Framework for Life Cycle Assessment of Complete Streets Projects

December 2018

A Research Report from the National Center for Sustainable Transportation

John T. Harvey, University of California, Davis
Alissa Kendall, University of California, Davis
Arash Saboori, University of California, Davis
Maryam Ostovar, University of California, Davis
Ali A. Butt, University of California, Davis
Jesus Hernandez, JCH Research, Sacramento
Bruce Haynes, University of California, Davis

National Center for Sustainable Transportation

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7. Author(s)
John T. Harvey, https://orcid.org/0000-0002-8924-6212
Arash Saboori, https://orcid.org/0000-0003-0656-8396
Ali A. Butt, https://orcid.org/0000-0002-4270-8993
Alissa Kendall, https://orcid.org/0000-0003-1964-9080
Maryam Ostovar, https://orcid.org/0000-0003-4006-9048
Jesus Hernandez, JCH Research, Sacramento, https://orcid.org/0000-0003-3112-0163
Bruce Haynes, University of California, Davis

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1 Shields Avenue, Davis, CA 95616

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16. Abstract
A multitude of goals have been stated for complete streets including non-motorized travel safety, reduced costs and environmental burdens, and creation of more livable communities, or in other words, the creation of livable, sustainable and economically vibrant communities. A number of performance measures have been proposed to address these goals. Environmental life cycle assessment (LCA) quantifies the energy, resource use, and emissions to air, water and land for a product or a system using a systems approach. One gap that has been 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 project developed a framework for LCA of complete streets projects, including the development of socio-economic impact indicators that also consider equity. The environmental impacts of complete streets were evaluated using LCA information for a range of complete street typologies. A parametric sensitivity analysis approach was performed to evaluate the impacts of different levels of mode choice and trip change. Another critical question addressed was what are different social goals (economic, health, safety, etc.) that should be considered and how to consider equity in performance metrics for social goals. This project lays the foundation for the creation of guidelines for social and environmental LCAs for complete streets.

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Disclaimer

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Jesus Hernandez, JCH Research, Sacramento

Bruce Haynes, University of California, Davis

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EXECUTIVE SUMMARY

Streets are shared public spaces whose functionality should not only accommodate vehicular traffic, but also facilitate safe active transportation and combined active transportation and transit travel, create economic benefits, provide cultural and social spaces, and do so considering equity.

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.

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. A number of performance measures have been proposed to address these goals.

Funding to create complete streets is increasing in many parts of the U.S. As funding increases, 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.

Life cycle assessment (LCA) 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 that has been 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 project developed a framework for LCA of complete streets projects, including the development of socio-economic impact indicators that also consider equity. The environmental impacts of complete streets were evaluated using LCA information for civil infrastructure previously developed by members of the research team applied to a range of complete street typologies. The typologies were developed based on a review of current well-known design alternatives. A "consequential" approach was used where

the physical, economic and social processes that go into a system are modelled and changes in the behavior of the system will be quantified. A critical question that was to be considered in the framework based on available information is how complete streets change mode choice within trips and generate or reduce the number and types of trips. Review of the existing literature and discussions with experts found that this question is still very difficult to answer quantitatively, and instead a parametric sensitivity analysis approach was used that evaluates the impacts of different levels of mode choice and trip change.

Another critical question was what are different social goals (economic, health, safety, etc.) that should be considered? The results of this study used available information regarding social goals and performance metrics, reviewed them for applicability to goals that were identified from discussions with stakeholders, redundancy, and expected difficulty of data collection.

A framework for considering equity was then developed, based on knowledge and experience of the team, the literature, and information from the stakeholder discussions. The performance measures were then "bench-tested" for how they would work when comparing advantaged and disadvantaged neighborhoods, and if they did not work as desired, they were modified or eliminated from the framework.

A limitation of the social performance metrics is that they are primarily oriented toward use in urban and suburban areas, and an evaluation of their efficacy for rural projects has not yet been done. From the outset of the project it was expected that gaps in knowledge and data would be found.

This project lays the foundation for the creation of guidelines for social and environmental LCAs for complete streets. Combined with life cycle cost analysis, it is desired that this project will contribute toward future use of processes and tools that produce a complete, transparent and quantitative picture of a complete street project within the context and goals of the region, neighborhood, corridor and street. The system boundaries are expected to consider impacts of changes beyond just the street itself but to its role and effects on the entire neighborhood and the project within the road network.

The next step in this research and development arc is to test the full framework by using it to quantify the environmental and social impacts of complete streets and to compare them with leaving the street in its vehicle centric configuration. To test the framework, case studies will be solicited in different parts of California and in more and less advantaged neighborhoods so that the equity aspects of the framework can also be evaluated. The case studies should include projects in rural areas in addition to urban and suburban areas, and comparison of rural projects with urban/suburban projects should be considered, as well as considerations within both of these types of projects. Case study evaluation will be based on project design for those that have not yet been constructed or completed. Where case study projects have been completed, projects will be evaluated based on performance before and after project completion.

1. Introduction

Background

Streets are shared public spaces whose functionality should not only accommodate vehicular traffic, but also facilitate safe active transportation and combined active transportation and transit travel, create economic benefits, provide cultural and social spaces, and do so considering equity.

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). This transformation of the purpose of a street to focus nearly exclusively on motorized vehicle safety and travel time has been driven by interactive changes in urban land forms, the pervasiveness of vehicle ownership, low fuel prices, lifestyle choices, and combinations of these and other factors. Streets that are primarily designed to allow motorized traffic to move efficiently often pose dangers to pedestrians and bicyclists. This is because such streets are designed to be wide, have little or no space for bicyclists, pedestrians and disabled persons, and often have unsafe and complicated intersections. Among the pedestrian population, children, older people and people with physical mobility issues are particularly vulnerable when crossing or walking on these streets.

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). Burden and Litman (2011) stated that the goal of a transportation system should not be mobility but rather accessibility; goals for mobility mainly are fast and inexpensive travel whereas those for accessibility are mode choices that can help bring one to the desired destination safely, efficiently and enjoyably. Streets that meet the goals for mobility are needed, but a sufficient network of streets that contribute to meeting the goals for transportation need to also be included in the system. (Burden et al., 2011)

The bicycle and pedestrian advocacy communities initiated the "complete streets" movement in order to raise concerns about streets that were not designed for safe pedestrian and bicyclist mobility. The call was not just to add bicycle lanes and sidewalks to streets, but rather to design streets that can safely be shared among all users of all ages and abilities (Lynott et al. 2009; McCann and Rynne, 2005).

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 (Caltrans 2017), or in other words, the creation of livable, sustainable and economically vibrant communities (Complete Streets Design Manual, 2010).

As pointed out by 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 (CSA Stakeholder Group, 2016).

Funding to create complete streets is increasing in many parts of the U.S. As funding increases, 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 (ACT LA, 2018).

Processes to consider where to build complete streets and how to design them in a context-sensitive and equitable way involve prioritization, including the comparison of alternative projects to fund and alternative design features to incorporate. These processes are more subjective the more that they are based on qualitative metrics. The use and outcomes from metrics depend also on the unit of measurement or scale on which they are applied: the individual, the neighborhood, or the region.

Life cycle assessment (LCA) 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.

LCA has a standardized generic methodology for analysis of environmental impacts that are primarily documented in standards from the International Standards Organization (ISO) (ISO 14040, 2006). These standards have been further developed for specific applications, including building materials (EN 15804, 2012) and pavement (FHWA 2016). The pavement LCA guidelines include consideration of the interaction of vehicles and nearby buildings with the pavement, which are applicable to the physical infrastructure of complete streets. One gap that has been identified in current LCA impact indicators is lack of socio-economic indicators to complement the existing environmental indicators (Evans et al., 2008, Rosenbaum, 2014).

Problem Statement

As funding for complete streets projects is becoming much more widely available, the development of project evaluation metrics that consider project-specific quantitative environmental and social impacts when assessing, prioritizing and designing projects has increasing importance. The development of social impact indicators that include consideration of equity for use as LCA performance metrics as part of project development and prioritization is a critical issue for complete streets as exemplified by concerns being voiced across California, and intense discussions at the 2015 Smart Growth America conference in Baltimore (SGA 2015) and the 2016 Smart Growth America Street Lights conference in Sacramento (SGA 2016).

Goal and Scope

To address the gaps in performance metrics, this project developed a framework for LCA of complete streets projects, including the development of socio-economic impact indicators that also consider equity. The original scope of the project included testing the framework on several case studies. The case studies were not completed in the timeframe for this project and will be completed and reported afterward using other funding.

The environmental impacts of complete streets were evaluated using LCA information for civil infrastructure previously developed by members of the research team applied to a range of complete street typologies. The typologies were developed based on a review of current well-known design alternatives. A "consequential" approach was used where the physical, economic and social processes that go into a system are modelled and changes in the behavior of the system will be quantified. A critical question that was to be considered in the framework based on available information is how complete streets change mode choice within trips and generate or reduce the number and types of trips. Review of the existing literature and discussions with experts found that this question is still very difficult to answer quantitatively, and instead a parametric sensitivity analysis approach was used that evaluates the impacts of different levels of mode choice and trip change.

