petroleum/data.php#summary, Accessed: Nov. 2019

EIA (2020) Units and calculators explained: Energy conversion calculators. Accessed May 2020. https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php

EIA (2020) PETROLEUM & OTHER LIQUIDS DATA, *U.S. Energy Information Administration (EIA)*, https://www.eia.gov/petroleum/data.php#summary, Accessed: May. 2020

EIA (2014a) U.S. Fuel Resiliency, Vol. I: U.S. Fuel supply infrastructure vulnerabilities and resiliency, *Office of Energy policy and system analysis and U.S. department of energy*.

EIA (2014b) U.S. Fuel Resiliency, Vol. III: U.S. Fuel supply infrastructure vulnerabilities and resiliency, *Office of Energy policy and system analysis and U.S. department of energy*.

EIA. (2015) West Coast Transportation Fuels Markets, *EIA and U.S. Department of Energy*.

Enerdata (2019) Global Energy Statistical Yearbook 2019. https://yearbook.enerdata.net/crude-oil/world-refineries-data.html, accessed Dec. 14, 2019.

Eurobitume (2012) Life Cycle Inventory: Bitumen. *European Bitumen Association*. https://www.eurobitume.eu/fileadmin/pdf-downloads/LCI%20Report-Website-2ndEdition-20120726.pdf, accessed= Sep. 2019.

Evans, G., Rosenbaum, J. (2008) Self-regulation and the Income-achievement Gap, *Journal of Early Childhood Research*. 2008, Vol. 23, Issue 4, 4th Quarter, pp. 504-514. http://dx.doi.org/10.1016/j.ecresq.2008.07.002

Ewing, R. and R. Cervero. (2010) Travel and the Built Environment. *Journal of the American Planning Association*, Vol. 76, No. 3, Summer 2010.

FHWA (1998), Capacity Analysis of Pedestrian and Bicycle Facilities, *Federal highway administration*, Report number: FHWA-RD-98-107, access May 2020 at https://www.fhwa.dot.gov/publications/research/safety/pedbike/98107/section4.cfm

FHWA (2018) Traffic Data Computation Method- POCKET GUIDE, *U.S. Department of Transportation and Federal Highway Administration*, Publication No.: FHWA-PL-18-027, Aug. 2018, https://www.fhwa.dot.gov/policyinformation/pubs/pl18027_traffic_data_pocket_guide.pdf

Fitch, D., Carlen, J., Handy, S. (2022). What makes bicyclists comfortable? Insights from a visual preference survey of casual and prospective bicyclists. *Transportation Research Part A*: Policy and Practice, Volume 155. https://doi.org/10.1016/j.tra.2021.11.008.

Fritz, P. (2013) Complete Streets: Economic development & Placemaking, *Indiana Complete streets Campaign presentation*, http://healthbydesignonline.org/documents/PeteFritz_CompleteStreetsEconomicDevelopmentandPlacemaking_08-22-2013.pdf , accessed: Nov. 28, 2017.

Furth, P. G. (2017) Level of Traffic Stress Criteria, *Northeastern University*. https://peterfurth.sites.northeastern.edu/2014/05/21/criteria-for-level-of-traffic-stress/, accessed Mar. 2020.

GaBi Life Cycle Assessment Software (2019). *Thinkstep International*, Stuttgart, Germany, 2019

Gámez-García, D., Saldaña Márquez, H., Gómez-Soberón, J., Corral Higuera, R., Arredondo-Rea, S. (2019). Life Cycle Assessment of residential streets from the perspective of favoring the human scale and reducing motorized traffic flow. From cradle to handover approach. *Sustainable Cities and Society*. 44. 332-342. 10.1016/j.scs.2018.10.018.

Garrett-Peltier, H. (2011) Pedestrian and bicycle infrastructure: a national study of employment impacts. *Political Economy Research Institute (PERI) at university of Massachusetts*, June 2011.

Goughnour, E., Albee, M., Thomas, L., Gelinne, D., Seymour, J. (2020). Pedestrian and Bicyclist Road Safety Audit (RSA) Guide and Prompt Lists. *Federal Highway Administration Report*, FHWA-SA-20-042. https://safety.fhwa.dot.gov/ped_bike/tools_solve/docs/fhwasa20042.pdf

Government of Canada. (2019). Natural Resources Canada. https://www.nrcan.gc.ca/energy/facts/crude-oil/20064, accessed Dec. 14, 2019.

Gregg. K., and Hess, P. (2019) Complete streets at the municipal level: A review of American municipal Complete Street Policy. *The International Journal of Sustainable*

Transportation, Vol. 13, No. 6, pp. 407-418, 2019. https://www.tandfonline.com/doi/abs/10.1080/15568318.2018.1476995

Haaster. B., Ciroth, A., Fontes, J., Wood, R., Ramirez, A. (2017). Development of a Methodological Framework for Social Life-Cycle Assessment of Novel Technologies. *International Journal of Life Cycle Assessment*, Vol. 22, pp. 423-440. https://link.springer.com/article/10.1007/s11367-016-1162-1

Haaster. B., Ciroth, A., Fontes, J., Wood, R., Ramirez, A. (2017) Development of a Methodological Framework for Social Life-Cycle assessment of Novel Technologies. *International Journal pf Life Cycle Assessment*, Vol. 22, pp. 423-440, 2017. https://link.springer.com/article/10.1007/s11367-016-1162-1

Harrington, D. S. and Fick, G. (2014). Guide to concrete overlays: Sustainable solutions for re-surfacing and rehabilitation existing pavements. *National Concrete Pavement Technology Center*.

Harvey, J. T., Kendall, A., Saboori, A., Ostovar, M., Butt, A.A., Hernandez, J., and Haynes, B. (2018). Framework for Life Cycle Assessment of Complete Streets Projects. Research Report, *National Center for Sustainable Transportation*, Report No.: NCST-UCD-RR-18-39. https://escholarship.org/uc/item/0vw335dp

Harvey, J. T., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A. and Kendall, A. (2016) Pavement Life Cycle Assessment Framework. *U.S. Department of Transportation Federal Highway Administration*, FHWA-HIF-16-014, Jul. 2016, Washington, DC. https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf.

Harvey, J. T., Kendall, A., Saboori, A., Butt, A. A., Lozano, M., and Ostovar, M. (2020). Supply curves using LCA and LCCA for conceptual evaluation of proposed policies to improve the environment, *Springer International Publishing*, Proceedings of the 5th International Symposium on Asphalt Pavements & Environment (APE) 5, p144-152, , https://link.springer.com/chapter/10.1007/978-3-030-29779-4_14

Harvey, J. T., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A. and Kendall, A. (2016). Pavement Life Cycle Assessment Framework. U.S. Department of Transportation, *Federal Highway Administration*, FHWA-HIF-16-014, Washington, DC. https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf.

Harvey, J.T., Lea, J., Saboori, A., Ostovar, M., and Butt, A. A. (2020). eLCAP: A Web Application for Environmental Life Cycle Assessment of Pavements Focused on California, Pavement, Roadway, and Bridge Life Cycle Assessment 2020: Proceedings of the *International Symposium on Pavement. Roadway, and Bridge Life Cycle Assessment, CRC Press*.

Harvey, J. T., Kendall, A., Butt, A.A., Saboori, A., Ostovar, M., Hernandez, J., and Haynes, B. (2021) Can Complete Streets Deliver on Sustainability?. Policy Brief, *National Center for Sustainable Transportation*. Institute of Transportation Studies, UC Davis. https://escholarship.org/uc/item/22m1z1x7

Harvey. J.T, A., Butt, A.A., Ostovar, M., Kendall, A., and Hernandez, J. (2022) Demonstrating the Life Cycle Assessment Framework for Complete Streets. Policy Brief, *National Center for Sustainable Transportation*. Institute of Transportation Studies, UC Davis. https://escholarship.org/uc/item/6wr8x21j

HCM (2016) Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis, *Transportation Research Board (TRB).* http://www.trb.org/Main/Blurbs/175169.aspx

Hernandez, J. (2016) The Franklin Plan: Using Neighborhood-Based Energy Efficiency and Economic Development to Implement Sustainable Community Principles. *Franklin Neighborhood Development Corporation and Franklin Boulevard Business Association*, https://docs.wixstatic.com/ugd/c1e9fd_2d41e32ae76c4502b88141801978d20d.pdf

Hernandez, J. (2021). Race and Place in Sacramento: A Report for the City of Sacramento to support preparation of the Environmental Justice Element of the Sacramento 2040 General Plan Update. *JCH Research*. Sacramento. https://www.cityofsacramento.org/-/media/Corporate/Files/CDD/Planning/General-Plan/2040-General-Plan/Race_Place_Nov-2021.pdf?la=en , accessed April 30 2022

Hertz, D., (2018) Urban buses are slowing down, City Commentary, Aug. 2018, http://cityobservatory.org/urban-buses-are-slowing-down/

Hexagon Transportation Consultants INC. (2018) Downtown Strategy 2040 EIR-Transportation Analysis, *City of San Jose*, Jul. 2018, https://www.sanjoseca.gov/your-government/departments/planning-building-code-enforcement/planning-division/environmental-planning/environmental-review/active-eirs/downtown-strategy-2040

Hoxha, E., H.R. Vignisdottir, D.M. Barbieri, F. Wang, R.A. Bohne, T. Kristensen, A. Passer (2021). Life cycle assessment of roads: Exploring research trends and harmonization challenges, *Science of The Total Environment*, Volume 759. https://doi.org/10.1016/j.scitotenv.2020.143506.

Huff, k.H., Liggett, R. (2014) The Highway Capacity Manual's Method for Calculating Bicycle and Pedestrian Levels of Service: the Ultimate White Paper. *Lewis Center for Regional Policy Studies, and University of California, Los Angeles,* September. 2014.

Hui, M., Zhang, Z., Zhoa, X., and Wu, S. (2019). A Comparative Life Cycle Assessment (LCA) of Warm Mix Asphalt (WMA) and Hot Mix Asphalt (HMA) Pavement: A Case Study in China, *Hindawi Journal: Advances in Civil Engineering*, Vol. 2019, Article ID 9391857, https://doi.org/10.1155/2019/9391857.

Hui, N., Saxe, S. Roorda, M., Hess, P. and Miller, E. (2018). Measuring the completeness of complete streets. *Transport Reviews*, 38:1, 73-95. DOI: 10.1080/01441647.2017.1299815

Humpel N, Owen N, Leslie E. (2002) Environmental factors associated with adults' participation in physical activity: a review. *American Journal of Preventive Medicine.* April 2002, Vol. 22, pp 188–199. https://www.sciencedirect.com/science/article/pii/S0749379701004263, Accessed: Aug. 14, 2018.

Kim, C.H., Butt, A.A. Harvey, J., Ostovar, M. and Saboori, A. (2022). Framework and Demonstration of Simulations of Environmental Impacts from Traffic on Highway Construction Work Zones. *Research Report, University of California Pavement Research Center*, DOI: 10.7922/G29W0CSX, https://escholarship.org/uc/item/02m0x1t7

ILG (2018), The Basics of SB 375, *Institute of Local Government (ILG) website*, http://www.ca-ilg.org/post/basics-sb-375, accessed Nov. 3, 2018

Ingevity. 2022. environmental product declaration for its Evotherm M1 Warm Mix Asphalt technology, https://www.ingevity.com/news/press-releases/ingevity-publishes-environmental-product-declaration-for-its-evotherm-m1-warm-mix-asphalt-technology/, accessed: Oct. 2022.

ISO (2006). Environmental Management – Life Cycle Assessment – Principles and Framework. *International Organization for Standardization*, ISO 14040, Geneva, Switzerland.

ISO 14040. (2006). Environmental management. Life cycle assessment- Principles and framework, *International Organization for Standardization*, ISO/TC 207/SC 5 Life cycle assessment, Geneva, Switzerland, 2006. https://www.iso.org/standard/37456.html, accessed: Sep. 2021.

Jay, R. (2019). Efficiency Asphalt Plant Heat Efficiency, *AsphaltPro*, https://theasphaltpro.com/articles/electrify-your-plants-heat-efficiency/

Jones, D., Wu, R., Tsai, B.-W., and Harvey, J. (2011)a. Warm-Mix Asphalt Study: Level Analysis of Phase 3b HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2), Research Report: UCPRC-RR-2011-02, *University of California Pavement Research center*.

Jones, D., Wu, R., Tsai, B.-W., and Harvey, J. (2011)b. Warm-Mix Asphalt Study: Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1), Research Report: UCPRC-RR-2011-03, *University of California Pavement Research center*.

Jones, D., Wu, R., Tsai, B.-W., and Harvey, J. (2014). Warm-Mix Asphalt Study: Summary Report on Warm-Mix Asphalt Research in California, Research Report: UCPRC-SR-2014-02, *University of California Pavement Research center*.

Karner, A., D. Rowangould and J. London. (2016) We Can Get There from Here: New Perspectives on Transportation Equity. *White paper*, *National Center for Sustainable Transportation*, UC Davis, September, 2016. https://ncst.ucdavis.edu/white-paper/you-can-get-there-from-here-new-perspectives-on-transportation-equity/, accessed July 20, 2018.

Kazemzadeh, Khashayar, Aliaksei Laureshyn, Lena Winslott Hiselius, and Enrico Ronchi. (2020). Expanding the Scope of the Bicycle Level-of-Service Concept: A Review of the Literature, *Sustainability Journal*, Vol. 12, no. 7: 2944. https://doi.org/10.3390/su12072944

Kendall, A. (2012). Life Cycle Assessment for Pavement: Introduction. Presentation in Minutes, *FHWA Sustainable Pavement Technical Working Group Meeting*, April 25-26, 2012, Davis, CA.

Kroeger, A. and Weber, C. (2015) Developing a Conceptual Framework for Comparing Social Value Creation. *Academy of Management Review*, Vol. 40, No. 1, pp. 43–70, 2015. https://journals.aom.org/doi/10.5465/amr.2012.0344

Kuhnen. M., and Hahn, R. A. (2017) Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience. *Journal pf Industrial Ecology*, Vol.