Another critical question was what are different social goals (economic, health, safety, etc.) that should be considered? The results of this study used available information regarding social goals and performance metrics, reviewed them for applicability to goals that were identified from discussions with stakeholders, redundancy, and expected difficulty of data collection.

A framework for considering equity was then developed, based on knowledge and experience of the team, the literature, and information from the stakeholder discussions. The performance measures were then "bench-tested" for how they would work when comparing advantaged and disadvantaged neighborhoods, and if they did not work as desired, they were modified or eliminated from the framework.

From the outset of the project it was expected that gaps in knowledge and data would be found. An outcome of the project is the identification of those gaps which should be included in a road-map for future development of the complete streets LCA guidelines and tools.

This project lays the foundation for the creation of guidelines for social and environmental LCAs for complete streets. Combined with life cycle cost analysis, it is desired that this project will contribute toward future use of processes and tools that produce a complete, transparent and quantitative picture of a complete street project within the context and goals of the region, neighborhood, corridor and street. The system boundaries are expected to consider impacts of changes beyond just the street itself but to its role and effects on the entire neighborhood and the project within the road network.

The following tasks were performed for the development of the complete streets LCA framework:

1. Literature review
    a. Published literature on complete street designs, primarily through design and policy documents, white papers, project reports and journal articles.
    b. Life cycle assessment of complete streets
2. Data collection from discussions and interviews
    a. Review of social goals and qualitative data sources from interviews:
        i. Individuals who are experts in different topics that helped fill in gaps in the literature when building the framework.
        ii. Agencies involved in prioritizing, planning, and designing complete streets projects
        iii. Community organizers and activist groups
        iv. A stakeholders group organized by Complete Streets America
        v. Individuals at conferences and meetings on complete streets, and information from their presentations and posters
    b. Discussions at conferences
3. Identification of typologies of complete street design features
4. Development of an LCA framework for complete streets
    a. Scope and functional units
    b. Environmental LCA approach
5. Environmental life cycle assessment and complete streets sensitivity payback analysis
6. Development of social and economic indicators and performance measures
7. Summarization of the LCA framework for complete streets and planning for case studies

The remaining six chapters of this report follow the outline of the tasks shown above.

2. Literature Review

Scope of Literature Review

The goals of the literature review were to understand the state of the practice for complete street design, document the outcomes of complete street implementation, and understand the goals and issues with regard to social and economic impacts of complete streets. The literature review covers five areas: background literature, existing complete street design guidelines, case studies, and environmental analysis (namely LCA) of complete street projects, and discussions and interviews with experts, agencies and stakeholders.

Additional literature review was completed in the context of indicator development, which is part of Task 4, and primarily consisted of review of published approaches for social and economic indicators related to active transportation. These literature reviews are discussed in Chapter 5 and Appendix B.

Background Literature

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).

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 (NACTO 2013; Caltrans 2014). Complete streets have been identified as an approach that has the potential to reduce greenhouse gas emissions (GHGs) and poor air quality by renovating street corridors in a way that encourages replacement of vehicular trips with non-motorized and/or public transit trips (Caltrans 2014). In addition to improved safety, increases in active transportation should have other public health benefits (Gordon-Larsen et al. 2005).

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 (Toronto Center 2017).

Complete Street Design Guidelines

Within the last decade, a number of national (NACTO 2013; NACTO 2014; Porter et al. 2016), state (Rabidou et al. 2011; NC Design Guidelines 2012; Florida design guidelines 2017; NYC design manual 2015;), local government (Knoxville Design Guidelines 2009; City of New Haven 2010; Chaplin 2012; Boston design guide 2013; South Nevada Design Guidelines 2013; Chicago Design Manual 2013; City of Philadelphia 2013; LA Design Manual 2014; City of LA 2017), and other (George 2013; Schlossberg et al. 2015) complete street design guidelines have been published. The American Association of Retired Persons (AARP) has published a list of some of the available guidelines at the state, regional, county and city levels (AARP 2017).

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. For example, national or state design guides may not be applicable to every location, and do not necessarily provide guidance on every design aspect of a complete street. This is likely why states and local governments develop their own complete street design guidelines, rather than rely on those that have already been proposed. Before using the guidelines, if a region does not have complete street design guides for its locality, it is important to determine the community needs and preferences, existing street typologies, climate, current and planned transport modes. It is expected in the future that more data collection, analyses, and more information documenting successful complete street projects and especially useful but rare, documentation of what has not worked, will result in changes in complete street design guidelines.

Complete Street Case Studies

Urban street design that uses the concepts of CSS, placemaking and shared public space has been tested and implemented in a number of cities around the world. Complete streets design concepts were revived in Europe in the mid-1990s and since then a number of cities in countries such as Denmark, Finland, the United Kingdom, Germany, France, and Belgium have adopted them. Cities in the U.S. in different states are also transforming their existing streets to complete streets, and a number of successful complete street projects from different states in the U.S. have also been reported (Schlossberg et al. 2015; Slotterback and Zerger, 2013; Frey et al., 2017). Some of the case studies from various sources are summarized in Table 1.

The complete street case studies that have been documented have reported using a variety of measures and there is no consistent framework evident for measuring and reporting the benefits of complete streets compared with the conventional street they replaced. Many of the measures are qualitative or essentially anecdotal and the data collection methodologies are highly variable.

Table 1. Summary of Some Example Complete Street Cases

Source	Street	Modifications	Outcomes
Schlossberg *et al.* 2015	S. Carrollton Avenue in New Orleans, LA	Sidewalks were repaired, curb ramps at the intersection were constructed and bike lanes were added by narrowing the roadway of a major arterial.	Bicyclists riding through the street in 2009 increased by 325% in 2010. An increase in female bicyclists was also observed.
Schlossberg *et al.* 2015	Barracks Row (8^{th} Street SE) in Washington, DC	1-way street was converted to 2-way street, and wider brick sidewalks, bike racks, landscaping, street lights were installed.	30 new businesses opened after construction. The street also won the "Great American Main Street Award".
Wagner and Penn 2017	Cloverdale Avenue, Winston-Salem, Forsyth County, NC	Sidewalks were added, resurfacing was done which reduced the width of the roadway for traffic and increased space for pedestrians and landscaping, concrete pads and benches at the bus stops were installed, intersection was realigned, pedestrian crossings were raised and bulb outs were constructed.	Slower moving traffic, higher pedestrian use and fewer pedestrian crashes are the outcomes. This project also served as a model for the whole city that promoted active lifestyle and improved safety for all users.
Seskin *et al.* 2015	Hennepin Avenue, Minneapolis, MN	In 2007, 1-way road was converted to contraflow lane and 2-way bicycle lane became shared lane for bicycles, buses and right turning vehicles.	Bicycle crash rates dropped from 1.03 to 0.4 percent, and perception of safety improved among the users. Crash data was recorded 3 years before construction and up to 6 months after construction.
Frey and Wagner (2017)	South Tryon Street, Charlotte, Mecklenburg County, NC	In 2012, vehicle lanes were converted from four to three and bicycle lanes were added. Sidewalks were widened to 12 feet and aesthetics of the street were improved by using decorative lightings and other techniques.	Pedestrian and bicyclists increase has been observed, though accurate numbers have not been recorded. Users have also given very positive feedback.

Quantitative approaches to the analysis of complete streets

A more quantitative approach than has been used to date is needed to be able to more objectively evaluate the benefits of complete streets when selecting alternative complete street designs and prioritizing funding for alternative projects. Thus, performance measures and indicators are required that can support decision-making. Although there are several systems for assessing the benefits of complete streets, they primarily consist of checklists (examples: City of Philadelphia 2013; CA 2017) and generally subjective ratings systems (examples: SGA & NCSC 2017) that award points based on criteria that are assessed independent of context or expected measurable change in system performance. There are performance measures reported by the National Association of City Transportation Officials (NACTO) that include level of service, safety (pedestrian, bicyclists, vehicles), travel time, ridership per revenue hour, operating cost per hour, and delay among other measures (NACTO 2013). The Federal Highway Administration (FHWA) has also provided guidelines for developing performance measures, including social performance measures such as access to jobs and community destinations, crashes, vehicle miles traveled (VMT), health impacts, land consumption, economic measures including job creation and land value (Semler et al. 2016).

There are studies that have evaluated street projects to quantify some benefits from constructed complete street projects based on several performance measures. A few examples are given in Table 1. The Minnesota Department of Transportation (MnDOT 2015) collects data for measures which include fuel use, public trust, transport assets condition, bicycle use, and pedestrian accessibility. The use of quantitative measures such as bicycle use and pedestrian accessibility have helped MnDOT prioritize which streets need to be reconfigured, redesigned or reconstructed to become complete streets.

Seskin et al. (2015) defined performance measures and metrics under seven goals (access, economy, environment, place, safety, equity and public health) and reported several project case study examples in which the data were gathered in order to quantify the measures. Under the access goal the authors identified a number of measures such as bicycle trips, walk trips, presence of facilities for walking, bicycling and transit, and on street parking.

In an example from downtown Phoenix, Arizona, the number of pedestrians was counted to quantify the walk trips measure. In 2012, people on foot in an intersection were counted in 30-minutes intervals, between 11:30am to 1:30pm during different weekdays in March and September. It was determined that 1600 people walked in Phoenix downtown each hour in the intersection. The measure helped businesses to expand and the city to make decisions regarding improvement and expansion of use of street design elements such as decorative paths, planters and crosswalks, for pedestrians.

Under the economic goal for complete streets, the authors reviewed the example of a main street in North Carolina. The main street intersection was considered the most dangerous in the state before it was reconfigured. The curbs were extended, landscaping was added, the roadway was resurfaced and traffic signals at two intersections were replaced with four-way stops. The project was evaluated after construction. The main street reconfiguration that cost $300,000 reduced the crashes to zero, and was credited with bringing 10 new businesses, 55 job openings and $500,000 worth of business investments. A 14-percent increase in visitors to the street was also reported by the Chamber of Commerce, which later increased to 27 percent.

In another study, data were collected in order to quantify several performance measures before and after a resurfacing project at Edgewater Drive, Orlando, Florida (Zykofsky and Hartman 2013). Four lanes (two lanes in each direction) of roadway were transformed to three lanes having a shared center lane for both traffic directions and added bike lanes between the roadway and curbside car parks. It was reported that the crash rates were reduced by 34% (146 per year to 87 per year), at the north end of the street, and the percentage of vehicles travelling over 36 mph was also reduced. Pedestrian volumes increased 23%, on street parking utilization increased from 29% to 41%, and bicyclist volumes increased 30%. Other anecdotal case studies exist in the literature.

Life Cycle Assessment of Complete Streets

A systems analysis approach that evaluates a complete street over its design life, and in the context of site specific effects and potential consequences has not been done. To date, the quantitative and context-relevant approach of LCA has not been used to assess the conversion of conventional streets to complete streets.

LCA methodology consists of the following steps (Harvey et al. 2016):

- **Goal and scope definition**. The goal and scope definition establishes the system to be evaluated and the boundaries of the study.
- **Life cycle inventory (LCI)**. The LCI is the accounting stage of the study, where life cycle data for all inputs to and outputs from the system are assessed and assembled.
- **Life cycle impact assessment**. Impact assessment translates the effects of the input and output flows tracked in the LCI into indictors of their effects on humans and the environment. The purpose of impact assessment is to better understand the environmental significance of the LCI by translating environmental flows into environmental impacts. Impacts are presented in different categories that can be broadly grouped into energy use, resource use, emissions, toxicity, and waste generation. Impacts often include eight or more separate impact indicators. Each of these types of impacts can be summarized at a higher level as impacts to people (humans); impacts to nature (ecosystems); and depletion of resources.
- **Interpretation**. Interpretation may occur during all stages, but is perhaps most important after impact assessment, because it will guide the development of conclusions and recommendations based on a study's outcome.

The U.S. Environmental Protection Agency (EPA) provides a comprehensive impact assessment methodology that include global warming, smog formation, energy use, ozone depletion, acidification, eutrophication, human health impacts and ecotoxicity as impact categories, which can be considered when evaluating environmental impacts for a system. They developed a tool for this impact assessment method, the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare 2011). TRACI is one of many impact assessment methods that may be selected for an LCA; however, it is the most well-developed method for the U.S. context and thus is widely used for LCAs conducted in the U.S.

The need for social and economic indicators has been identified world-wide and is on the frontier of LCA research (UNEP 2009). LCA methodology has recently been extended to address the missing social components of sustainability and is referred to as Social LCA (S-LCA). Social LCAs quantify the social and socio-economic impacts of a system. Environmental impacts are comparatively easier to quantify than social impacts, reflecting more than 50 years of development since the mid-1960s. Social LCAs are not very common as of today but researchers are developing models and collecting data to be able to quantify social and socio-economic indicators and performance measures.

Summary

There are several case studies presenting intermediate measurements of intermediate performance measures, and a number of design guidelines published. There is also a fairly comprehensive and extensive literature on the public health effects of active transportation, economic development and transportation mode choice. However, there is a lack of literature regarding the quantitative analysis of case studies that measure mode choice, public health, economic and transportation mode choice benefits that can be achieved from complete street conceptual design or systematic comparison of environmental and socio-economic performance change outcomes for implementation of complete streets in different contexts at either the neighborhood or inter-neighborhood levels.

In general, it appears that there is some “boosterism” in the reporting as advocates work to change the current dominant culture of near complete attention to motorized vehicle travel. This is to be expected as it takes a major sustained effort to change a culture as engrained as the construction of the built environment around the automobile. However, it is important that more quantitative and standardized methods of project evaluation are used as funding is brought to bear on the reconfiguration of infrastructure and culture towards support for active transportation as part of the improvement of quality of life.

A review of existing literature shows that no LCA has been conducted for any complete street project. Moreover, there is a lack of socio-economic impact indicators in LCAs for transportation projects. McCann (2010) stated that the U.S. needs “to learn how to build the political consensus that roads serve purposes beyond automobile travel”. This will be difficult until or unless the benefits and/or impacts are quantifiable. LCA is a relevant tool that can be used to quantify environmental and social impacts and can help determine the benefits of building streets that are context based and follow the concepts of placemaking.

3. Data Collection from Discussions and Interviews

Overview of Qualitative Research Performed in this Study

Qualitative research methods were used as a first step in the development of quantitative indicators for LCA and social LCA. The objectives of the qualitative research done in this study were:

- Identify potential indicators outside of the normal literature review process
- Incorporate goals and concerns from on-the-ground practitioners, advocates, and agencies engaged in actual infrastructure development

The approach used for qualitative data collection began with preparation of a basic outline for the environmental and social LCA framework based on within-team discussions of the literature review, relevant knowledge from each team member which provided broad multi-disciplinary and experiential input. The primary basis for the initial approach for environmental LCA came from the experience of several team members involved in international, federal and state initiatives to develop LCA for transportation infrastructure, including consideration of the use stage. The primary basis for the development by the team of the initial approach for social LCA indicators was based on the literature and critiques the team developed based on review of the existing literature. The approach was developed through a series of discussions by the full team, with updates to the approach developed between meetings.

Next, the range of stakeholders involved and affected by complete streets was identified. A plan was developed for review of the environmental and social LCA approaches with qualitative data sources across the range of stakeholders. The plan was intended to provide a comprehensive critical review of the proposed impact indicators to help make them appropriate and practical. It was understood that the discussions would primarily involve brief explanation of the relatively mature environmental LCA approach and indicators, and focus on the nascent social LCA approach and indicators. The plan for the review of indicators included a series of interviews, including interviews with individuals and facilitated group discussions, as well as observations at neighborhood, local, state and national-level meetings, and attendance and discussions at workshops and conferences.

Each focus/discussion group, interview, workshop, and conference was used to improve the team's understanding of stakeholder goals, existing processes and outcomes, and needs for improvement before the next encounter. The process began with a workshop and two follow up facilitated group discussions. These meetings were used to provide major refinement of the proposed approach and also helped identify additional stakeholders to interview through arranged meetings or through encounters at conferences. This purposive approach to interview participant selection also allowed the research to target a broad range of places and organizations. These included planning organizations involved in delivery of transportation and other development, various non-governmental advocacy groups involved in the overall promotion and delivery of complete streets and others involved with different stakeholder groups affected by complete streets, and local, state and national agencies involved in funding and delivering complete streets as part of their broader responsibility for transportation services. The advantage to this method is that a "snowball sample" could more easily target a population of practitioners and advocates most concerned with the concept of complete streets.

Data collected from most of the approximately 30 people included in the process came from in-depth interviews conducted either individually or in facilitated group discussions. For the rest of the sample, data collection came from presentations by individuals at workshops, which were followed up with shorter one-on-one interviews after the presentation. This method allowed the interview process to concentrate on obtaining responses from those most engaged in the subject area. A summary of the meetings, workshops and conferences is shown in Table 2.

This chapter of the report is primarily focused on generating insight into how stakeholders view and use complete streets, or are affected by them, therefore this section is not focused on statistical validation or prediction. Our use of a purposive sample approach represents a practical method for identifying social, economic, health and transportation indicators.

The data and analysis gathered from the qualitative data collection discussed in this chapter were used to change, refine and bench-test the set of social indicators for complete streets projects as is discussed in Chapter 5.