21, No. 6, DOI: 10.1111/jiec.12663, Sep. 2017. https://www.researchgate.net/publication/318725853_Indicators_in_Social_Life_Cycle_Assessment_A_Review_of_Frameworks_Theories_and_Empirical_Experience

Kuhnen. M., and Hahn, R. A. (2017). Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience. *Journal of Industrial Ecology*, Vol. 21, No. 6, DOI: 10.1111/jiec.12663.

Kupfer, T., Baitz, M., Makishi Colodel, C., Kokborg, C., Schöll, S., Rudolf, M., Thellier, L., Bos, U., Bosch, F., Gonzalez, F., Schuller, O., Hengstler, J., Stoffregen, A., Thylmann, D. (2019). GaBi database& modelling principles, *Thinkstep AG*.

LaPlante, J.N. and McCann, B. (2011). Complete streets in the United States. *90th Annual Meeting of the Transportation Research Board*, Washington DC, http://docs.trb.org/prp/11-0413.pdf

League of American Bicyclists. (2022). Bipartisan Infrastructure Bill Passes with Major Funding for Better Biking. https://bikeleague.org/content/bipartisan-infrastructure-bill-passes-major-funding-better-biking , accessed April 29, 2022

Lenker, J. A., Maisel. J. L., and Ranahan. M.E. (2016). Measuring the Impact of Complete Streets Projects: Preliminary Field Testing. *Research Report, New York State of Opportunity (NYSERDA), Department of Transportation*, No. 16-19, Dec. 2016. https://rosap.ntl.bts.gov/view/dot/31830

Martinez-Blanco, J., Lehmann, A., Chang, Y. J. and Finkbeiner, M. (2015) Social organizational LCA (SOLCA): A new approach for implementing social LCA. *The*

International Journal of Life Cycle Assessment, Vol. 20, No. 11, pp. 1586–1599, 2015, https://link.springer.com/content/pdf/10.1007/s11367-015-0960-1.pdf, accessed Jan. 2020.

Mateos, A., Harvey, J.T., Paniagua, F., Paniagua, J., and Wu, R. (2019). Development of Improved Guidelines and Designs for Thin BCOA: Summary, Conclusions, and Recommendations. *University of California Pavement Research Center*, Summary Report: UCPRC-SR-2018-01.

Mateos, A., J. Harvey, Millan, M.A., Wu, R., Paniagua, F., Cisneros, J., and Paniagua, J. (2021). Concrete Overlay on Asphalt Pilot Project at Woodland SR 113: Construction. *University of California Pavement Research Center*, Summary Report: UCPRC-SR-2021-07, DOI. 10.7922/G2PV6HN4.

McCann, B. and Rynne, S. (2010) Complete streets: Best policy and implementation practices. *American Planning Association*, https://www.planning.org/publications/report/9026883/

Metropolitan Transportation Commission (MTC) (2020a) Complete Streets, San Fernando St Enhanced Bikeway and Pedestrian Access. *Metropolitan Transportation Commission*, https://completestreets.mtc.ca.gov/checklists/68, accessed Jan. 2020.

Metropolitan Transportation Commission (MTC) (2020b) Better BikewaySJ - San Fernando Corridor. *Metropolitan Transportation Commission*, https://completestreets.mtc.ca.gov/checklists/1241, accessed: Jan. 2020.

MIG, Inc. (2019). Franklin Boulevard Complete Street Plan. *Bennett Engineering Services, Fehr & Peers, ESA.* Oct. 2019. https://www.cityofsacramento.org/-

/media/Corporate/Files/Public-Works/Projects/Franklin-Complete-Street/FBCS_Report-Fin_Oct2019.pdf?la=en

Miliutenko, S., (2016). Consideration of Life Cycle Energy Use and Greenhouse Gas Emissions for Improved Road Infrastructure Planning. *Doctoral thesis, KTH Royal Institute of Technology*. Sweden.

Monsere, C., McNeil, N., Sanders, R. (2020). User-Rated Comfort and Preference of Separated Bike Lane Intersection Designs. *Transportation Research Record*, Vol. 2674, Issue 9. https://doi.org/10.1177/0361198120927694

Moreland-Russell, S., Eyler, A., Barbero, C., Hipp, J. A., Walsh, H. (2013). Diffusion of Complete Streets Policies Across US Communities, *Journal of Public Health Management Practice*, 19(3) E-Supp, S89–S96

Mukherjee, A. (2016). Life Cycle Assessment of Asphalt Mixtures in Support of an Environmental Product Declaration, *National Asphalt Pavement Association (NAPA)*, https://www.asphaltpavement.org/uploads/documents/EPD_Program/LCA_final.pdf

Nabizadeh, H., Von Quintus, H., and Bonaquist, R. (2022). Expansion of AASHTOWare ME design inputs for asphalt layers, *Wisconsin Highway Research Program*, 0092-20-03, https://rosap.ntl.bts.gov/view/dot/62611, accessed Dec. 20, 2022.

Nabizadeh, H., Hajj, E., Aschenbrener, T., and Von Quintus, H. (2022). Tech Brief: Advances in the Design, Production, and Construction of Stone Matrix Asphalt (SMA), *Federal Highway Administration*, 0092-20-03, FHWA-HIF-22-042, https://scholarworks.unr.edu/bitstream/handle/11714/8256/hif22042.pdf?sequence=4, accessed Nov. 27, 2022.

Nabizadeh, H., Naderi, B., and Tabatabee, N. (2017). Effects of moisture on warm mix asphalt containing Sasobit, *Scientia Iranica Journal*, Transactions A: Civil Engineering, Vol. 24, pp 1866-1873.

NACEI. (2019). Crude oil flows data. *North American Cooperation on Energy Information (NACEI)*, https://www.nacei.org/#!/data, accessed Nov. 2019.

NACTO Guide. (2013). Urban Street Design Guide. *National Association of City Transportation Officials*, ISBN: 9781610915342 , New York. https://nacto.org/publication/urban-street-design-guide/, accessed Nov. 27, 2017.

National Association of City Transportation Officials (NACTO). (2015). Chattanooga Complete Streets Ordinance. https://nacto.org/wp-content/uploads/2015/06/Chattanooga-Complete-Streets-Ordinance.pdf, Accessed February 15, 2022

National Complete Streets Coalition. (2010). Complete Streets Policy Inventory and Evaluation, Washington, DC:

NCHRP Report 616 (2008) Multimodal Level of Service Analysis for Urban Streets. *Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration*, TRB. https://www.nap.edu/download/14175#

NCHRP Report 812 (2015) Signal Timing Manual. *American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration*. Second Edition. TRB, 2015.

https://transops.s3.amazonaws.com/uploaded_files/Signal%20Timing%20Manual%20812.pdf, Accessed August 8, 2021

NEB. (2019). Crude oil and petroleum products, *National Energy Board (NEB) of Canada*, accessed Nov. 2019. https://www.cer-rec.gc.ca/nrg/sttstc/crdlndptrlmprdct/index-eng.html

New York State Energy Research and Development Authority. (2018). Complete Streets Considerations for Freight and Emergency Vehicle Operations. https://www.metrans.org/assets/research/complete%20streets%20freight%20booklet_v6_hires-0.pdf, accessed October 8, 2021

Nouryon. (2017). NYSDOT WMA Technology Approval, WMA Technology Production, Testing and Compaction Details, Rediset® LQ Safety Data Sheet. accessed Jul. 30, 2020, https://www.dot.ny.gov/divisions/engineering/technical-services/technical-services-repository/details/rediset.pdf

NREL (National Renewable Laboratory). (2004). Energy Tips, U.S. Department of Energy, Energy Efficiency and Renewable Energy, Industrial Technology Program, https://www.nrel.gov/docs/fy04osti/33470.pdf

NREL. (2003). U.S. Life Cycle Inventory Database; Crude oil, in refinery. *National Renewable Energy Laboratory*. https://uslci.lcacommons.gov/uslci/search, accessed Sep. 2019.

O'Toole, R. (2018). Charting Public Transit's Decline, *CATO Institute. Policy Analysis,* No. 853, Nov. 2018, https://www.cato.org/policy-analysis/charting-public-transits-decline

OEHHA. (2020). CalEnviroScreen tool. *California Office of Health and Hazards Assessments*, https://oehha.ca.gov/calenviroscreen, accessed Mar. 2020.

Office of Fossil Energy. (2020). Enhanced Oil Recovery, *Science & innovation.* www.energy.gov. accessed Apr. 14, 2020.

OGJ. (2019). 2018 worldwide refining survey, *Oil and Gas Journal*, Dec., 2018. https://www.ogj.com/ogj-survey-downloads/worldwide-production/document/14073232/worldwide-production-december-2019, accessed: Nov. 2019.

OPR, Walsh, S., Roberts, and T., Pellman, S. (2005). California Planning Guide: An Introduction to Planning in California. *Governor's Office of Planning and Research*, Dec. 2005.

OSM. (2019). Canadian data, *Oil Sands Magazines*.

OSM. (2019). U.S. monthly data, *Oil Sands Magazines*, https://www.oilsandsdata.com, accessed Nov. 2019.

OSM. (2019). U.S. weekly data, *Oil Sands Magazines*.

Ostovar, M., Butt, A.A., Mateos, A., and Harvey, J.T. (2020) Life Cycle Assessment of a Thin Bonded Concrete Overlay of Asphalt Project in Woodland, California, Pavement, Roadway, and Bridge Life Cycle Assessment 2020: *Proceedings of the International Symposium on Pavement*. Roadway, and Bridge Life Cycle Assessment, CRC Press, Jul. 2020.

Ostovar, M., Butt, A.A., Mateos, A., and Harvey, J.T. (2020). Life Cycle Assessment of a Thin Bonded Concrete Overlay of Asphalt (BCOA) Project in Woodland, California. *LCA2020 conference*, Davis, 2020.

Ostovar, M., Butt, Harvey, J., A., Ramalingam, Z. (2022). Data for: Socio-economic and environmental life cycle assessment of complete streets, *DRYAD*, Supporting Dataset, University of California, Davis, https://datadryad.org/stash/dataset/doi:10.25338/B85K99

Ostovar, M., Butt, A. A., Harvey, J. T., Ramalingam, Z., Hernandez, J., and Kendall, A. (2022). Case Studies of Socio-Economic and Environmental Life Cycle Assessment of Complete Streets, *Research Report, National Center for Sustainable Transportation and UC Davis Institute of Transportation Studies*, Report No. UCD-ITS-RR-22-02, 2022, https://escholarship.org/uc/item/4n4081k8

Owen N, Humpel N, Leslie E, Bauman A, Sallis JF. (2004). Understanding environmental influences on walking; Review and research agenda. *American Journal of Preventive Medicine*. Vol. 27, pp 67–76, July 2004. https://www.ncbi.nlm.nih.gov/pubmed/15212778, accessed Aug. 14, 2018.

Pacific Institute. (2016). Fracking in California Overview. https://pacinst.org/wp-content/uploads/2016/02/PI_IssueBrief_FrackinginCalifornia_Overview.pdf

Pizarro, S. (2019) VTA changes should ease clogged downtown San Jose: Pizarro, *the Mercury News*, Dec. 2019. https://www.mercurynews.com/2019/12/10/vta-changes-should-ease-clogged-downtown-san-jose-pizarro/

PQ Corporation. (2015). ADVERA 401P Aluminosilicate, Safety Data Sheet. accessed Jul. 18, 2020, https://www.pqcorp.com/docs/default-source/msds/pq-corporation/zeolites/advera/advera-401p_msds_2015.pdf?sfvrsn=75b0ec01_3

Project for Public Spaces (PPS). (2017). What is Shared Space?. Project for Public Spaces. https://www.pps.org/reference/what-is-shared-space/, accessed: Nov. 22, 2018.

Pucher, J., Buehler, R., Bassett, D.R., Dannenberg, A.L. (2010). Walking and cycling to health: a comparative analysis of city, state, and international data. *American Journal of Public Health*. 100(10):1986-1992. DOI:10.2105/AJPH.2009.189324

Ranahan. M.E., Lenker, J. A., and Maisel. J. L. (2014). Evaluating the impact of complete streets initiatives, Center for inclusive design and environmental access GOBike Buffalo. *Transportation research board*. https://trid.trb.org/view.aspx?id=1336016

Rangelov, M., Dylla, H., Davies, J., and Sivaneswaran, N. (2020). "Integration of life cycle assessment into planning and project delivery for pavements in the USA" The International Journal of Life Cycle Assessment, Vol. 25, p 1605-1619, https://doi.org/10.1007/s11367-020-01777-x

Ridington, E. and Norman, K, Richardson, R. (2016). Fracking by the Numbers: The Damage to Our Water, Land and Climate from a Decade of Dirty Drilling. *Frontier Group and Environment America Research & Policy Center*, https://environmentamerica.org/sites/environment/files/reports/Fracking%20by%20the%20Numbers%20vUS.pdf

Rite Aid (2020) Rite Aid Corporation History. https://www.riteaid.com/about-us/our-story , accessed Jun. 2020.

Rosenbaum, R. (2014) Towards the big picture – the path from one-dimensional footprints to complete environmental sustainability assessments. *Keynote address, Pavement Life Cycle Assessment Symposium*, Davis, CA. Nov. 14-16. http://www.ucprc.ucdavis.edu/p-lca2014/media/pdf/Presentation/LCA14_Big_Picture_Rosenbaum.pdf, accessed May 30, 2018.

Saboori, A., Butt, A., and Harvey, J. Ostovar, M., Li, H., and Wang, T. (2022), UCPRC Life Cycle Assessment Inventories (LCIs) from Three Studies. Research Report, UCPRC-TM-2020-01, *University of California Pavement Research Center*.

Saboori, A., Harvey, J., Ostovar, M., Butt, A. A., Kendall, A. (2020). Comparison of life cycle greenhouse gas emissions and energy consumption between complete streets vs. conventional streets. *Pavement*, *Roadway, and Bridge Life Cycle Assessment* 2020, CRC Press.