Table 2. A Summary of the Meetings, Workshops and Conferences

Meeting or Conference	Subjects	Participant organizations	Date	Location
Conf: Street Lights: Illuminating Implementation and Equity in Complete Streets	Expected benefits, equity issues.	State, national and local policy-makers and practitioners	November 15, 2016	Downtown Sacramento
Mtg: Complete Streets America practitioners discussion group*	Discuss project; learn practices; priorities for indicators; get ideas for social and equity indicators	American Association of Retired Persons, National Complete Streets Coalition, Sacramento Area Council of Governments, Caltrans Traffic Operations, consultants, pedestrian advocacy, Caltrans Smart Mobility, Caltrans Research, Safe Routes to Schools National Partnership	November 16, 2016	UC Center Sacramento offices, downtown Sacramento

Meeting or Conference	Subjects	Participant organizations	Date	Location
Mtg: Sacramento Council of Governments (SACOG)*	Discuss project; learn SACOG practices for complete streets prioritization and design; identify potential case studies	Regional transportation planning and funding organization	January 18, 2017	SACOG offices, Sacramento
Mtg: Dillon Fitch, UCD active transportation modeler	Review active transportation mode choice modeling	Transportation mode choice including mode change from vehicles to active transportation	May 9, 2017	UC Davis
Mtg: Monique Lopez, LA Bicycle Coalition	Review LABC views on complete streets implementation and equity questions; review ideas for indicators	Bicycle transportation as part of equitable community development	June 20, 2017	LABC office, downtown Los Angeles
Mtg: Arsen Mangasarian, City of Los Angeles Department of Transportation	Review funding prioritization approaches for complete streets and active transportation	Large municipal transportation planning, design, construction, maintenance and operations agency	June 20, 2017	City of LA DOT offices, downtown Los Angeles
Conf: Institute for Sustainability, Energy, and Environment	Present and discuss initial work on complete streets LCA framework	Environmental and social LCA and urban metabolism practitioners, researchers and government agencies	June 26, 2017	Chicago
Conf: 2017 California Bike Summit	Hear and discuss presentations on resolving prioritization of pedestrian and bicycle functionalities, funding; equity issues	State, regional and local policy makers and government agencies, non-governmental active transportation advocacy groups, researchers focused on active transportation, primarily bicycles	October 4, 2017	Downtown Sacramento

Meeting or Conference	Subjects	Participant organizations	Date	Location
Interviews: Georgia Tech	Methods of assessing condition of streets and paths for functionality, estimating mode choice change	Researchers investigating various technologies for assessing streets and paths for elements and conditions affecting functionality; researchers investigating factors affecting mode shift from vehicle to active transportation.	April 18-19, 2018	Atlanta, Ga
Conf: American Society of Civil Engineers International Conference on Transportation and Development	Present and discuss final work on complete streets framework	Researchers and practicing civil engineers and planners in government and consulting focused on transportation and land use	July 17, 2018	Pittsburgh, PA

Information from Discussions and Interviews

Initial Conference: Street Lights Conference

A number of presentations were made at conference of direct bearing on this study. Five to twenty minute interviews were held after the presentations with the speakers noted.

Primary findings from the conference were:

- Safety is a paramount concern.
    - Barbara McCann of the US DOT discussed safety for all users including pedestrians and bicyclists the (then) primary goals of the US DOT.
- It is difficult for neighborhood groups to participate in the grant writing process to obtain active transportation projects that address changes desired at the neighborhood scale.
    - A speaker from the California Endowment discussed approaches by which neighborhood groups were able to get funding to be able to participate in the planning in their own neighborhoods and put together competitive grants. It was noted that disadvantaged neighborhoods often have difficulty putting together information needed for grants, and regional organizations do not necessarily make these neighborhoods a priority.

- There is a need for performance measures to design complete streets projects to achieve desired outcomes, and to prioritize funding for competitive projects.
    - Kome Ajise from Caltrans discussed Caltrans goals for 2020 and the Caltrans bicycle and pedestrian plan for 2040, which includes performance measures. He also pointed to the Main Street Guide published by Caltrans that has a number of design policy directives. He also noted that there is a considerable amount of funding from the state that is now being directed towards active transportation.
- Equity is a major issue (it was the theme of the conference) in distributing funding, design projects to improve the lives of existing residents, consider quality of life improvement as the goal and not the complete streets itself, and to begin to manage the problem of displacement.
    - Robert Sanchez from the City of Los Angeles Department of Transportation (LADOT) discussed in detail their considerations of equity in active transportation planning[1]. He said that the DOT considers transportation to be a right, considering security and access. LADOT maintains a GIS based database and mapping capability to quantitatively consider equity when developing and prioritizing projects. The calculation to produce their Equity Index considers:
            - Injuries and fatalities
            - Access to resources
            - Previous funding and attention
            - Vulnerability
            - Income
            - Health
        - The LADOT provides challenge grants to develop community relationships in disadvantaged communities. He showed a flow chart demonstrating how they prioritize projects using both qualitative and quantitative information. Qualitative information considered to produce a Qualitative Rating includes:
            - Leveraging opportunities
            - Funding availability
            - Community support
            - Existing commitments
            - Geographic equity
            - Avoidance of excess maintenance
        - Quantitative information used to produce a Quantitative Rating includes advancement toward goals for:

[1] After discussion of his presentation at the conference, efforts to reach Mr. Sanchez to get a copy of his presentation and additional information, including a trip to Los Angeles to visit LADOT, were unsuccessful. It is not known the status of the prioritization project and no information was found on the LADOT website. the last posts on the LADOT bicycle program website are from the time this study was following up in the spring of 2017.

        - Safe city
        - Interconnected city
        - Vibrant city
        - Affordable city
    - The results are used to prioritize projects for the 10-year capital investment program.
- Tamika Butler from the LA Bicycle Coalition discussed:
    - That there are different reasons for bicycling in different communities and for different individuals
    - Everyone wants to be safe when bicycling
    - Equity is a complex subject, but when simplified means that those who have been getting the least need to be getting more than those who have been getting the most
    - In a time and place (California) with intense increases in housing costs, there is fear in neighborhoods that improvements intended to improve quality of life, such as complete streets and green spaces, are the start to displacement of existing families by increased rents; this is not understood in many cases in the complete streets community where it is seen as a resistance to active transportation itself.

Complete Streets America Discussion Group

Emiko Atherton, director of National Complete Streets Coalition of Smart Growth America organized a meeting for this study's participants with a focus group of practitioners from the organization's stakeholders the morning after the Street Lights Conference, including user advocacy groups, practicing consultants, regional and state government agencies. The facilitated discussion answered the following questions with input from multiple members of the group to each question.

Question: How do you define a complete street?

There is a range of complete streets. There is no such thing as a single definition of a complete street. The national coalition does not see a complete street as a product but instead as a process. They don't endorse a certain street design type. Even adding a paved shoulder is also considered a complete street.

Question: Is there a place making component to it?

Sometimes, the context needs to be understood. There is no cookbook. It depends on the land use typology.

Question: What are Complete Streets process decision points where quantitative evaluation of environmental impact, economic impact and social equity impact would be helpful?

The question should be "who is driving the process?" Current land use and future needs set forth the alternatives, then you need to compare and choose so it depends on that process. Expected changes in active modes of transport that could be tied in public health models. Needs **metrics**, inputs to the planning process. **Data**-rich decision making process.

Question: Is there a go-to design guide that engineers use?

Land use must also be included when evaluating the design and need for complete streets. Charlotte, NC, has a good 6-step process for how to design streets. The FHWA published a document this year called "Creating Multi-modal Networks". It defines the types/solutions related to complete streets, and is a good reference document. Each section has twelve situations plus the solution. The last session of the Street Lights Conference held in Sacramento (the day before this discussion) is where FHWA, AASHTO, and NACTO spoke about where all the documents are (note: none of the team members were able to attend that session and there is no documentation available on the internet).

Getting state engineers to adopt new design materials can be very difficult because they are very conservative with regard to changes in design documents.

Sometimes the community vision is compromised because there is concern about the performance of the materials. For example, the community vision can call out the use of permeable pavements but then this element is not built because engineers do not have confidence in the performance of that material. Maintenance and preservation engineers need more data.

Question: What are the metrics? As planners how do you quantify the goals?

For safety, the data exists for pedestrian and bicycle safety in California, but it is hard to obtain in other states.

Metrics are needed for jobs and access to food, work, education, etc. Data are needed on changes in crime rate, property crime, grand theft auto, assault in the public place, and for economic benefits. There are not enough economic data regarding before and after the complete street is built. These data can include sales in the neighborhood, and how businesses may benefit. There are not enough before/after studies of increase in property tax and sales. As an example, SACOG does cost/benefit analyses only for projects larger than $10 million.

A question that is difficult to answer is what will the actual mode shifts be? There are no standard inputs in to methods of estimation. Practitioners may choose inputs that make their project look better, and which can undermine trust in the modeling, which may then be disregarded by decision-makers

A question asked by the group is whether behavior change can be modeled in terms of increases in walking and biking in various population segments when complete streets are built. For example, the Health Policy Center in the Institute for Health Research and Policy at the University of Illinois at Chicago is researching whether where Complete Streets policies have been in place, there has been an increase in active transportation.

Safety and public health metrics are important. Regarding safety, the Safety program at Caltrans determines what gets into the state-wide highway rehabilitation program based on identification of high concentrations of crashes. They then provide multiple alternatives for mitigation. If there is an LCA approach that can help them figure out which counter measure would be helpful based on a variety of metrics, then this would couple environmental and safety goals. However, some districts do not have existing bike maps or proposed networks. Can LCA be used to help set up those street networks for bikes?

The group asked whether there are technologies to assess the condition of bike lanes and satisfaction with the service. This could be part of overall assessment of level of satisfaction with the service.

There are many vehicle traffic counts, but pedestrian and bike counts are not as accurate. There should be more money invested in the active transportation counts.

Question: What are the current metrics and/or considerations (e.g., environmental, economic, social, etc.) used when evaluating complete streets projects or prioritizing between competing projects?

There are a lot of requests to Caltrans for prioritization of complete streets projects. A question that the department asks is "if they build it will they come?" Caltrans does not have money to build complete streets everywhere, so how can they be more effective on figuring out where to fund complete streets?

The group suggested that metrics need to include measures that consider social-demographics, proximity to affordable housing, healthcare access, etc. They said that metrics should consider safety at different times of the day as well, and include lighting as a consideration.

When practitioners work on complete streets it is in the broader issues of livable communities. They do not want to see older people displaced. Access to services and public transit is a priority, as well as increased access to groceries and social services. They also want to minimize use of paratransit and maximize use of public transit.

It is important to consider how to link infrastructure and transit and paratransit to make current transit usable. First- and last-mile access issues for transit are important to consider when looking at complete streets. Integration of different modes, including on-call ride services, when you get out of the public transit should be considered.

A metric is needed for measuring integration with other modes, how does the Complete Street help piece together the full system (walking, biking, transit)?

With regard to consideration of economic benefits:

- There is difficulty in understanding what is the return on investment (ROI)
- There is difficulty in understanding the value that is provided
- Behavior change and the increase in use of active transportation modes is uncertain; need to understand the reason for the trip and what kinds of trips.
- Economic studies should identify return on investment to the agency as well as the community.

Displacement is a major issue, but it was uncertain how to estimate the impacts of a project on displacement or a displacement metric. Metrics are needed to measure: accessibility and access to opportunity. They need to consider equity when being used to prioritize projects.

There is a desire to better be able to consider risks (uncertainties) in complete streets benefit evaluation.

Question: Are there specific projects you are aware of that we could use as a case study for testing the LCA framework?

Lancaster in north LA county had a very impressive complete project for a boulevard where they have done the cost-benefit in terms of economic studies. USC has done a study on displacement (Bostic).

LA Metro put out an active transportation strategic plan, looked at 600 bus stops in the region and priced out costs for improving them. This helped understand how complete streets can be used to improve first and last mile for transit.

The City of Seattle has maps on displacement, access to opportunities.

It is important to know who is at the table when the project was decided.

Many projects do not document well who is using different services in terms of race, gender, etc. They do not consider who is travelling, who is getting the benefit and who is not.

Sacramento Council of Governments (SACOG)

Introduction to SACOG programs

One program of SACOG's is a community design program that produces projects worth about $15 to $20 million every two years with state and federal funding to promote the transportation blue print. The projects improve:

- main streets,
- commercial corridors in the public right of the way,

- quality of life,
- safety,
- and projects related to implementing the blueprint program which consists of policies that define smart growth vision for the region.

This program accounts for about 15 to 20 percent of the projects that are oriented towards bicycle and pedestrian travel, the majority of which are complete streets projects. Active transportation projects are also funded by a separate program that funds about 15 to 20 percent of the total active transportation projects, and the remainder are funded from the general regional funding program.

Following the brief introduction to the SACOG programs, a set of questions was asked.

Question: Can you step us through the process of how Complete Street projects are identified, designed, prioritized, funded, and implemented in the SACOG region?

The selection criteria are competitive, decided by two juries, one that conducts a qualitative assessment and a second that conducts a purely technical review. Some jurisdictions in the region are well organized, and have their own process and prioritization criteria for moving projects to SACOG. In some of the larger jurisdictions elected district officials play a larger role in moving projects forward from their districts. In some of the smaller jurisdictions there is not enough capacity in terms of time and ability to put together applications, and they often rely heavily on volunteer help. There is also a requirement for an 11.7 percent funding match which can be a hindrance for smaller, disadvantaged jurisdictions or communities. SACOG was working on a benefit/cost methodology and outcomes assessment for grant applicants to use and the selection committee to consider. A hybrid approach is sometimes used, with SACOG working with applicants before submitting applications. SACOG program directors have sat in on juries to see how the selection process operates.

It is important to have done the work for the application to be able to show details and designs. There is much more emphasis on the qualitative part of the proposal. One of the questions that is asked by the jury during review is whether there is going to be any future investment in the corridor because of the proposed funding or any investment that promotes smart growth will follow the initial investment.

Question: At each step in the process, what type of information, metrics, and/or criteria are used to inform decision-making and who is making the decisions?

To get a big picture, SACOG is working on a project to develop a methodology to evaluate investments that are included in the long-range plan and eventually to the funding plan. In this process SACOG will do a Benefit/Cost Analysis (BCA) and outcomes assessment that involves running an analysis with a travel-demand model. It is expected that the analysis approach will be powerful but with limits. The scope of the analysis will be for revitalization and not analysis of neighborhood effects, and is not completely focused on complete streets. The project will be finished in December (2017). The approach is similar to that taken by the Metropolitan

Transportation Commission (MTC, San Francisco Bay Area) using BCA and their targeted outcome assessments. MTC compares their investment with expected target outcomes. As part of their evaluation, SACOG will have a working group consisting of advocates, public work engineers, planners, and interested businesses in the region review the BCA methodology. SACOG plans to use the process on 600 to 2400 projects in their project list that they need to prioritize.

This process is part of the Metropolitan Transportation Plan/Sustainable Communities Strategy planning that SACOG is expanding to regional transportation planning. This is done every 3 years that they schedule based on the 20-year long term plan. SACOG wants to consider performance outcomes in the funding programs. The metrics will not specifically consider the change in the metric from the project or try to achieve a targeted value. They and their working group will be developing the metrics for their review process and want to be able to geo-code the results (through GIS) and show the impacts on a map. The working group will also determine whether there will be a weighting method for considering multiple metrics. As a part of the process SACOG wants to find catalyst projects that spark additional development and have synergies. Their desire for the process is that it finds good projects and not good applications. A quantitative component of the funding application will help them in this regard.

Question: Specifically, how (if at all) are environmental impacts, economic impacts and social equity impacts quantified and/or addressed at each step?

Some of the criteria SACOG is thinking about for their metrics are safety, mode shift, and public health benefits. There is a desire to align with the active transportation program administered by the state and funded through the California Transportation Commission. The reason to align metrics is to get projects that align with SACOG goals, not just local priorities, and state criteria. There currently are no metrics for impacts on public health. For this reason a proposal can be written for including such metrics or just include check boxes that as part of this project public health experts were involved. There is also no quantitative way to determine the mode shift for any kind of project. Projects are funded to help fill gaps and expand the network in the active transportation plan for bicycles and pedestrians, and are largely reactive to the built environment. An Active Transportation Accessibility Index is a metric that they currently use, which is tied to GIS and an accessibility map.

Some sources of additional information are:

- Transportation Council at Davis
- City of Davis Transportation Performance Rubric, part of Capital Improvement Plan
- Transportation Planning Guide (TPG) for Sacramento

Question: What are the mode choice change estimation approaches/models being used when evaluating estimated Complete Street performance, and what is your confidence in them?

The question when evaluating bicycle and pedestrian projects is whether or not the project going to secure the mode shift it is claiming it will. Currently, there is no metric for it. At this point, the approach is to evaluate the design and see if it is feasible. The question of mode choice becomes more of a discussion point for the juries and panels where they ask questions of the project sponsors. The results are a combination of disparate set of quantitative metrics that are combined into a qualitative assessment. If there is a city with funding that includes on the order of $100,000 of non-federal, non-state money as seed money for jurisdiction general plan updates/housing updates then there is more ability to get data. If the metrics are purely quantitative then there will be a project that will never be funded and the same is true if the metrics are purely qualitative. This is why it is thought that having a committee that is well rounded will help to combine both.

There are models for mode shift available but translation to funding programs is not smooth in part because of the run-time for the program. Sketch models are used which are big activity-based travel demand models. They are more sensitive to land use than to design details in the right of way. Some have been used by UC Berkeley researchers (Cervero, 2006; Ewing and Cervero, 2010) to evaluate different scenarios. There are several models available and they are becoming applications that can be used for model evaluation. Different information can be input, including different street design characteristics in some, and they provide output regarding vehicle mile traveled reductions and estimates for bicycle/pedestrian trips and transit trips.

Note: the study of models that estimate reduction in VMT from different kinds of projects that was discussed by Amy Lee of SACOG and ITS-Davis in the meeting was published in August 2017 (Lee et al, 2017). The study reviewed 13 tools for estimating VMT changes from different kinds of projects, used six of the tools for comparison using case studies, and performed a sensitivity analysis that compared estimates of reduction in VMT from the following tools:

- Sketch 7, developed by Fehr & Peers, Sacramento Area Council of Governments, UC Davis Urban Land Use and Transportation Center (ULTRANS); this model considers street design in its input variables
- GreenTrip Connect, developed by the Center for Neighborhood Technology and hosted by the advocacy group TransForm; this model does not consider street design but does consider parking charges, bike memberships, car memberships, and residential transit passes
- California Emissions Estimator Model (CalEEMod), developed by the California Air Pollution Control Officers Association (CAPCOA); this model considers a number of complete street type design inputs and can produce estimates of some social performance metrics discussed later in this report

A conclusion of the study particularly relevant to this project looking at complete streets is:

> "The variation in estimates between these three tools illustrates that meaningful VMT analysis requires evaluation of a range of scenarios by a single tool. A single project will produce a range of results depending on which tool is used, but the magnitude and

direction of VMT estimates between several scenarios will illustrate a project's efficient (or not) transportation performance. For example, a project sponsor could use GreenTrip Connect to evaluate a housing development in several locations throughout its jurisdiction, demonstrating which location promotes the most efficient land use and transportation choices. A single run of GreenTrip Connect, or any of these tools, provides limited insight into the efficiency of the project or project location.