SACOG (2010), MTP/SCS Project Listings, Caltrans District 3, Final Metropolitan Transportation Plan / Sustainable Communities Strategy Project List, *Sacramento Area Council of Governments*, https://www.sacog.org/sites/main/files/file-attachments/a-1_project_listreetpdf?1456333787

SACOG (2013), Regional Planning Partnership Action, Flexible Funding Programming Round Recommendations for Public Review, *Sacramento Area Council of Governments*, Oct., https://www.sacog.org/sites/main/files/file-attachments/5-programming_complete.pdf?1458842596

SACOG (2020) Project Performance Assessment (PPA) Tool, *Sacramento Area Council of Governments*, https://portal.sacog.org/portal/apps/webappviewer/index.html?id=77be2a57f59f47699af6c31599e0fa50&extent=6261661.6891,1724595.8709,7452612.6765,2373658.138,102642, *accessed Mar. 2020.*

SACOG (undated). https://www.sacog.org/sites/main/files/file-attachments/sb_1_handout_2.pdf?1512670455 (Accessed 29 April 2022)

Sacramento County (2020) Sacramento County General Plan 2035, Sacramento County, *Planning and Environmental Review*. https://planning.saccounty.net/PlansandProjectsIn-Progress/Pages/GeneralPlan.aspx, accessed Feb. 2020.

SacRT. (2020) SacRT's SmaRT Ride Microtransit Service Among the Most Successful in the U.S., *Sacramento Regional Transit District (SacRT).* Sep. 2020. https://www.sacrt.com/apps/sacrts-smartride-microtransit-service-among-the-most-successful-in-the-u-s/

Saelens, B. and Handy, S. (2008). Built Environment Correlates of Walking: A Review. *Med Sci Sports Exerc*, July 2008, Vol. 40, No.7, pp S550–S566. doi: 10.1249/MSS.0b013e31817c67a4, https://www.ncbi.nlm.nih.gov/pubmed/18562973, accessed Aug. 14, 2018.

San Jose Downtown Association (2016) Focus Area: San Fernando Street. *San Jose Downtown Association*. https://sjdowntown.com/wp_2016/wp-content/uploads/2018/01/CHAPTER-06B-1.pdf

Santero, N. J. and Horvath, A. (2009). Global warming potential of pavements. *Environmental Research Letters*, Vol. 4, No. 3, p.034011.

Sasol. (2016). SASOBIT® Bitumen Additives, Safety Data Sheet. Accessed Jul. 28, 2020, https://americasinternational.com/wp-content/uploads/2018/08/SASOBIT-SDS-SASOL.pdf

Saxe, S, Kasraian, D. (2020). Rethinking environmental LCA life stages for transport infrastructure to facilitate holistic assessment. *Journal of Industrial Ecology*. 2020; 24: 1031– 1046. https://doi.org/10.1111/jiec.13010.

SCAG (2016) Active Transportation Health and Economic Impact Study. *Southern California Association of Governments (SCAG),* 15-019-C1, November 2016. https://www.scag.ca.gov/programs/Documents/ATHealthImpactStudy/2016ATHealthEconomicImpactStudy_REPORT.pdf

SCCGOV (2014) The County of Santa Clara- Facilities Needs Assessment. *County of Santa Clara*. https://www.sccgov.org/sites/faf/capital-projects/cc/Documents/County%20of%20Santa%20Clara%20Facilities%20Needs%20Assessment%20%28October%202014%29.pdf

Schremp, G. Nov. (2017). California Refinery Crude Oil Sources and Trends, OSPR TAC Informational Meeting on Non-Floating Oil, Sacramento, *California Energy Commission (CEC).*

Schremp, G. (2016). PADD 5 & California Transportation Fuel Overview, *California Energy Commission (CEC) and National Association of State Energy Officials (NASEO).*

Schuller, O. (2016). The GaBi LCA Refinery Model 2016, *thinkstep*. https://sphera.com/wp-content/uploads/2016/02/The-GaBi-LCA-Refinery-Model.pdf

Schuller, O. (2020). The GaBi LCA Refinery Model 2020, *Sphera*.

Schuller, O., Hengstler, J. and Thellier, L. (2019). Energy modelling in GaBi 2019 edition. *Thinkstep AG.*

Sea distances online tool. (2019). Sea Distances of Port Distances- online tool for calculation distances between sea ports, https://sea-distances.org/, Accessed: Nov. 2019.

Semler, C., Vest, A., Kingsley, K., Mah, S., Kittelson, W., Sundstrom, C., and Brookshire, K. (2016) Guidebook for Developing Pedestrian & Bicycle Performance Measures. *U.S. Department of Transportation Federal Highway Administration*, *FHWA-HEP-16-037*, March 2016, New Jersey. https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/performance_measures_guidebook/pm_guidebook.pdf.

Smart Growth America & National Complete Streets Coalition (2016) The best complete streets policies of 2016. *Smart Growth America and National Complete Streets Coalition*,

2017. https://smartgrowthamerica.org/app/uploads/2017/06/best-complete-streets-policies-of-2016-1.pdf, accessed: Nov. 29, 2017.

Smart Growth America & National Complete Streets Coalition (2018) The elements of a Complete Streets Policy, effective 2018. *Smart Growth America and National Complete Streets Coalition*, 2018. https://smartgrowthamerica.org/resources/elements-complete-streets-policy/

Smart Growth America & National Complete Streets Coalition (2019) The best complete streets policies of 2018. *Smart Growth America and National Complete Streets Coalition*, May 2019. https://smartgrowthamerica.org/resources/the-best-complete-streets-policies-of-2018/

Smart Growth America & National Complete Streets Coalition (2017) The best complete streets policies of 2016. *Smart Growth America and National Complete Streets Coalition*. 2017. https://smartgrowthamerica.org/app/uploads/2017/06/best-complete-streets-policies-of-2016-1.pdf, accessed: Jan. 2020.

Smiley, R.A. (2000). Hexamethylenediamin, *Wiley Online Library*, Wilmington, Delaware, https://onlinelibrary.wiley.com/doi/full/10.1002/14356007.a12_629

Smith, R., Reed, S. and Baker, S. (2010). Street Design: Part 1-Complete Streets. *Public Roads, FHWA-HRT-10-005*, July/August 2010, Vol 74, No. 1.

Sonneborn Refined Product. (2015). SonneWarmix RT, Safety Data Sheet, Accessed Aug. 2, 2020, https://asmg.com/wp-content/uploads/2020/10/SonneWarmix_RT_SDS.pdf

Sukmana. C., Hamzah, B., and Rahim, D. (2019) An Application of the Bicycle Lane on the Complete Street Concept in Efforts Reducing Global Warming Impact. *IOP Conf. Series: Earth and Environmental Science 235*, doi:10.1088/1755-1315/235/1/012091, 2019. https://iopscience.iop.org/article/10.1088/1755-1315/235/1/012091

Tagliaferri, C. and Lettieri, P. (2019). Methane from waste: Thermal and biological technologies compared under a life cycle assessment perspective, Substitute Natural Gas from Waste Technical Assessment and Industrial Applications of Biochemical and Thermochemical Processes, p 275-315.

Tatatri, O., Nazzal, M., and Kucukvar, M. (2012). Comparative sustainability assessment of warm-mix asphalts: A thermodynamic based hybrid life cycle analysis, *Resource, Conservation and Recycling Journal*, Vol. 58, pp 18-24, doi:10.1016/j.resconrec.2011.07.005.

Taylor, M. (2017). Transportation Funding Package, *Legislative Analyst's Office (LAO)*, LAO Report, https://lao.ca.gov/publications/report/3572

The Montgomery County Planning Department (2018) The Montgomery County Bicycle Master Plan. *Maryland-National Capital Park and Planning Commission*, Dec. 2018. https://montgomeryplanning.org/wp-content/uploads/2019/09/Bicycle-Master-Plan-Web-Version.pdf

Thinkstep. (2020). Process data set: Crude oil mix; technology mix of conventional (primary, secondary and tertiary production) and unconventional production (oil sands, in-situ); consumer; (en), GaBi Database Content, *thinkstep*, gabi-6-lci-documentation.gabi-software.com/xml-data/processes/f3e83b9f-8ebc-4e83-a13c-d061ae537a32.xml, access Jan. 2020.

TIMS (2019) Transportation Injury Mapping System (TIMS) database 2015-2019 https://tims.berkeley.edu/tools/atp/, accessed Dec. 2019.

Toronto center for active transportation. (2017). How is Complete streets different from context sensitive solutions? *Complete streets for Canada*, 2017. http://completestreetsforcanada.ca/faq/how-complete-streets-different-context-sensitive-solutions, accessed: Nov. 28, 2017.

Traffic Signal Timing Manual (2008) *U.S. Department of Transportation, Federal Highway Administration, FHWA-HOP-08-024,* June 2008. https://ops.fhwa.dot.gov/publications/ fhwahop08024/index.htm

Trancik, R. (1986). Finding lost space: theories of urban design. *John Wiley & Sons*, ISBN-13: 978-0471289562.

Transmountain (2020). Project Expansion, https://www.transmountain.com/project-overview, Accessed: Nov. 2020 and Feb. 2023.

TRB (2013) TCRP Report 165: Transit Capacity and Quality of Service Manual, Third Edition, *Transportation research Board of the National Academies*, ISBN 978-0-309-28344-1 | DOI 10.17226/24766, 2013. https://www.nap.edu/catalog/24766/transit-capacity-and-quality-of-service-manual-third-edition

TRB (2017) Pedestrian and Bicycle Safety; Summary of the 10th University Transportation Centers Spotlight Conference. *Transportation Research Board*, December 1–2, 2016, Washington, D.C. https://onlinepubs.trb.org/onlinepubs/conf/cpw21.pdf, Accessed 30 April 2022

U.S. Government Accountability Office (2018), FEDERAL BUILDINGS- Agencies Focus on Space Utilization As They Reduce Office and Warehouse Space, *United States Government Accountability Office*, *Report to Congressional Requesters*, March 2018, access June 2020 at https://www.gao.gov/assets/700/690536.pdf

Vance Brothers. (2017). Bringing Integrity to the Surface, Evotherm DAT, Material Safety Data Sheet. Accessed Jul. 25, 2020.

Vidal, R., Moliner, E., Martinez, G., and Robio, M.C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement, Resource, *Conservation and Recycling Journal*, Vol. 74, pp 101-114, https://doi.org/10.1016/j.resconrec.2013.02.018.

Virginia Tech (2020) Construction and Professional Services Manual. *Virginia Technology University, Facilities Department*. Jan. 2020. https://www.facilities.vt.edu/content/dam/facilities_vt_edu/design-and-construction-standards/Maroon%20Manual%20January%202020.pdf

Voulgaris, C., Smart, M., Taylor, B. (2019). Tired of commuting? Relationships among journeys to school, sleep, and exercise among American teenagers. *Journal of Planning Education and Research* 39, no. 2: 142-154. https://doi.org/10.1177/0739456X17725148, accessed 10 May 2022

Walgreens (2007) A New Perspective: The State of Pharmacy in America, https://www.walgreens.com/images/pdfs/state.pdf

Walgreens (2020) How many customers does Walgreens interact with daily, *Walgreens News Room*. https://news.walgreens.com/fact-sheets/frequently-asked-questions.htm#:~:text=See%20our%20store%20count%20by,stores%20and%20online%20each%20day, accessed Jun. 2020.

Wanat, J., Haggerty, M. and Rolle, S. (2016) Placemaking through complete streets *Government & Nonprofit*, Dec. 2016. https://www.slideshare.net/SNEAPA2015/placemaking-through-complete-streets-69880976, accessed: Nov. 28, 2017.

Wang, T., Harvey, J.T., Kendall, A. and University of California (System). (2015) Pavement Research Center. Network-Level Life-Cycle Energy Consumption and Greenhouse Gas from CAPM Treatments. *University of California Pavement Research Center*.

Wendell, C. H. (2015) Review: Urban Street Design Guide. *Journal of Planning Education and Research*, Vol. 35, Issue. 3, pp: 393-394. http://journals.sagepub.com/doi/full/10.1177/0739456X15588911

Wildnauer, M., Mulholland, E., Liddie, J., Murphy, S. (2019). Life Cycle Assessment of Asphalt Binder, *thinkstep, and Asphalt Institute* (AI).

Wolf, Sh., Siegel, K., Nowicki, B., Su, J., Bundy, K., Fleming, J., Fouco, R., and Sullivan, P. (2017). Oil Stain, How Dirty Crude Undercuts California's Climate Progress, *Center for Biological Diversity*, https://www.biologicaldiversity.org/programs/climate_law_institute/energy_and_global_warming/pdfs/Oil_Stain.pdf

Yang, R.Y. (2014). Development of a Pavement Life Cycle Assessment Tool Utilizing Regional Data and Introducing an Asphalt Binder Model, MS Thesis. *Urbana-Champaign: University of Illinois at Urbana-Champaign*. http://hdl.handle.net/2142/50651

Yang. Y. and Diez-Roux, A. V. (2012) Walking Distance by Trip Purpose and Population Subgroups, *Department of Epidemiology, Center for Social Epidemiology and Population Health, University Michigan, Ann Arbor*, National Institute of Health (NIH), Vol. 43, No. 1, pp.11–19, Jul., 2012. doi:10.1016/j.amepre.2012.03.015

Yolo County Bicycle Transportation Plan(2013) County of Yolo Bicycle Transportation Plan- Bicycle Routes and Priorities, *Yolo County Transportation Advisory Committee*, https://www.yolocounty.org/home/showdocument?id=2538, accessed Jun. 2020

APPENDIX A. ACCESSIBILITY ASSUMPTIONS AND CALCULATIONS

Average walking speed:

- The average speed of Walking is 1.88 miles per hour (Yang and Diez-Roux, 2012).
- 0.84 m/s (1.88 mi/h). [Or 0.63mile in 20 minutes]
- Considering delay based on “Pedestrian and Bicyclist Delay” performance measure, the final cycling area is calculated:
- 1.88 (mi/h) * (20min-10min)/60min = 0.32 mile for children
- 3 (mi/h) * (20min-10min)/60min = 0.5 mile for average adults

Average cycling speed:

- The beginner’s speed is 10mph. So, 8 mph is assumed for children. [Or 2.67mile in 20 minutes] (Yang and Diez-Roux, 2012)
- Considering delay based on “Pedestrian and Bicyclist Delay” performance measure, the final walking area is calculated:
- 8 (mi/h) * (20min-10min)/60min = 1.33 mile for beginners
- 12 (mi/h) * (20min-10min)/60min = 2 mile for average adults