Further, this analysis shows that comparing outputs from two different tools would be deceptive; outputs from CalEEMod, GreenTrip Connect, and Sketch7 are best compared to other results from CalEEMod, GreenTrip Connect, and Sketch7, respectively. In short, the accuracy of the absolute VMT estimate from each tool is uncertain; sketch tools are better suited to illustrate and compare differences between scenarios." (Lee et al, 2017)

It was noted that the travel demand model was calibrated based on surveys and not counts on a facility. It was thought that the Sketch 7 model could be adjusted go better consider street design characteristics.

Question: Are we capturing the main approaches and applications of Complete Street projects correctly below, and what would you recommend as the go-to document(s) that define Complete Streets approaches that you consider?

The SACOG discussion participants suggested that the following be considered in metrics for evaluating projects that might include complete streets:

- Can mode choice elasticities for models be estimated from literature?
- Think about land use and transit access including bus shelters, intermodal stations and other infrastructure.
- In general, suburban arterials have been made into complete streets and suburban corridors are a big focus area; urban, suburban, and rural is the primary categorization they are concerned about not the detailed list.
- Consider the types of projects
    - All the corridor
    - Part of the corridor
    - A particular item in a corridor
- Consider community types:
    - Lands not planned for development
    - Rural residential (not agriculture)
    - Centers and corridors (lots of mixed uses and high intensities across all modes)
    - Established communities
    - Developing communities

- With regard to economic analysis:
    - Look at Bay Area Economics Community (a company) that specializes in the quantitative side of the planning including transit oriented development and other types of non-motorized transportation projects tied to land use
    - The study by Popovich and Handy (2014) found that bicyclists on shopping trips spent less than those shopping on a vehicle based trip, but the bicyclists made more shopping trips, resulting in similar economic impact

Some corridors for case studies were suggested.

SACOG has a number of tools, maps and other documents relevant to this study on their website. In particular, the Active Transportation Program Planning map[2] was found useful for looking at different neighborhoods in the region.

Notes: SACOG held an Infill and Redevelopment Workshop on April 13, 2017 that looked at overall strategies, with some consideration of active transportation. SACOG has a state grant to look at economics and land use.

Dillon Fitch, UCD active transportation modeler

The discussion with Dillon Fitch focused on summarizing the ability to predict mode choice changes that will result from building complete streets projects, and what variables have been found to be important in the active transportation mode choice research to date.

The most widely used travel mode choice models are used to select the expected distribution of mode choice for a given set of trips between origin-destination pairs in a four-step demand modeling framework. These are largely tied to travel to and from jobs (commute trips) from households on a block-level basis. Explanatory variables that typically have high significance in the empirical models for assigning mode choice to the projected trips include socio-demographic variables, cost and travel time. Another type of model, called "activity-based models" are based on census data and travel survey diaries which are then extrapolated to the network. Both methods use travel survey data for predicting trips.

Mode choice that involves active transportation and combined active transportation and transit trips is complicated, context-sensitive in terms of a number of variables that fall into the categories of trip type (commute, child-transporting, shopping, recreation, etc.), trip length and travel time, socio-demographic characteristics, personal attitudes regarding the importance of choosing a mode for a trip, residential location choice, and built infrastructure characteristics, the interactions of these variables, and these variables as compared to vehicle travel alternatives, as is readily apparent from even a small sampling of the available literature (Handy et al., 2010, Schwanen et al., 2005, Johansson et al., 2005, Popovich et al., 2015). These variables can be handled in terms of predicting mode choice for the set of trips in a discrete

[2] Available at: http://arcg.is/1PyP44

choice model, or predicting an individual's likelihood to choose a mode for a trip. A high-level view of these models is shown in Figure 1 (Handy et al., 2010).

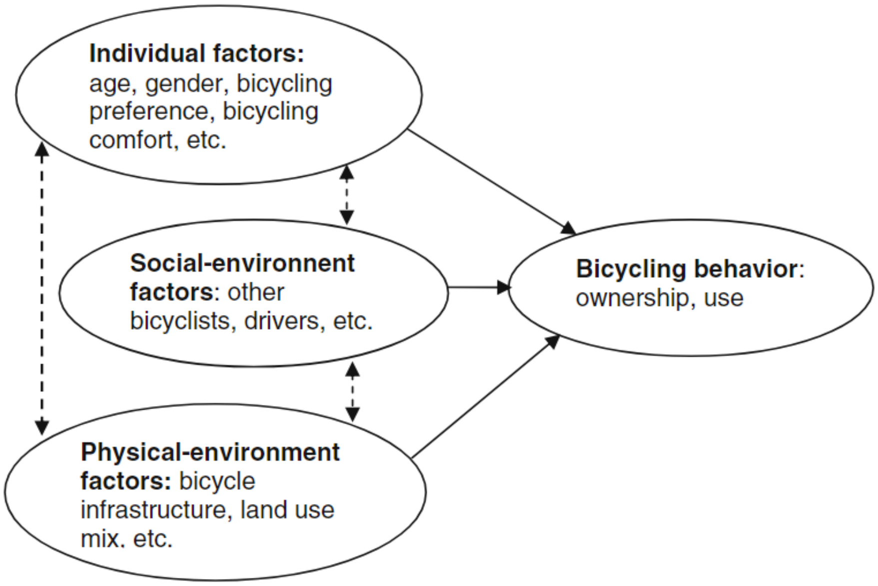

Figure 1. Conceptual model of bicycle use (indirectly modeled by modeling bicycle use in Handy et al. 2010)

Summarizing the extensive literature in the discussion: in general, important variables explaining mode choice for bicycling are expected to include perception of safety. Also, safety perceptions should theoretically link to other characteristics (experience, vigilance, fear) that are potentially correlated with socio-demographics. It might also be worthwhile to consider models of "willingness to change," a concept from psychology that is also used in transportation decision modeling. There is a standard simplified survey approach used in Europe to evaluate the likelihood of shifting driving habits to other modes that only involves answering 18 total questions, which are referred to as the "golden questions" (Anable and Wright). Variables that are expected to be important for mode choice selection for walking include perceived safety, which includes whether there are sidewalks, vehicle speeds and crossing safety, vertical grades, and travel time, including and time spent waiting at crossings. Both measurements and perceptions of these variables likely matter. For disabled travel the completeness and quality of ADA features are expected to be important in addition to the other variables.

One modeling approach is to relate many of these variables into what is called ''bicycling stress" using marginal rates of substitution which are commonly developed through empirical behavioral research on bicyclist route choice. A marginal rate of substitution is the rate at which a consumer is willing to give up one good in exchange for another good. Marginal rate of substitution values are input parameters representing bicycling stress associated with the number of lanes and speed limit of a street. Various kinds of bicycle stress ratings exist which are applicable to different links. Trips involving multiple links can be summed considering the length of the trip and the vertical grades and bicycle stress on the links to help explain the likelihood that the trip will be taken by bicycle. Similar approaches are applicable to walking trips. (Lowry et al, 2016).

The Lowry et al. paper is an example of taking marginal rate of substitution values from bicycling route choice studies (those that included GPS routes of bicyclists), and predicting where people would ride in a completely different context. Dr. Fitch believes that the idea of bicycle stress is a good way for planners to quickly get an idea where there are problems with bicycle safety; using stress as measured by marginal rate of substitution will be difficult in practice for predicting mode changes. He considers the route choice models and interception surveys of mode tradeoffs to be state of the art.

While research is advancing rapidly on a number of fronts, there are no generally accepted mode choice models that consider active transportation and all of the important variables discussed. A conclusion of the discussion was that these variables should be kept in mind, and approaches other than directly attempting to estimate mode choice need to be considered in the framework at this time.

Monique Lopez, LA Bicycle Coalition

The LA Bicycle Coalition (LABC) suggested that it would be worthwhile for the study team to see the recommendations for improvement of the CalEnviroscreen by the California Environmental Justice Alliance (CEJA, 2016). CalEnviroscreen is software published by the California Office of Environmental Health Hazard Assessment (OEHHA) that is intended to identify disadvantaged communities that are at-risk due to cumulative health burdens from environmental contamination, which are commonly referred to by the short-hand term “environmental justice” (EJ) communities. A review of that document found that those recommendations were:

1. Publish regional rankings on the OEHHA CalEnviroScreen website to analyze and produce data on the top EJ communities from a regional perspective;
2. Provide recommendations for the best uses of CalEnviroScreen at the local and state levels beyond funding allocation
3. Give environmental effects indicators a full weight instead of a half weight for calculating overall pollution burden scores in CalEnviroScreen
4. As an alternative to omitting the age indicator from CalEnviroScreen, include an indicator that measures the percentage of children within a census tract
5. Incorporate data from the California Air Resources Board’s (ARB’s) “Facilities of Interest” database to capture important local pollution sources
6. Enhance specific pollution indicators to incorporate measurements that can effectively capture smaller and additional sources of pollution
7. Incorporate a metric on hazard proximity beyond waste generators and facilities

The applicability of the recommendations from the CEJA for changes in the next version of CalEnviroscreen to this study is that their intent is to have better information available for consideration of the effects of local and regional decisions on disadvantaged communities, not just allocation of funding from the state. Included in many of these recommendations was the identification of children and senior citizens as special populations who are more vulnerable to the cumulative effects of pollution. These points can be considered in the development of social performance metrics for complete streets.

Regarding the main point of this complete streets project, it was recommended by the LA Bicycle Coalition that the project take care to not create a completely new and difficult to use process for complete streets. Instead, it should be made easier to get them through a process.

Regarding indicators (bulleted) that were being considered by this study, the following comments were made (sub-bullets):

- Changes in travel behavior due to complete streets/networks
    - LABC: Multi-modal trips that include active transportation as well as transit are important. How will multi-modal trips be counted?
- Change in Accessibility
    - LABC: For accessibility of housing to jobs, consider vehicle to transit versus transit to active transportation. Think about reduction of transportation cost burden for the whole trip.
    - LABC: For accessibility of schools, include charter schools.
    - LABC: For accessibility to social activities, consider the locations with social activities using a metric such as parks per capita. Also, separate "real parks" from streets that might be where children play, which are not real parks.
- Change induced from infrastructure change
    - LABC: Consider regionalization of impacts
- Change in health indicators (segmented by age and income)
    - LABC: From change in activity due to active transportation and resultant changes in physical well-being, look at childhood obesity reports, models from consultants
    - LABC: For social connectivity, look at aging in place
    - LABC: For change in safety, be aware that safety is complex with respect to law enforcement. As an example, ICE enforcement has decreased use of the LA Metro Blue Line. It is important to distinguish the type of law enforcement.
- Change in economic indicators
    - LABC: This is mostly measured in terms of sales tax dollars at this time.
- Economic equity indicators
    - LABC: Regarding displacement of low income residents due to an improvement in neighborhood desirability followed by an increase in rents, it is important to

look at the destinations of displaced persons. It was recommended to review the San Diego Center for Policy Initiatives, ACT LA about housing and transportation.

Note: that study could not be found. The search for it identified a summary of theories and examples of displacement and gentrification, and considerations and strategies for public investments in public infrastructure tied to climate change to minimize displacement, and is presented in in a thesis by Lupine (2017). In a review of the funding criteria for the state's Active Transportation Program (ATP) Lupine notes that "[t]he Guidelines for this program make no reference to gentrification or displacement, although 10 points out of 100 are allocated to public participation and planning. However, it is unclear how many points are given for a project-specific public participation process versus being included in a city or county plan." The thesis also notes that the state's Transformative Climate Communities (TCC) program also allocates about ten percent of its points to processes for local collaboration. The TCC program gives five percent of the points for prioritization to consideration of displacement, while the ATP criteria do not consider displacement. This review indicates that points for the local community (neighborhood) public participation processes appear to not require that the processes have any outcomes.

Arsen Mangasarian, City of Los Angeles Department of Transportation (LADOT)

The discussion began with a background on funding for complete streets projects. Funding began with passage of Propositions C and A in the early 1990s. LA Metro shared funding with the metropolitan planning organization, Caltrans and others. There are different guidelines for different sources of funding. There is more funding devoted to active transportation now.

The overall goals of the LA DOT are:

1. Safety (Highway Safety Improvement Program, HSIP)
    a. For drivers
    b. For pedestrians and bicyclists. Currently the LADOT is experimenting with road diets.
2. Complete streets (Active Transportation Program, ATP)

Funding for LADOT's regular work program projects comes from the local general fund, and grant funding for projects can come from the California Transportation Commission, the Caltrans safety program (HSIP) through District 7, the Metro MPO, the Federal Highway Administration through Caltrans District 7 and the Federal Transit Administration.

The prioritization process for complete streets projects is as follows:

1. The LADOT receives a Notice of Funding Available (NOFA)
2. The LADOT lets elected officials know about the NOFA. If only technical issues are involved, a committee of experts on safety is created. The experts look at the relevant

safety data, including district engineers and headquarters. They review the number of projects that can be delivered with funding.

3. Projects go to the City Council for review, discussion with the affected neighborhoods, which results in a reduced list of projects to fund. Other considerations include:
    a. Data available, which is often a problem for local projects
    b. Technology available
    c. Staffing available
    d. Cost of countermeasures
4. LADOT considers the following when reviewing projects:
    a. Sales tax change as an economic indicator
    b. Pedestrian and bicycle counts
    c. Pedestrian and bicycle crashes, using data from the California Highway Patrol's Internet Statewide Integrated Traffic Records System (SWITRS), which includes information about the level of crash severity
    d. Travel speeds and flows
    e. Flows of children going to schools as part of the Safe Routes to Schools program

The LADOT works with consultants on ATP project applications. The Caltrans ATP program requires pre- and post-studies. The LADOT proposes performance measures. Equity is considered through safety needs and trying to achieve Vision Zero (no traffic deaths by 2035). Active transportation projects, including complete streets, can also be looked at in terms of regional plans and goals for reducing emissions.

Design is done using the Highway Capacity Manual (HCM) to look at street classifications, which are cross-checked with LADOT classifications.

There was some discussion of the Los Angeles Mobility Plan 2035 which would have resulted in a large increase in bicycle lanes and other active transportation features. The LADOT has a map for a planned built-out network of bicycle routes. In July 2018 the Mobility Plan 2035 document was been taken down from the LADOT Planning Department's website, and it appears that it is not currently available on the department's website. Note: A review of the history of the Mobility Plan 2035 shows that there is active organized opposition to inclusion of bicycle lanes and other features on Los Angeles streets. The primary arguments of the opposition are that reducing lane capacity for vehicles will increase congestion and therefore travel times to work and emissions, and that the congestion will increase the response time for emergency responders. The assumption is that there will be little mode shift to active transportation and transit and that a similar number of vehicles will be using less capacity.

In June 2018, the City of LA launched its Complete Streets program with six projects on major routes. The mayor's office stated that prioritization of the projects considered that "[t]o maximize the effectiveness of Complete Streets, all projects will occur on the Vision Zero High

Injury Network (HIN) Priority Corridors in areas that have demonstrated the greatest need for repair." (LA mayor's office, 2018)

An example project discussed with the LADOT was to put bicycle lanes on a route parallel to the Pacific Coast Highway (PCH) in a beach community. The parallel route had high speeds for vehicles trying to bypass congestion on the PCH. The proposal was to restripe for bicycle lanes and put in lighting. The beach towns complained that their car parallel route would become too crowded with bike lanes.

Other projects are initiated by elected officials. In those cases, the elected official comes to the LADOT with a vision, based on business and resident concerns. In these projects, there are discussions regarding place-making versus the engineering characterization of the projects.

Institute for Sustainability, Energy, and Environment

The preliminary results of this study were presented at this conference in a short podium presentation. The questions were with regard to the functional unit for the analysis, which is the complete street for the environmental LCA, and the neighborhood the complete street is in and connections to adjacent neighborhoods for the S-LCA metrics.

A workshop on S-LCA was attended. The workshop was generally found to be irrelevant to the project because it focused on country-level assessments of abuses in consumer product supply chains. No project funds were spent for travel to this conference.

California Bike Summit 2017

Some of the main points from the California Bike Summit were relevant to this study

There were discussions regarding the need for data and modeling, including:

- The need for low cost measures to improve bicycle transportation
- The need for better bicycle and pedestrian safety data
- The need to be able to model accidents and deaths per bicycle mile traveled (BMT) and pedestrian mile traveled (PMT)

There was a talk from the California Walks organization that particularly discussed the concept of "untokening" in the discussion and practice of equity in active transportation. Essentially, the concept of untokening starts from the observation that there is lack of recognition in much of the active transportation advocacy enterprise that economically disadvantaged communities, which are often communities of color, have large percentages of their population who are completely dependent on active transportation and transit because they cannot afford to own a vehicle, or in some cases have difficulty in getting licensed. The argument is that much of active transportation advocacy is anchored in a context where people have multiple choices for transportation including owning and using a vehicle, and focuses the advocacy on traffic, infrastructure, and subjects who have a variety of mobility options at their disposal, including vehicles they own (Sulaiman, 2015).

The argument is based on the statement that the highest levels of active transportation use are actually in economically disadvantaged and communities of color where there are few other choices, which is not identified in current approaches for collecting active transportation data, i.e., it is “hidden.” A recent study sought to measure this hidden use (Kinder Institute, 2015). Transportation in these communities often relies on a mix of active transportation, particularly pedestrian, and transit, rather than bicycle alone. The statement that the current advocacy tends to focus on bicycle routes alone rather than on identifying context-sensitive needs to meet broader understandings and goals of the communities for mobility, livability, safety, and health. In some places it’s better infrastructure, but in others, it’s finding a balance between safety, education and enforcement (Sulaiman, 2015).