Average transit speed:

- The average speed of rail transit is 21.5 miles per hour, while the average speed of bus transit is 14.1 mph. (O’Toole 2018, Hertz 2015)
- The average public bus speed drops from 13.6 mph to 12.7 mph.
- 14 mph is assumed for the average transit speed.
- 14 (mi/h) * (20min-10min)/60min = 2.3 mile for average adults
- 20 (mi/h) * (15min-10min)/60min = 1.67 mile for average adults

Single Mode Buffers

- Walking
    - Walking Speed = 3 mph
    - Optimal trip time = 20 minutes
    - Delay: 10 minutes
    - Buffer: $\boldsymbol{3\frac{miles}{hour} * (20-10) mintes = 0.5\ miles}$
- Biking
    - Biking Speed = 12 mph
    - Optimal trip time = 20 minutes
    - Delay: 10 minutes

- Buffer: $\mathbf{12\frac{miles}{hour} * (20-10)mintes = 2\ miles}$

Multi-Modal Buffers

<u>Buffers for each mode</u>

- Walking and Bus
    - 2 miles in 20 minutes including 10-min bus + 10-min walking
    - A pedestrian crosses the road twice, considering a 50-sec delay, which is negligible.
    - **2-mile buffer**
    - Reference Google Maps: https://www.google.com/maps/dir/37.3418199,-121.8980419/E+San+Fernando+St,+San+Jose,+CA/@37.3396405,-121.9016691,14.27z/data=!4m9!4m8!1m0!1m5!1m1!1s0x808fccc248dc86eb:0xee750dc4f51b498b!2m2!1d-121.8705735!2d37.3427555!3e3
- Walking and Train
    - It takes 4 minutes to get from Diridon Station to College Park Station
    - That leaves 16 minutes for walking including 10-min of delay (assumption+ 6-min of pure walking time
    - At 3-mph walking speed, the walking distance is 0.3 miles.
    - The train travels 1.17 miles in 4-min (measure tool in google maps)
    - 1.17+0.3 = 1.47 miles
    - **1.5-mile buffer**
- Walking and Light Rail
    - It takes 15-min to get light rail from Santa Clara Station to Metro/Airport Station, with an additional 4-min of walking +1-min of delay in walking.
    - Total distance 3.19 miles
    - **3.2-mile buffer**
    - Reference Google Maps: https://www.google.com/maps/dir/San+Antonio+Station,+San+Jose,+CA+95113/37.368398,-121.9180117/@37.3342194,-121.8922237,1023m/data=!3m1!1e3!4m9!4m8!1m5!1m1!1s0x808fccbb03bde79b:0x1b10c80522fa96ac!2m2!1d-121.8875933!2d37.3331342!1m0!3e3
- Biking and Bus
    - 10 min of transit, then 10 minutes of biking
        - 10 min transit covers 1.92 miles
    - 6 minutes of biking plus 3 minutes of delay (25 sec delay/intersection, 7 intersections), comes out to 1.1 miles
    - 1.92+1.1= 3.02 miles, rounding up to **3-mile buffer**
    - Reference Google Maps: https://www.google.com/maps/dir/37.3418827,-121.8935456/37.3406408,-121.870062/@37.3404787,-121.8915132,15.08z/data=!4m2!4m1!3e3
    - (https://www.google.com/maps/dir/37.3418568,-121.8935896/37.3548708,-121.900247/@37.3500039,-121.8990292,15.81z/data=!4m2!4m1!3e1)

- Biking and Train
    - It takes 4 minutes to get from Diridon Station to College Park Station
    - That leaves 16 minutes for biking including 13 minutes of pure biking and 3 minutes of delay
        - Biking covers 2.1 miles.
    - (https://www.google.com/maps/dir/37.3427145,-121.9156179/37.3582384,-121.9323095/@37.3565274,-121.9335545,16.33z/data=!4m2!4m1!3e1)
        - 2.1+1.17 = 3.27 miles, rounding up to **3.3-mile buffer**

- Biking and Light Rail
    - Reference Google Maps: https://www.google.com/maps/dir/Gish+Station+(North),+San+Jose,+CA+95112/37.3714096,-121.9167446/@37.3712791,-121.9167407,454m/data=!3m1!1e3!4m9!4m8!1m5!1m1!1s0x808fcb8f784b6673:0xc5ed97412fc703be!2m2!1d-121.9100781!2d37.3623803!1m0!3e1
    - It takes 15 minutes to get from Santa Clara Station to Gish Station, with an additional 4 minutes of walking and 1.25 minute of walking delay (3 intersections and 25 sec delay/intersection)—this comes out to 0.7 miles
    - Total distance: 0.7 miles + 3.19 miles = **3. 9-mile buffer**

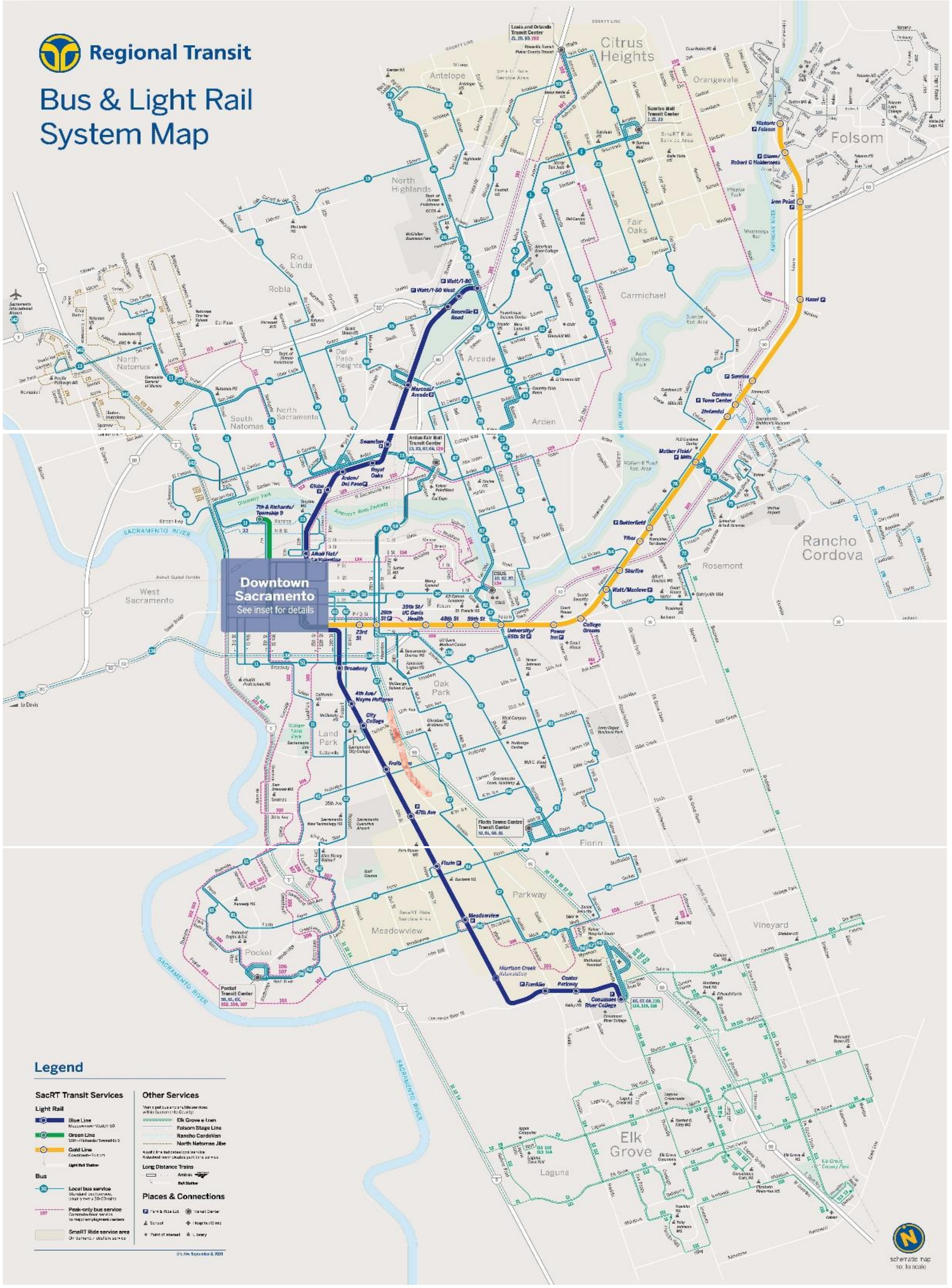


Figure A-1. Sacramento County Transit Map

APPENDIX B. ACCESS TO DESTINATION CALCULATIONS

Pharmacy

- According to a Walgreens publication, there are roughly 3.6 Pharmacists per store and 5.9 technicians per store. (https://www.walgreens.com/images/pdfs/state.pdf). 3.6 + 5.9 = 9.5
- Including cashiers and retail workers that work in the rest of the store: if the pharmacy is open 8am – 11pm, and there are two 8-hour shifts, and there are five workers per shift, then 9.5 + 2*(5) = roughly **20 employees per day.**
- **CVS** statistics are available from this website (https://cvshealth.com/about/facts-and-company-information). $\frac{4.5\ million\ customers}{day} \div 9900\ stores\ \frac{customers}{day} = \frac{455\ customers}{day}$.
- **Walgreens**: (https://news.walgreens.com/fact-sheets/frequently-asked-questions.htm)
- $\frac{8\ million\ customers}{day} \div 9277 stores\ \frac{customers}{day} = \frac{862\ customers}{day}$
- **Rite Aid:** https://www.riteaid.com/about-us/our-story, https://www.riteaid.com/corporate/news/-/pressreleases/news-room/2020/rite-aid-to-outline-corporate-strategy-and-growth-plan-at-analyst-day
- $\frac{1.6\ million\ customers}{day} \div 2464\ stores\ \frac{customers}{day} = \frac{650\ customers}{day}$
- The average daily customer of these three popular pharmacies is **635 customers per day.**

Coffee Shop

If the store is open from 6 am to 10 pm, the total hours would be 16 hrs. Two 8 hr shifts and three people per shift make it six employees. Add 1 for the manager, and there are **seven employees** going to work every day.

This logic took inspiration from https://www.quora.com/How-many-employees-do-I-need-for-my-coffee-shop

Starbucks has 500 customers/day (https://www.businessinsider.com/how-many-customers-starbucks-will-have-2013-10). A smaller place might have 200 (https://www.entrepreneur.com/article/334463). The average of these two is **350 customers/day**.

Restaurant

“Seated but casual dining: Customers expect more in the way of service if they are not helping themselves, and more staff per customer are needed to make sure that you keep up with the logistics of orders and clearing. One server for 5 – 6 tables per shift and four back of house staff per 50 tables is a balance that can work quite well.”

Assuming there are 2 shifts per day and 30 tables, (4 back house staff + 5 servers) * 2 = **18 employees**

https://www.nestleprofessional.com/news/how-many-people-do-you-need-run-your-restaurant#:~:text=One%20server%20for%20every%203,chef%20depending%20on%20your%20establishment.

Customers: According to a blog post, causal restaurants have **230 customers/day**. (https://blog.projectionhub.com/4-financial-projection-models-for-the-4-restaurant-styles/#:~:text=Using%20an%20estimate%20of%2030,used%20in%20my%20projections%20too.)

Banks

Assume **seven employees** per branch for credit unions and 6 for banks.

https://thefinancialbrand.com/55305/banking-branch-remodel-build-transformation-trends/#:~:text=For%20new%20branches%20added%2C%20the,staffed%20by%20only%20four%20employees.

Assumptions: So 6.5% do not have a bank account. Most people visit the bank six times a year. Downtown SJ has a population of 87,113.

So $87{,}113\ people * 0.935 * 6\ \frac{visits}{person-year} = 488{,}703\ bank\,\frac{visits}{year}\,in\ downtown\ SJ.$

SJ has 37 banks. So $\frac{488{,}703\ bank\ visits}{year} \div 37\ banks \div (312\,\frac{days\ open}{year}) = \frac{42\ bank\ visits}{bank-day}$

(https://apnews.com/8b2b93d4e9474c418853e0f20e79aaa8#:~:text=In%202017%20approximately%206.5%20percent,adults%20without%20a%20bank%20account.).

https://thefinancialbrand.com/66228/bank-credit-union-branch-traffic/#:~:text=Currently%2C%20consumers%20are%20averaging%20around,two%20visits%20annually%20by%202022.

https://www.areavibes.com/san+jose-ca/downtown/demographics/

Gas Station

There are two to three employees per shift on average. If the gas station is open 24hrs/day, and there are three shifts, then 2 * 3 = **6 employees**

Shell serves 30M customers every day and has 44,000 gas stations; that works out to **682 customers/day.** (https://www.shell.com/business-customers/shell-retail-licensing/about-shell-retail.html#:~:text=Shell%20Retail%20is%20the%20world's,in%20more%20than%2075%20countries.)

Grocery store

According to EnergyStar, "The average number of employees is 0.92 per 1000 square feet (92.8 square meters) for small supermarkets and 1.10 per 1000 square feet (92.8 square meters) for large supermarkets."

The Whole Foods in San Jose has a GSF of roughly 30,000 square feet:

$30{,}000\ ft^2 * \frac{1.1\ employees}{1000\ ft^2} =$ **33 employees**

https://www.energystar.gov/ia/business/tools_resources/target_finder/help/Space_Use_Information__Supermarket_Grocery_Store.htm#:~:text=The%20average%20number%20of%20employees%20are%200.92%20per%201000%20square,square%20meters)%20for%20large%20supermarkets.

According to research from some websites, there are 38,000 grocery stores in the US, and there are close to 32M customers per day. This comes out to **853 customers/day**.

https://spendmenot.com/grocery-shopping-statistics/#:~:text=Grocery%20stores%20in%20the%20US,million%20from%20Friday%20to%20Sunday.

Hospital

There were no hospitals within a 0.5-mile radius or a 2-mile radius of San Fernando Street, so I did not calculate this metric.

https://www.quora.com/How-many-employees-does-a-250-bed-hospital-have-on-average#:~:text=The%20answer%20to%20the%20question,needs%20to%20provide%20adequate%20services.

Post Office

According to a paper published by the Post Office, there were 496,934 employees in 2019 (https://about.usps.com/who-we-are/postal-history/employees-since-1926.pdf).

There are 31,322 Post Offices in the US (https://facts.usps.com/size-and-scope/#:~:text=There%20are%2031%2C322%20Postal%20Service,Offices%20in%20the%20United%20States.)

Therefore there is an average of $\frac{496{,}934\ employees}{31{,}322\ stores} = \boldsymbol{16\ employees/store}$

USPS statistics are available on their website. 811.8M customer visits in 2019 and 31,322 post offices work out to **71 customer visits/day**. (https://facts.usps.com/retail/#:~:text=There%20are%207.1%20million%20daily%20visits%20to%20usps.com.&text=In%202019%2C%20usps.com%20recorded,most%20frequently%20visited

%20government%20sites.&text=In%202019%2C%20stamp%20and%20retail,Office%20%2D%2D%20totaled%20%24301%20million.)

Library

There are 9,075 public libraries in the US (https://libguides.ala.org/numberoflibraries). There is 136,851 paid staff in public libraries in the US. (http://www.ala.org/tools/libfactsheets/alalibraryfactsheet02).

$136{,}851\ staff/9{,}075\ libraies\ =\ 15\ employees/library$

In the fiscal year 2018/2019, the San Jose Public Library had 6,226,561 visitors. (https://www.sjpl.org/facts) With 25 branches, that comes out to 682 customers/day.

Police Station

According to the San Jose Police Department website, they have 1400 employees. All of the SJPD offices are located within 2 miles of San Fernando Street. According to an uncited Wikipedia page, there are 959 officers and 370 staff. Most officers' shifts are staggered, so the entire police force is not active at the same time. If two-thirds are deployed every day, and one-third of staff do not work at the police station, then (1/3)*370 + (2/3)*(959) = **762 employees**

According to an article from the Mercury News, (https://www.mercurynews.com/2020/06/24/sjsu-students-faculty-petition-to-defund-reform-campus-police/#:~:text=The%20University%20Police%20Department%20consists,according%20to%20the%20SJSU%20website.) SJSUPD has 32 sworn officers and 45 civilian employees.

Using a similar methodology to the above, (2/3)*32 + 45 = **66 employees/day**

According to the SJPD website, there were 29,725 arrests in 2019. There are 81 arrests per day and are assumed to round up to **100 "customers"/day**.

Places of Worship

Assumptions: According to the Hartford Institute of Religion, 59% of churches have attendance between 1-99. Assuming that churches meet twice a week and that staff of 5 people go to the church office every day, $\frac{99*2+5(6)}{7} = \boldsymbol{32\ people/day}$ (http://hirr.hartsem.edu/research/fastfacts/fast_facts.html#sizecong)

Museum

Thirty-one employees are listed on the San Jose Museum of Art website.

44 staff are mentioned on the San Jose Children’s Discovery Museum.

13 staff at the Quilts and Textiles Museum

Assumption: in San Jose, 2/3 of the museums are small, and 1/3 are big. Big museums have around 38 employees (the average of 31 and 44), and small museums have 13.

$$\frac{2}{3} * 38 + \frac{1}{3} * 13 = 30\ employees$$

The San Jose Museum of art serves more than 100,000 visitors (https://sjmusart.org/about). If they are open seven days a week, that works out to **273 visitors/day**.

Government Buildings Methodology

Two criteria are needed to determine accessibility to jobs for government offices, including the number of government buildings and a number of people working in each building. The number of government buildings is found from Google Maps or a similar mapping application. However, the number of people working in each building is usually unavailable on the internet, so it is necessary to make some estimates. One method is to find the gross square footage (GSF) of the buildings using Google Maps (using the measure tool) and then look up County or City guidelines on how much space is allocated per person. However, not all GSF is usable space for employees since space is commonly taken up by elevators, walls, and support pillars. Therefore, it is necessary to determine the usable square footage (USF), as the assignable square footage (ASF). Dividing the ASF by the average space per person estimates the number of employees in that building. Some helpful references include:

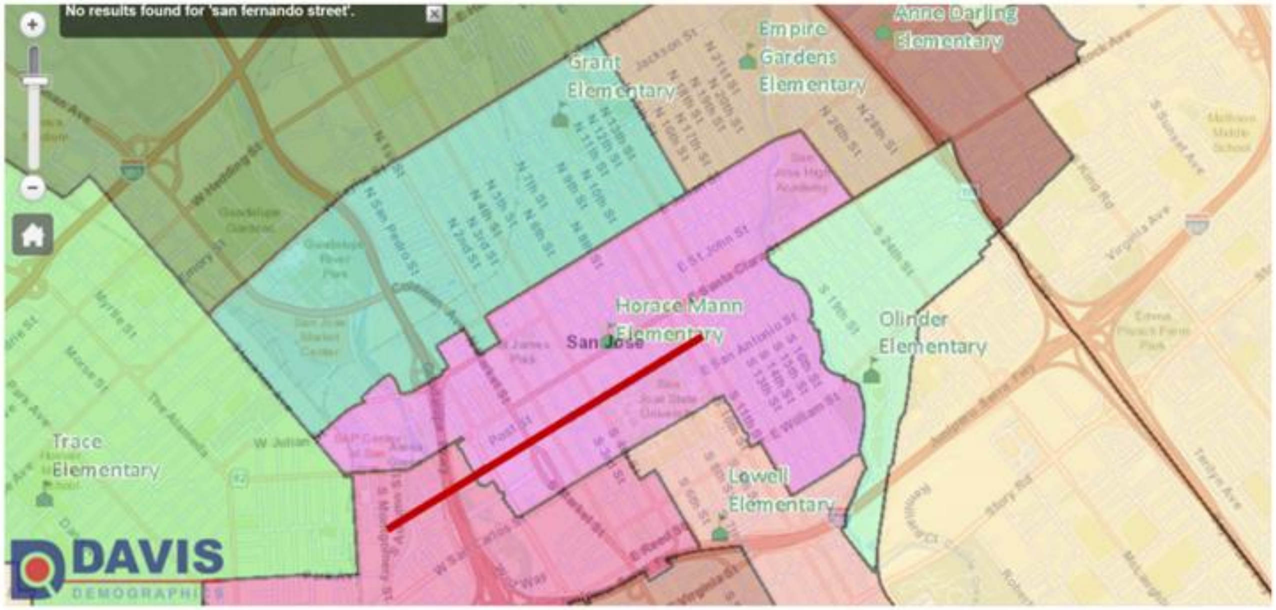
- the Government Accountability Office published guidelines for space utilization (U.S. government accountability Office, 2018),
- Virginia Tech published a policy paper that describes how much of the Gross Square Footage (GSF) is Assignable Square Footage (ASF). The ratio of ASF/GSF for office buildings with partitioned offices should be roughly 70% (Virginia Tech, 2020).
- California State University: According to a policy from the CalState university system, “Depending on the type of facility, the ratio [of ASF/GSF] should be no less than 60%.” (California State University, 2019),
- Austin Tenant Advisors (access at June 2020 at https://www.austintenantadvisors.com/blog/what-is-the-average-square-footage-of-office-space-per-person/)

It would be reasonable to use a ratio of ASF/GSF within the range of 60-70%. For the calculations in this study, an average ratio of 65% was used to estimate the number of employees.

Some useful terms in this regard include:

- GSF: Gross Square Footage
- ASF: Assignable Square Footage
- USF: Usable Square Feet (USF) per person or density
- No. of employees: ASF/USF

APPENDIX C. ACCESS TO SCHOOL COMPLEMENTARY INFORMATION



School name	No. of Students	No. of employees
1. Horace	402	14
2. Lowel	847	33
3. Olinder	395	20
4.Gardner	360	15
5. Grant	542	24
6.Empire Garden	349	16

Figure C-1. Access to School (considering school district boundary)- San Fernando Case Study

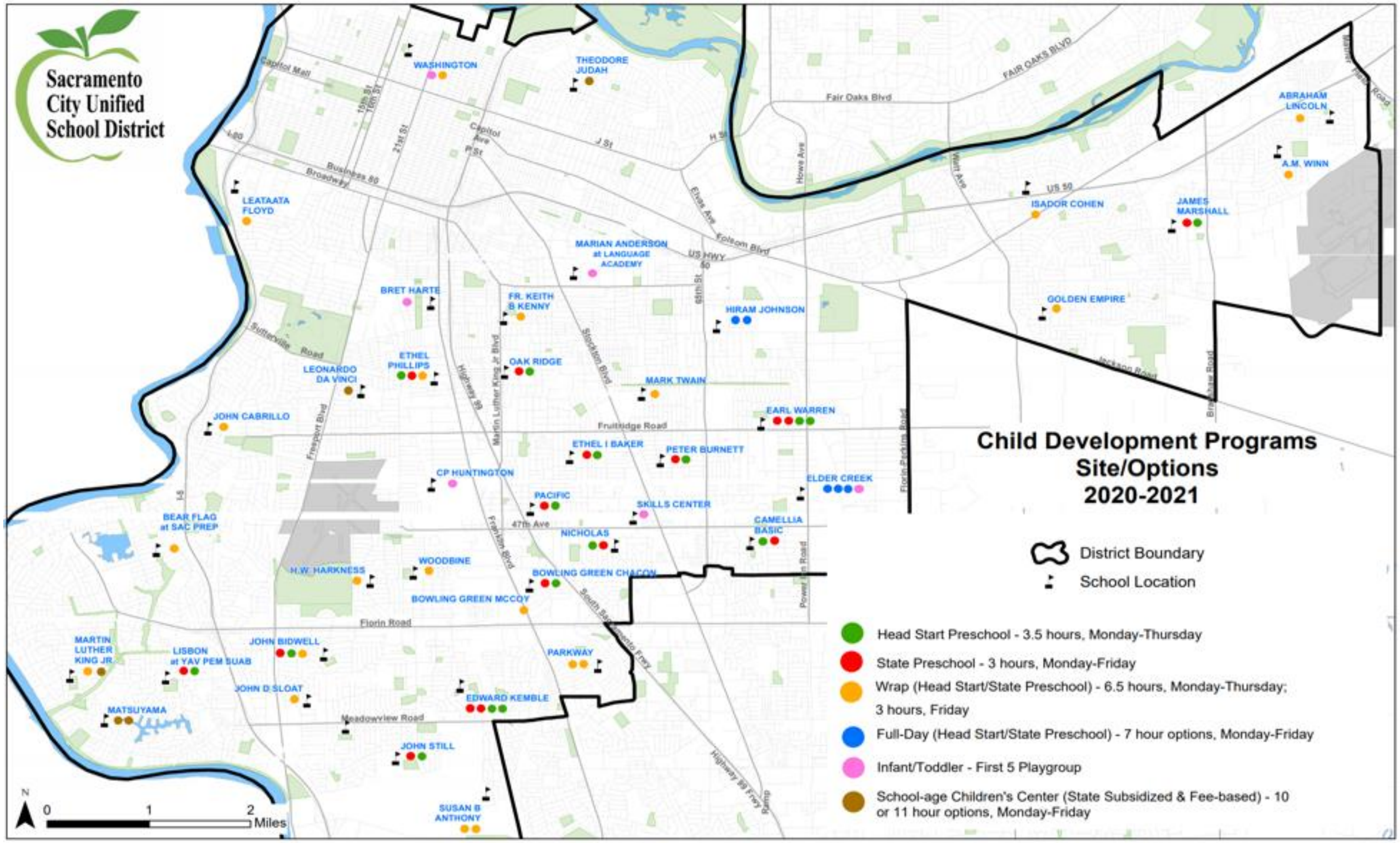


Figure C-2. Sacramento City Unified School District (including 81 schools)

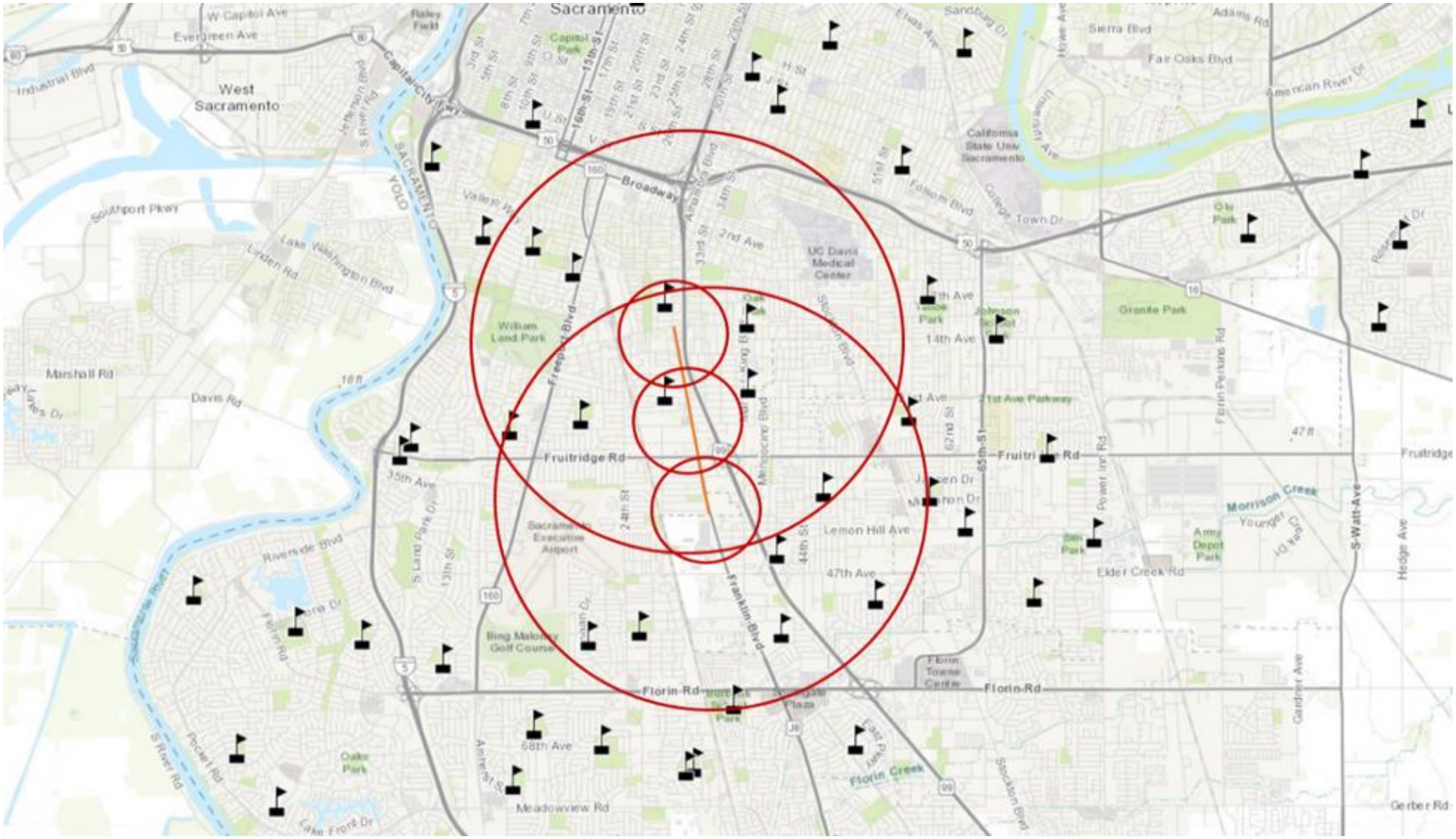


Figure C-3. Sacramento City School maps combined with the 0.5-mile walking and 2-mile cycling Circular buffer
(https://saccityusd.maps.arcgis.com/apps/webappviewer/index.html?id=65299203ccef4df4969dc9169f61a424)

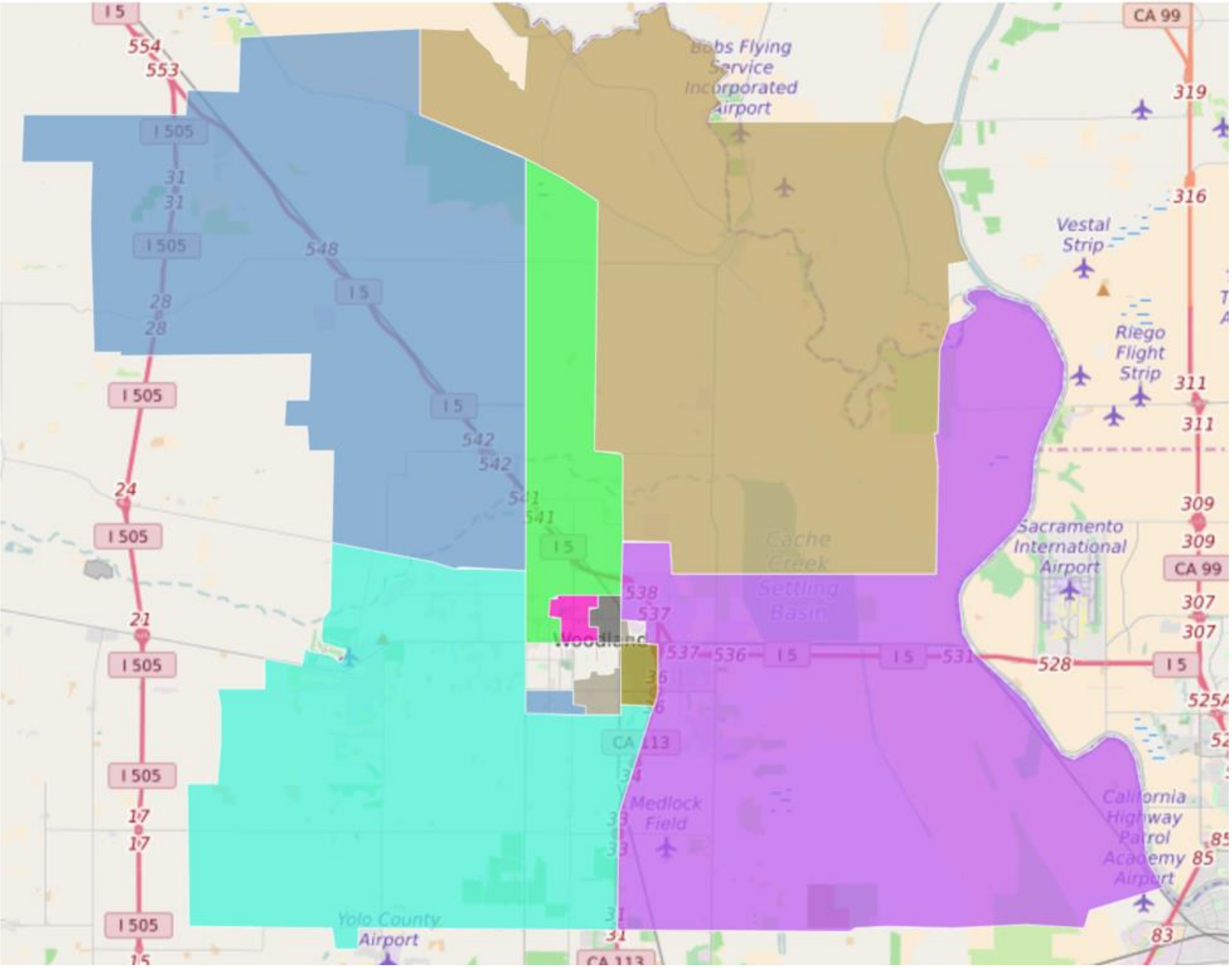


Figure C-4. Map of Woodland Joint Unified School District

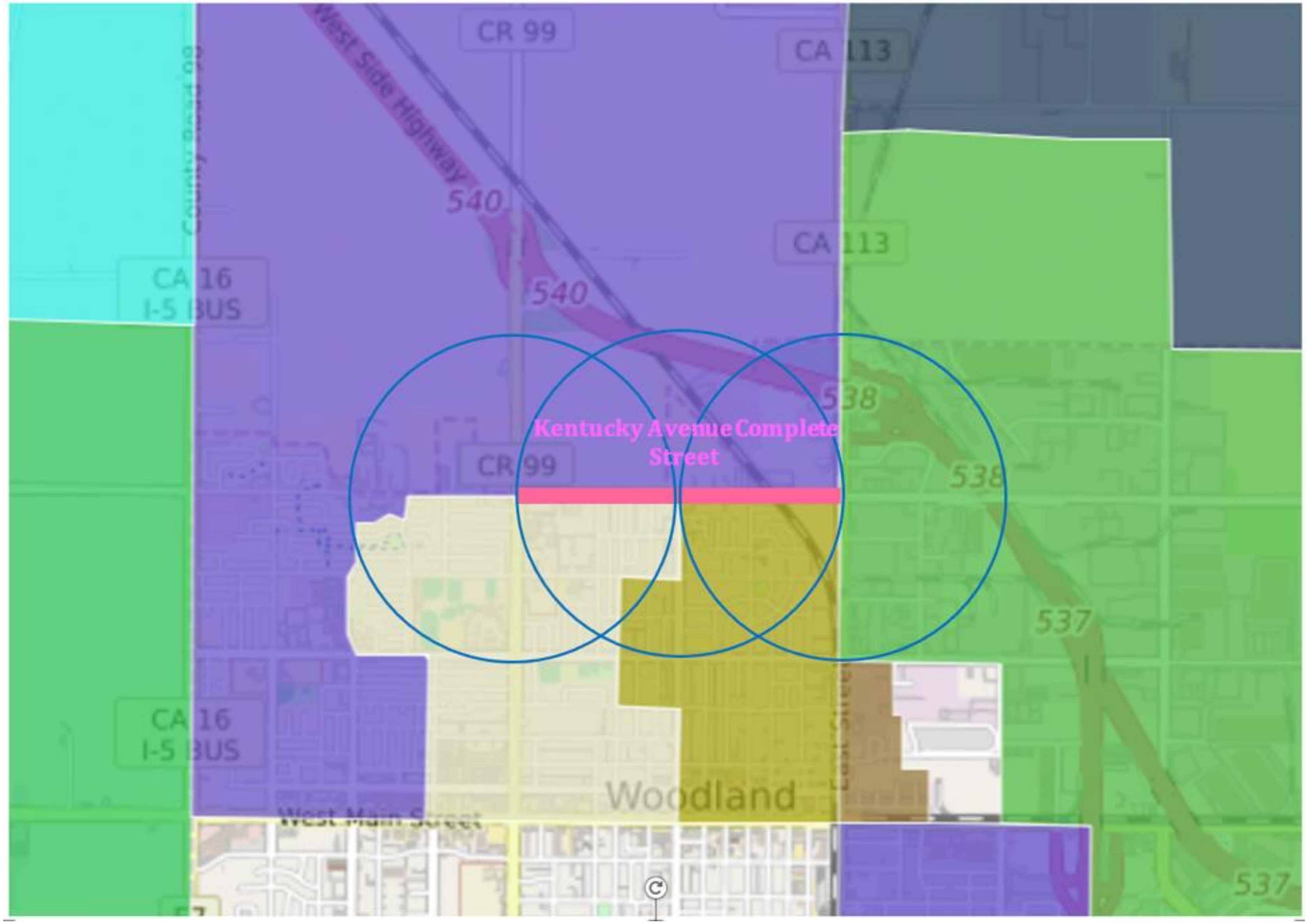


Figure C-5. City of Woodland school maps combined with the 0.5-mile walking and 2-mile cycling Circular buffer

C.1. Example of Survey for School Principals

University of California, Davis

Letter of Information

Title of study: Life Cycle Assessment of Complete Streets: Case Studies

Investigator: Professor John Harvey

Survey identifier:

Introduction and Purpose

You are being invited to join a research study. If you agree to participate in this research, you will be asked to provide answers to the best of your knowledge about travel by students to your school, and students' and parents' perceptions. Your participation in this research should take no more than one hour of your time.

You understand that the results of this study will be used to improve the quantification of benefits to students from the conversion of streets into complete streets. Any responses you provide will be anonymized. Your school's name will also be anonymous; however some other data such as distances of the school from transit stations and streets will be included and published in the report. The researcher will not be collecting or requesting any personal data of you (principals), students or parents. You may fill in the survey and email it to the researcher, or we will fill it out with you through a phone/web meeting.

Participation in research is completely voluntary. You are free to decline to take part in the project. You can decline to answer any questions and you can stop taking part in the project at any time. Whether or not you choose to participate, or answer any question, or stop participating in the project, there will be no penalty to you or loss of benefits to which you are otherwise entitled.

Questions

If you have any questions about this research, please feel free to contact the investigators:

- PI (*5102068349 or jtharvey@ucdavis.edu*)
- Co-PI (*aabutt@ucdavis.edu*)

Accessibility to School Survey
Spring 2021
-Questionnaire for the X Complete Street Project-

This *Questionnaire* is designed to aid our understanding about how children get to school and parent perceptions of safety and convenience including transit services and active transportation now available as a result of the San Fernando complete streets project located in the City of X. The researcher is interested in:

- Estimates of mode choice between student's homes and schools, and
- Understanding the effects of complete streets on student travel to and from school.

This research is being performed with a grant from the National Center for Sustainable Transportation at UC Davis. The research being conducted investigates the social and economic impacts of complete streets improvements in transit corridors near public schools. The study of transit near schools requires our focus on public schools near the project site. We do not want to interview students and parents, but instead assess their perceptions and choices by surveying the principals of the schools. There are X schools located near the X complete street project. The researcher will be requesting the school principals to fill in the survey. If they prefer to provide their feedback on the phone or web meeting, no more than one-hour interviews will be conducted. This same survey questionnaire will be used as the interview script.

The questions mainly focus on how the complete street project affects students' commutes in terms of safety and time. No personal information about students or parents is being requested. We will keep the identities of the principals interviewed confidentially[6].

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[6] The researcher affirms that they, as the only authorized people, will have access to the identifiers, which will be stored on computers, electronic notebooks, mobile devices, and/or data-storage devices encrypted and

The final report will include publicly available data (such as distances to streets and transit stations, number of students, other information about student population) and analyzed results without stating the school name or principal's name. Importantly, school principals may decline to take part in this survey and can choose to stop participating at any time, for any reason, when being interviewed.

C.2. Questionnaire for Principals of Elementary Schools

NOTE: All questions are with regard to travel before and after completion of the X complete street project and before Covid closures of schools in March 2020.

1. Based upon what you know about your students, what percentage of your students reside outside the district attendance boundaries for your school?
2. Based upon what you know about your students and their parents, do parents use the proposed complete X street when dropping off/ picking up students to/from school?
3. Based upon your estimation, do students use X the proposed complete street when commuting to or from school?
4. What do you think can be done to improve accessibility and safety for students commuting to school? Does the X complete street conversion help?

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password-protected, and will be kept in a locked area (if maintained in paper format) with access limited only to researcher who require access to conduct the study. Identifiers will be removed from the identifiable private information and after the data are de-identified, they could be used for future research studies or distributed to another researcher. The survey information collected as part of the research, and even if identifiers are removed, they will not be used or distributed for future research studies.

5. Based upon what you know about your students, what percentage of students take the following modes of transportation to/from school based on the season, (after building the complete street conversion and before the Covid closure)?

Season	Walk	Bike	Bus/Train	Car	Combination trip	Other
Fall						
Winter						
Spring						

6. Based upon what you know about your students, what percentage of students took the following modes of transportation to/from school based on the season (before building a complete street)?

Season	**Walk**	**Bike**	**Bus/Train**	**Car**	**Combination trip**	**Other**
Fall						
Winter						
Spring						

7. Based upon the age and grade of your students, can you estimate the time it takes your students to commute to school?

Time	**Walk (Kindergarten)**	**Walk (1st to 5th grade)**	**Bike (Kindergarten)**	**Bike (1st to 5th grade)**	**Bus/ Train (Kindergarten)**	**Bus/Train (1st to 5th grade)**	**Car (Kindergarten)**	**Car (1st to 5th grade)**	**Combination trip (Kindergarten)**	**Combination trip (1st to 5th grade)**	**Other**
0-10 minutes											
11-20 minutes											
21-30 minutes											
31-40 minutes											

8. Please provide an estimate of what percentages of students walk or bike without adult supervision (on their own or with other children), by their grade in school:

Grade	**Kindergarten**	**1st**	**2nd**	**3rd**	**4th**	**5th**
Percentage Biking						
Percentage Walking						

9. Which street is the main route for students to take to school based on your estimation?

Mode	**Walk**	**Bike**	**Train/Bus**	**Car**	**Other**
Main route(s)					

10. Do you think parents perceive that the X complete street project has made it safer?

11. Based upon your estimation, do your students feel safe and comfortable when walking/ biking or using transit?

12. Does your school have enough bike parking for the students? If yes, what kind of security for bike parking do you have?

13. Based on your perception, how safe do you think it is for students to bike/walk or use transit or combined bike or walk and transit to school? If not, please explain why (eg. no bike lanes, heavy traffic, street crime, etc.)

14. Do you think parents feel comfortable with their children:
    a. biking/walking or using transit to school alone?
    b. biking/walking or using transit to school with at least one adult?
    c. traveling to school with other children?

15. From your observations and what you know about your students, what additional streets, corridors or intersections used by students to travel to school need improvements or repairs to make them safer and more comfortable walking, biking, and using transit?

16. Based on what you know about the school district, are there any recent changes in school district activity that may influence where a student attends school? (e.g., students are going to different schools and the students may no longer be able to walk or bike to school; or students will be passing through the complete streets project to get to their new school)?

C.3. Questionnaire for Principals of Middle Schools

NOTE: All questions are with regard to travel before and after completion of the X complete street project and before Covid closures of schools in March 2020.

1. Based upon what you know about your students, what percentage of your students reside outside the district attendance boundaries for your school?
2. Based upon what you know about your students and their parents, do parents use Xcomplete street when dropping off/ picking up students to/from school?
3. Based upon your estimation, do students use X complete street when commuting to or from school?
4. What do you think can be done to improve accessibility and safety for students commuting to school? Does the Xcomplete street conversion help?
5. Based upon what you know about your students, what percentage of students take the following modes of transportation to/from school based on the season, (after building the complete street conversion and before the Covid closure)?

Season	Walk	Bike	Bus/Train	Car	Combination trip	Other
Fall						
Winter						
Spring						

6. Based upon what you know about your students, what percentage of students took the following modes of transportation to/from school based on the season (before building a complete street)?

Season	Walk	Bike	Bus/Train	Car	Combination trip	Other
Fall						
Winter						
Spring						

7. Based upon the age and grade of your students, can you estimate the time it takes your students to commute to school?

Time	**Walk (6th to 8th grade)**	**Bike (6th to 8th grade)**	**Bus/ Train (6th to 8th grade)**	**Car (6th to 8th grade)**	**Combination trip (6th to 8th grade)**	**Other**
0-10 minutes						
11-20 minutes						
21-30 minutes						
31-40 minutes						

8. Please provide an estimate of what percentages of students bike or walk to school without adult supervision (on their own), by their grade school:

Grade	**6st**	**7TH**	**8TH**
Percentage Biking			
Percentage Walking			

9. Which street is the main route for students to take to school based on your estimation?

Mode	**Walk**	**Bike**	**Train/Bus**	**Car**	**Other**
Main route(s)					

10. Do you think parents perceive that the complete street project has made it safer?

11. Based upon your estimation, do your students feel safe and comfortable when walking/biking or using transit?

12. Does your school have enough bike parking for the students? If yes, what kind of security for bike parking do you have?

13. Based on your perception, how safe do you think it is for students to bike/walk or use transit or combined bike or walk and transit to school? If not, please explain why (eg. no bike lanes, heavy traffic, street crime, etc.)

14. Do you think parents feel comfortable with their children:
    a. biking/walking or using transit to school alone?
    b. biking/walking or using transit to school with at least one adult?
    c. traveling to school with other children?

15. From your observations and what you know about your students, what additional streets, corridors or intersections used by students to travel to school need improvements or repairs to make them safer and more comfortable walking, biking, and using transit?

16. Based on what you know about the school district, are there any recent changes in school district activity that may influence where a student attends school? (e.g., students are going to different schools and the students may no longer be able to walk or bike to school; or students will be passing through the complete streets project to get to their new school)?

C.4. Questionnaire for Principals of High Schools

NOTE: All questions are with regard to travel before and after completion of the X complete street project and before Covid closures of schools in March 2020.

1. Based upon what you know about your students, what percentage of your students reside outside the district attendance boundaries for your school?

2. Based upon what you know about your students and their parents, do parents use complete street when dropping off/ picking up students to/from school?

3. Based upon your estimation, do students use Xcomplete street when commuting to or from school?

4. What do you think can be done to improve accessibility and safety for students commuting to school? Does the complete street conversion help?

5. Based upon what you know about your students, what percentage of students take the following modes of transportation to/from school based on the season, (after building the complete street conversion and before the Covid closure)?

Season	Walk	Bike	Bus/Train	Car	Combination trip	Other
Fall						
Winter						
Spring						

6. Based upon what you know about your students, what percentage of students take the following modes of transportation to/from school based on the season (before building a complete street)?

Season	Walk	Bike	Bus/Train	Car	Combination trip	Other
Fall						
Winter						
Spring						

7. How long does it take students of different ages to commute to school for each mode based on your estimation?

Time	Walk (9th to 10th grade)	Walk (11th to 12th grade)	Bike (9th to 10th grade)	Bike (11th to 12th grade)	Bus/Train (9th to 10th grade)	Bus/Train (11th to 12th grade)	Car (9th to 10th grade)	Car (11th to 12th grade)	Combination trip (9th to 10th grade)	Combination trip (11th to 12th grade)	Other
0-10 minutes											
10-20 minutes											
20-30 minutes											
30-40 minutes											

8. Please provide an estimate of what percentages of students bike or walk to school without adult supervision (by their own), by class:

Grade	9th	10th	11th	12th
Biking Percentage				
Walking Percentage				

9. Which street is the main route for students to take to school based on your estimation?

Mode	Walk	Bike	Train/Bus	Car	Other
Main route(s)					

10. Do you think parents perceive that the X complete street project has made it safer?

11. Based upon your estimation, do your students feel safe and comfortable when walking/ biking or using transit?

12. Does your school have enough bike parking for the students? If yes, what kind of security for bike parking do you have?

13. Based on your perception, how safe do you think it is for students to bike/walk or use transit or combined bike or walk and transit to school? If not, please explain why (eg. no bike lanes, heavy traffic, street crime, etc.)

14. Do you think parents feel comfortable with their children:
    a. biking/walking or using transit to school alone?
    b. biking/walking or using transit to school with at least one adult?
    c. traveling to school with other children?

15. From your observations and what you know about your students, what additional streets, corridors or intersections used by students to travel to school need improvements or repairs to make them safer and more comfortable walking, biking, and using transit?

16. Based on what you know about the school district, are there any recent changes in school district activity that may influence where a student attends school? (e.g., students are going to different schools and the students may no longer be able to walk or bike to school; or students will be passing through the complete streets project to get to their new school)?

17. Do you have a magnet program for students who live outside your school's boundaries?

APPENDIX D. LEVEL OF TRAFFIC STRESS COMPLEMENTARY TABLES

Tables used in the calculation of LTS for the San Fernando Case Study derived from Montgomery LTS tables (Montgomery County Bicycle Master Plan, 2018)

Table D-1. Intersection LTS used for finding the LTS for Before and After Building the Complete Street

	# of Lanes of Street Being Crossed					
Posted Speed Limit on Street Being Crossed	No Median Refuge			Median Refuge (≥6 ft wide)		
	2 to 3	4 to 5	6+	2 to 3	4 to 5	6+
≤25	1	2	4	1	1	2
30	1	2	4	1	2	3
35	2	3	4	2	3	4
≥40	3	4	4	3	4	4

The width of the bike lane and the parking, before building the complete street is 13.4 feet, which is less than 14 ft. Therefore, the LTS for before building the Complete Street is 2.5 because

Table D-2. Bike Lanes used for finding the LTS for After Building the Complete Street

Street Segments: Revised Level of Traffic Stress
Bikeway: Bike Lanes

Posted Speed Limit (mph)	# of Through Lanes	Bike Lanes						
		No Parking			Parking			
		Infrequently Obstructed		Frequently Obstructed	Infrequently Obstructed / Low Parking Turnover			Frequently Obstructed / High Parking Turnover
		Bike Lane £ 5.5 ft	Bike Lane ³ 6.0 ft		Bike Lane + Parking	Bike Lane + Parking = 14.0 – 14.5 ft	Bike Lane + Parking = 15.0 ft	
≤25	2-3	2	1	2.5	2.5 (2a)	2	1	2.5
	4-5	2.5 (2b)	2.5 (2b)	2.5	3			
	³6	3			3			
30	2-3	2	2	2.5	2.5	2	2	2.5
	4-5	2.5 (2b)	2.5 (2b)	2.5	3			
	³6	3			3			
35	2-3	3			3			
	4-5							
	³6							
40	2-3	3			n/a			
	4-5	4 (3b)						
	³6	4						
≥45	2-3	4			n/a			
	4-5							
	³6							

Table D-3. Shared/ Separated Bike Lanes used for finding the LTS for After Building the Complete Street

Street Segments: Revised Level of Traffic Stress
Bikeway: Sidepaths, Independent Right-of-Way and Separated Bike Lanes

Posted Speed Limit (mph)	# of Through Lanes	Shared Use Path			Separated Bike Lanes			
		Sidepath with Buffer < 5 ft (and no railing) OR Many Driveways	Sidepath with Buffer ³ 5 ft (or railing) AND Few Driveways	Independent ROW	Flex Posts	Separated Bike Lanes with Buffer < 5 ft (and no railing) OR Many Driveways	Separated Bike Lanes with Buffer ³ 5 ft (or railing) AND Few Driveways	Parked Cars
≤25	3-Feb	2 (1f)	1	0	1	2 (1f)	1	1
	5-Apr				2			
	³6				2.5			
30	3-Feb	2 (1f)	1	0	2	2 (1f)	1	1
	5-Apr				2.5			
	³6				2.5			
35	3-Feb	2 (1f)	1	0	2	2 (1f)	1	1
	5-Apr				2.5			
	³6				2.5			
40	3-Feb	2	2 (1e)	0	2.5	2	2 (1e)	n/a
	5-Apr							
	³6							
≥45	3-Feb	2	2 (1e)	0	2.5	2	2 (1e)	n/a
	5-Apr							
	³6							

Tables used in the calculation of LTS for Franklin Boulevard and Kentucky Avenue Case Study (Furth, 2017)

Table D-4. LTS for Segment by Bikeway Type

Segment Type	Level of Traffic Stress
Stand-alone paths	LTS = 1
Segregated paths (sidepaths, cycle tracks)	LTS = 1
Bike lanes	LTS can vary from 1 to 4; see Tables 2 and 3
Mixed traffic	LTS can vary from 1 to 4; see Table 4

Table D-5. Criteria for Bike Lanes Alongside a Parking Lane

	LTS ^{3} 1	**LTS ^{3} 2**	**LTS ^{3} 3**	**LTS ^{3} 4**
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	More than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Note: Dimensions aggregate using Weakest Link logic

Table D-6. Criteria for Mixed Traffic

	Street Width		
Speed Limit or Prevailing Speed	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 [a] or 2 [a]	LTS 3	LTS 4
30 mph	LTS 2 [a] or 3 [a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets without marked centerlines and with ADT ≤ 3000; use higher value otherwise.

Table D-7. Criteria for Bike Lanes and Mixed Traffic on Intersection Approaches in the Presence of a Right Turn Lane

Configuration	Level of Traffic Stress
Single RT lane up to 150 ft long, starting abruptly while the bike lane continues straight; intersection angle such that turning speed is £ 15 mph.	LTS ³ 2
Single RT lane longer than 150 ft, starting abruptly while the bike lane continues straight; intersection angle such that turning speed is £ 20 mph.	LTS ³ 3
Single RT lane in which the bike lane shifts to the left, but the intersection angle and curb radius are such that turning speed is £ 15 mph.	LTS ³ 3
Single RT lane with any other configuration; dual RT lanes; or RT lane plus option (through-right) lane.	LTS = 4

Note: "Bike lane" here means either a pocket bike lane (between the RT lane and a through lane), or a bike lane marked within the right turn lane. These criteria do not apply if a segregated bike lane is kept to the right of a right turn lane and provided a safe means of crossing.

Table D-8. Criteria for Unsignalized Crossings

a. NO CROSSING ISLAND	**Width of Street Being Crossed**		
Speed Limit or Prevailing Speed	Up to 3 lanes	4 - 5 lanes	6+ lanes
Up to 25 mph	LTS 1	LTS 2	LTS 4
30 mph	LTS 1	LTS 2	LTS 4
35 mph	LTS 2	LTS 3	LTS 4
40+	LTS 3	LTS 4	LTS 4

b. WITH CROSSING ISLAND	**Width of Street Being Crossed**		
Speed Limit or Prevailing Speed	Up to 3 lanes	4 - 5 lanes	6+ lanes
Up to 25 mph	LTS 1	LTS 1	LTS 2
30 mph	LTS 1	LTS 2	LTS 3
35 mph	LTS 2	LTS 3	LTS 4
40+	LTS 3	LTS 4	LTS 4

APPENDIX E. ITEMIZED ENVIRONMENTAL LCA IMPACT RESULTS

Table E-1. Itemized Impacts of The Conventional Option During the Analysis Period for Materials, Transportation, and Construction Stages- San Fernando Street

Treatment (during the analysis period)	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Service Life [yrs]	Thickness (cm)	# of Treat. App.	Width (m)	# per block	Note	Share of this item in Total GWP
HMA (overlay)	1 Block	3.33E+04	4.21E+03	2.13E+01	3.80E+05	1.21E+06	10.0	8.9	3	3.70	3	Street Top Layer	40.6%
Aggregate, Crushed	1 Block	1.77E+04	3.14E+03	6.75E+00	2.73E+05	0.00E+00	15.0	33.0	2	3.70	3	Street AB	21.6%
PCC	1 Block	1.38E+04	1.28E+03	7.57E+00	1.07E+05	0.00E+00	20.0	15.2	2	0.91	2	Curb & Gutter Surface	16.9%
Aggregate, Crushed	1 Block	1.17E+03	2.07E+02	4.45E-01	1.80E+04	0.00E+00	15.0	15.2	2	0.91	2	Curb & Gutter AB	1.4%
Planting	1 Block	1.91E+01	1.07E+01	6.56E-02	7.71E+02	0.00E+00	5.0	NA	6	1.83	2	Landscape	0.0%
PCC	1 Block	1.39E+04	1.29E+03	7.63E+00	1.08E+05	0.00E+00	20.0	9.2	2	1.52	2	Sidewalk Surface	17.0%
Aggregate, Crushed	1 Block	1.95E+03	3.45E+02	7.42E-01	3.00E+04	0.00E+00	15.0	15.2	2	1.52	2	Sidewalk AB	2.4%
Total	**1 Block**	**8.19E+04**	**1.05E+04**	**4.45E+01**	**9.17E+05**	**1.21E+06**							

Table E-2. Itemized Impacts of The Complete Street Option During the Analysis Period for Materials, Transportation, and Construction Stages- San Fernando Street

CS Element	Material	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Service Life	# per Block	Length (m)	Width (m)	Area of the Element (m2)	% of area that is replacing conventional treatment	Total Mass/Area/Length/Count over that of the CS element in the CS tab
Coloring Lanes	Paint (area)	6.77E-03	8.33E-02	6.19E-07	1.09E-02	0.00E+00	3	2	81	2.44	197	0%	394
Shelter/ Transit station	PCC on AB	3.75E+03	3.77E+02	1.99E+00	3.17E+04	0.00E+00	15	1	15	3.00	45	100%	45
Planted Furniture Zone	Planting	1.18E+01	2.45E+00	1.50E-02	1.76E+02	0.00E+00	5	1	61	3.00	182	100%	182
Curb Type 5	PCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	15	1		NA	NA	0%	0
Coloring Lanes	Paint (area)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3	2			0	0%	0
Raised Bicycle Buffer	HMA (overlay)	2.26E+02	2.86E+01	1.45E-01	2.59E+03	8.22E+03	10	2	81	NA	NA	0%	162
Buffered Cycle Track	HMA (overlay)	1.27E-03	1.56E-02	1.16E-07	2.05E-03	0.00E+00	3	2	81	1.52	123	100%	246
Total (for 1 Block)		**3.99E+03**	**4.08E+02**	**2.15E+00**	**3.45E+04**	**8.22E+03**							

Table E-3. Itemized Impacts of The Conventional Option During the Analysis Period for Materials, Transportation, and Construction Stages- Franklin Boulevard

Treatment (during the analysis period)	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Service Life [yrs]	Thickness (cm)	# of Treat. App.	Salvage (% of Service	Width (m)	# per block	Note	Share of this item in Total GWP
HMA (overlay)	1 Block	4.27E+04	5.40E+03	2.73E+01	4.88E+05	1.55E+06	10.0	8.9	3	0%	3.70	3	Street Top Layer	40.6%
Aggregate, Crushed	1 Block	2.27E+04	4.03E+03	8.67E+00	3.50E+05	0.00E+00	15.0	33.0	2	0%	3.70	3	Street AB	21.6%
PCC	1 Block	1.78E+04	1.64E+03	9.72E+00	1.37E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	16.9%
Aggregate, Crushed	1 Block	1.50E+03	2.65E+02	5.71E-01	2.31E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.4%
Planting	1 Block	2.45E+01	1.38E+01	8.41E-02	9.90E+02	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	1 Block	1.79E+04	1.65E+03	9.79E+00	1.38E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	17.0%
Aggregate, Crushed	1 Block	2.50E+03	4.42E+02	9.52E-01	3.85E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	2.4%
Total	**1 Block**	**1.05E+05**	**1.34E+04**	**5.71E+01**	**1.18E+06**	**1.55E+06**								

Table E-4. Itemized Impacts of The Complete Street Option During the Analysis Period for Materials, Transportation, and Construction Stages- Franklin Boulevard

CS Element	Material	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Service Life (yrs)	# per Block	Length (m)	Width (m)	Area of the Element (m2)	% of area that is replacing conventional treatment	Total Mass/Area/ Length/ Count over that of the CS element in the CS tab
Coloring Lanes	Paint (area)	7.60E-03	9.35E-02	6.95E-07	1.23E-02	0.00E+00	3	2	104	2.13	221	0%	442
Shelter/Transit station	PCC on AB	3.75E+03	3.77E+02	1.99E+00	3.17E+04	0.00E+00	15	1	15	3.00	45	100%	45
Planted Furniture Zone	Planting	1.08E+01	2.25E+00	1.37E-02	1.62E+02	0.00E+00	5	1	84	2.00	167	100%	167
Curb Type 5	PCC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	15	1		NA	NA	0%	0
Coloring Lanes	Paint (area)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3	2			0	0%	0
Raised Bicycle Buffer	HMA (overlay)	2.90E+02	3.67E+01	1.86E-01	3.32E+03	1.05E+04	10	2	104	NA	NA	0%	207
Buffered Cycle Track	HMA (overlay)	6.51E-04	8.01E-03	5.95E-08	1.05E-03	0.00E+00	3	2	104	0.61	63	100%	126
Total (for 1 Block)		**3.99E+03**	**4.05E+03**	**4.16E+02**	**2.19E+00**	**3.52E+04**							

Table E-5. Itemized Impacts of The Conventional Option During the Analysis Period for Materials, Transportation, and Construction Stages- Kentucky Avenue

	Treatment (during the analysis period)	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Service Life [yrs]	Thickness (cm)	# of Treat. App.	Salvage (% of Service Life)	Width (m)	# per block	Note	Share of this item in Total GWP
West Kentucky	HMA (overlay)	1 Block	8.47E+04	1.07E+04	5.43E+01	9.68E+05	3.08E+06	10.0	8.9	3	0%	3.70	3	Street Top Layer	38.0%
	Aggregate, Crushed	1 Block	3.47E+04	6.15E+03	1.32E+01	5.35E+05	0.00E+00	15.0	25.4	2	0%	3.70	3	Street AB	15.6%
	PCC	1 Block	4.63E+04	4.28E+03	2.53E+01	3.57E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	20.8%
	Aggregate, Crushed	1 Block	3.90E+03	6.91E+02	1.49E+00	6.02E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.8%
	Planting	1 Block	6.39E+01	3.59E+01	2.19E-01	2.58E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
	PCC	1 Block	4.66E+04	4.31E+03	2.55E+01	3.60E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	20.9%
	Aggregate, Crushed	1 Block	6.51E+03	1.15E+03	2.48E+00	1.00E+05	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	2.9%
	Total	**1 Block**	**2.23E+05**	**2.73E+04**	**1.23E+02**	**2.38E+06**	**3.08E+06**								
East Kentucky	HMA (overlay)	1 Block	9.53E+04	1.21E+04	6.11E+01	1.09E+06	3.46E+06	10.0	7.6	3	0%	3.70	3	Street Top Layer	38.1%
	Aggregate, Crushed	1 Block	5.14E+04	9.09E+03	1.96E+01	7.92E+05	0.00E+00	15.0	33.0	2	0%	3.70	3	Street AB	20.5%
	PCC	1 Block	4.63E+04	4.28E+03	2.53E+01	3.57E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	18.5%
	Aggregate, Crushed	1 Block	3.90E+03	6.91E+02	1.49E+00	6.02E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.6%
	Planting	1 Block	6.39E+01	3.59E+01	2.19E-01	2.58E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
	PCC	1 Block	4.66E+04	4.31E+03	2.55E+01	3.60E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	18.6%
	Aggregate, Crushed	1 Block	6.51E+03	1.15E+03	2.48E+00	1.00E+05	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	2.6%
	Total	**1 Block**	**2.50E+05**	**3.16E+04**	**1.36E+02**	**2.76E+06**	**3.46E+06**								

Table E-6. Itemized Impacts of The Complete Street Option During the Analysis Period for Materials, Transportation, and Construction Stages- Kentucky Avenue

	CS Element	**Material**	**GWP [kg CO2e]**	**POCP [kg O3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Non-Fuel) [MJ]**	**Service Life (yrs)**	**# per Block**	**Length (m)**	**Width (m)**	**Area of the Element (m2)**	**% of area that is replacing conventional treatment**	**Total Mass/Area/Length/Count over that of the CS element in the CS tab**
West Kentucky	Coloring Lanes	Paint (area)	9.90E-03	1.22E-01	9.05E-07	1.60E-02	0.00E+00	3	1	270	2.13	576	0%	576
	Curb Extension	PCC on AB	4.88E+03	4.91E+02	2.59E+00	4.13E+04	0.00E+00	15	3	8	2.44	20	100%	59
	Raising the Intersection to Sidewalk Grade	HMA (overlay)	1.08E+03	1.36E+02	6.89E-01	1.23E+04	3.91E+04	10	1	10	3.00	29	0%	29
	Raised Bicycle Buffer	HMA (overlay)	2.24E+01	2.83E+00	1.44E-02	2.56E+02	8.14E+02	10	2	8	NA	NA	0%	16
	Buffered Cycle Track	HMA (overlay)	8.48E-04	1.04E-02	7.76E-08	1.37E-03	0.00E+00	3	2	270	0.30	82	100%	165
	Total (for 1 Block)		**5.98E+03**	**6.30E+02**	**3.30E+00**	**5.38E+04**	**3.99E+04**							
East Kentucky	Coloring Lanes	Paint (area)	1.98E-02	2.44E-01	1.81E-06	3.20E-02	0.00E+00	3	2	270	2.13	576	0%	1152
	Planted Furniture Zone	Planting	3.24E+01	6.73E+00	4.11E-02	4.83E+02	0.00E+00	5	1	250	2.00	500	100%	500
	Raised Bicycle Buffer	HMA (overlay)	7.56E+02	9.57E+01	4.85E-01	8.64E+03	2.75E+04	10	2	270	NA	NA	0%	540
	Buffered Cycle Track	HMA (overlay)	8.48E-04	1.04E-02	7.76E-08	1.37E-03	0.00E+00	3	2	270	0.30	82	100%	165
	Total (for 1 Block)		**7.88E+02**	**1.03E+02**	**5.26E-01**	**9.13E+03**	**2.75E+04**							

APPENDIX F. NEIGHBORHOOD INFORMATION FROM CALENVIROSCREEN

Table F-1. Summary of percentile rankings for environmental and public health burdens and populations for neighborhoods near complete streets from CalEnviroScreen

Complete Street	**Census tract**	**Neighborhood ID number**	**0.5 or 2.0 mile distance**	**CalEnviroScreen percentile ranking (%)**	**Population**
San Fernando St.					
	95110	6085500300	0.5	55-60	3140
	95110	6085500800	0.5	60-65	2600
	95112	6085501000	0.5	70-75	4769
	95192	6085500901	0.5	55-60	3723
	95112	6085501200	0.5	60-65	4186
	95128	6085502102	2	55-60	7469
	95126	6085502002	2	70-75	4887
	95128	6085502001	2	50-55	5022
	95126	6085500500	2	30-35	5275
	95050	6085505203	2	55-60	4809
	95110	6085505100	2	65-70	3027
	95110	6085500300	2	55-60	3140
	95126	6085500400	2	40-45	2369
	95126	6085500600	2	35-40	4586
	95126	6085501900	2	50-55	4641
	95125	6085502302	2	10-15	2826
	95125	6085502301	2	30-35	3245
	95126	6085502201	2	25-30	6260
	95125	6085503121	2	70-75	4499
	95112	6085503122	2	85-90	3449
	95112	6085503112	2	70-75	4025
	95122	6085503105	2	90-95	2484
	95122	6085503117	2	75-80	3120
	95122	6085503110	2	80-85	4618
	95116	6085501501	2	75-80	4278
	95116	6085501402	2	60-65	2947
	95116	6085501401	2	75-80	3295
	95112	6085501200	2	60-65	4186
	95131	6085504318	2	85-90	5265
	95133	6085503601	2	85-90	2992
	95133	6085504319	2	70-75	6936
	95133	6085503709	2	65-70	5088
	95116	6085503707	2	50-55	5462
	95116	6085503602	2	80-85	4741
	95116	6085503710	2	70-75	3599
	95116	6085503711	2	60-65	4763
	95122	6085503105	2	90-95	2488
	95110	6085500300	2	55-60	3140
	95112	6085501101	2	55-60	4074

Complete Street	**Census tract**	**Neighborhood ID number**	**0.5 or 2.0 mile distance**	**CalEnviroScreen percentile ranking (%)**	**Population**
	95112	6085501000	2	70-75	4769
	95110	6085500800	2	60-65	2600
	95116	6085501502	2	70-75	4549
	95110	6085503113	2	75-80	4760
	95112	6085503112	2	70-75	4025
Franklin Blvd.					
	95822	6067003501	0.5	50-55	2629
	95820	6067003600	0.5	65-70	2826
	95818	6067002500	0.5	10-15	1587
	95820	6067003700	0.5	75-80	4219
	95822	6067003501	2	50-55	2629
	95818	6067002400	2	30-35	4387
	65818	6067002200	2	90-95	4004
	95818	6067002300	2	35-40	3156
	95818	6067002000	2	85-90	2376
	95816	6067001500	2	30-35	4329
	95817	6067001800	2	70-75	4686
	95817	6067001700	2	55-60	4794
	95822	6067003502	2	50-55	2916
	95822	6067004100	2	65-70	5015
	95823	6067004903	2	70-75	6740
	95823	6067004701	2	85-90	3303
	95823	6067004702	2	90-95	4945
	95824	6067004601	2	75-80	7614
	95824	6067003202	2	60-65	5052
	95820	6067004401	2	75-80	4122
	95820	6067002900	2	55-60	4499
	95819	6067001600	2	20-25	5421
Kentucky Ave.					
	95776	6113011206	0.5	60-65	7329
	95695	6113010901	0.5	40-45	5311
	95776	6113010800	0.5	55-60	3881
	95695	6113011001	2	35-40	6464
	95776	6113011206	2	60-65	7329
	95776	6113010800	2	55-60	3881
	95695	6113011002	2	10-15	3093