It was identified that approximately $500 million per year will be available for the Caltrans managed Active Transportation Program under Senate Bill 1 (SB 1), and that the focus of CalBike is on equity with regard to income and race, prioritizing improvements in low-income areas, complete streets policies, design practices, and increasing funding.

The California Bicycle Coalition identified that Goal 6 in SB 1 is performance measures, and that the coalition was advocating that complete streets be considered for all SB 1 funded projects, that no gentrification occurs and that there be equity in funding of road projects. The ATP requires 25 percent of funding to go to disadvantaged communities. The consideration of projects that create the greatest change rather than an equity of distribution was suggested in a discussion on prioritizing funding from SB 1.

Interviews at Georgia Tech

Short discussions were held with researchers at Georgia Tech working in three areas: technologies for measuring the conditions and features of streets and paths affecting functionality for active transportation, including particular consideration of disabled and senior travelers, mode choice for active transportation, and modeling of air emissions, including effects on active transportation travelers and impacts from changes in transportation mode choice.

Professors James Tsai and Randall Guensler discussed and showed technologies that can be used for sensing and inventorying conditions on streets and paths for development of condition metrics and inclusion in asset management systems. Tsai’s work has focused on functionality for vehicles, but has extended this work to applications for bicycle lanes and pedestrian paths. Guensler showed applications already in use for wheelchair and pedestrian functionality on paths. The results of these discussions indicate that these technologies are mature enough for use in asset management systems and for project-level evaluations, and they should be considered for collecting data for complete streets metrics. This is a promising near-future area for improved metrics of functionality of active transportation infrastructure and integration of active transportation into transportation asset management.

Professors Pat Mokhtarian and Kari Watkins discussed research regarding prediction of mode choice for active transportation. They are currently working on improved survey methods to further develop mode choice models for active transportation, much of which hinges on perceived safety. Their conclusions regarding the current status and important variables affecting mode choice corroborated the information from the discussion with Dillon Fitch that perception of safety and functionality are important variables and are different for different contexts and travelers.

Michael Rodgers and Randy Guensler discussed their development of models for air emissions considering vehicle movements and air emissions effects on active transportation travelers.

From these interviews it was found that condition and functionality assessment of active transportation infrastructure is ready to be brought into overall transportation asset management, but it generally is not considered at this time in standard practice. It was also found that while mode choice change prediction for active transportation projects is still an area with ongoing research arrive at better predictive ability, important variables are known, and in large part they have to do with perceptions of safety and utility which are highly variable depending on context. Modeling for air emissions from changes in street configuration are available and appear to be ready to be brought into both environmental indicators that consider changes in emissions, and social indicators that consider the effects of emissions on travelers. All of these areas warrant further investigation as the development of indicators and performance measures for complete streets evolve.

ASCE ICTD

The results of this project were presented at this conference. An important comment from the audience that reflected the discussion of “untokening” at the California Bicycle Summit was that “safety has different meanings in different neighborhoods.” The comment was that traffic safety for bicyclists in low-crime neighborhoods is not the only type of safety that must be considered everywhere and that improving all forms of safety, in a context-sensitive way, is important for allowing people to safely travel.

There was discussion in another session moderated by a member of the team after a presentation about a complete streets project in Somerville, Massachusetts in a middle-class neighborhood and comparison with a working-class neighborhood in Providence, Rhode Island. The discussion focused on the rising home values that come with a complete street project, and the fears of displacement from rising rents in the neighborhood in Providence, in comparison with the project in Somerville.

There was discussion of the apparent fact that many complete street projects that reduce vehicle flow capacity, likely result in small reductions (less than 3 percent) in actual VMT, but instead the vehicle use goes to other routes. There is little data available to measure this leakage.

Summary of Data Collected

The most important points taken from the data collected through the interviews and conferences is summarized as follows, and were used for the evaluation of existing performance metrics for use in the framework:

1. It is important to have quantitative performance metrics for complete streets
    a. They are needed for objective analysis of potential benefits from projects
    b. They are needed for more objective comparison between alternative projects
2. It is important that the metrics are practical, use available data and are straight-forward in their calculation.
3. The processes that use the metrics be no more difficult than current processes, and preferably easier to participate in.
4. There are needs for more data,
    a. The data need to be summarized at a neighborhood level (census tract is often a good surrogate) level to support pre- and post-construction of neighborhood improvement projects that include complete streets.
    b. They need to be able to show changes in the neighborhood
    c. They need to be able to show changes in the total system affected by the project
    d. They should include data about long-term maintainability and performance of the project, not just the initial performance
    e. Data are needed regarding jobs and access to food, work, education, schools, health care, child care; change in crime rate, and specific types of crime; economic benefit and who benefits
    f. The variables that affect mode choice are generally known, but have very different elasticities in different contexts.
    g. Data need to consider the particular needs and vulnerabilities of children and senior citizens (particularly to support aging in place), and the personal safety of women
    h. Data needs to be able to measure "hidden" active transportation in disadvantaged communities
    i. Better ways to consider uncertainty in data is important.
5. There are a number of goals for neighborhood projects that may include a complete street.
    a. Current goals
        i. Seem to be primarily focused on safety and leveraging economic development.
        ii. Other goals that funders have to consider are reductions in vehicle miles traveled and resulting greenhouse gas emission reductions and public health benefits, hence the focus on mode shift, which is currently difficult

to estimate a priori and for which leakage off the project is difficult to consider.

   iii. There are tools that are being evaluated to estimate mode choice change tied to VMT reduction.
   iv. Filling gaps in planned active transportation networks is tied to the VMT and other goals.

b. Projects containing complete streets should have the goal of improvement of quality of life as defined by the residents of the neighborhood, not a goal of building a bicycle-centric complete street.
c. The goal of safety needs to be neighborhood context sensitive, including:
   i. Traffic safety
   ii. Safety from crime, with consideration of the type of law enforcement and its relationship with the community
   iii. Safety from displacement due to increased rents
d. Displacement due to increased rents is a major concern, and a reason to resist complete streets projects in many disadvantaged neighborhoods.
e. There is no single definition or typology for a complete street, it needs to be context-sensitive based on the goals of the neighborhood
f. Long-term maintainability and cost of maintenance should be considered as a performance metric, but this should not be used against projects in disadvantaged communities without strong maintenance funding
g. The question regarding complete streets of grant-providing organizations such as Caltrans of "if they build it will they come?" should probably be changed to "what do they want and how can we help them get it?", with focus on the delivery of the outcome of what is wanted and the resulting improved quality of life as the metric for answering the question, particularly for disadvantaged communities.
h. It is important to consider how to link infrastructure and transit (and paratransit although it is often more costly) to make current transit usable.
   i. First- and last-mile access issues for transit are important to consider when looking at complete streets.
   ii. A metric that considers total cost burden of transportation for entire trips that occur in a neighborhood, normalized by income levels would be useful
i. Freight access that supports economic activity in the neighborhood needs to be considered
j. Access of emergency responders needs to be considered

6. Neighborhoods that are disadvantaged have difficulty being considered for projects that may include complete streets that can improve quality of life,
    a. If performance outcomes are not a part of the prioritization process,
    b. If regional organizations with the expertise to put together grant applications do not have processes that are context-sensitive to the needs and desires of different neighborhoods
    c. If the regional or state prioritization processes use performance metrics that have not been checked for inherent biases in their set-up against neighborhoods that are disadvantaged.
    d. Access variables need to consider the presence in neighborhoods of locations that are desirable to access, such as schools, parks, health care, and jobs and promote inequity if they do not consider the density of points worth accessing; improvements to meet neighborhood needs should consider the complete street as a means to the end of more activity, and not the goal itself.
7. Future development of complete streets indicators and performance measures should include integration of:
    a. Technologies for assessing condition and functionality of active transportation infrastructure, which should be integrated into transportation asset management for measurement and prioritization of maintenance, rehabilitation and improvement as a standard practice.
    b. New research regarding variables affecting use of active transportation, particularly perceived safety.
    c. Neighborhood modeling of air emissions from changes in transportation infrastructure.
    d. Modeling of the effects of vehicle emissions on active transportation travelers.

4. Complete Street Design Typologies

As noted in the answer to the first question in the Complete Streets America Discussion Group in Chapter 3, there is no single definition of what features make a complete street, or in other words "what makes a street complete?" The features that are included in a complete street design are dependent on the desired functionalities of the street, and the context in which it is used, including but not limited to the space available, the different modes and characteristics of traffic it is intended to serve, and the non-transportation goals that are desired.

To quantify the environmental, economic and social impacts of converting an existing street into a complete street for this complete street LCA framework, the open-ended definition of what a complete street can look like needed to be captured in a set of typologies. The typologies are the street types and the characteristics of the complete street design. These typologies provide a way to organize streets by the service(s) they are intended to provide and the context, facilitating analysis and data collection for complete street research. The intention of developing a set of typologies is to create an initial representative set that spans the current range of possibilities so that metrics can be applied to them. It is not intended to define or limit what can or should be included in a complete streets conversion.

Streets are context-specific; therefore, every city, based on its geographic location, community needs, and resources, will have a range of street typologies that exist or may reasonably be built for that city. As a reflection of this, complete street design guidelines and manuals are produced at the regional scale (e.g., a city) and are tailored to the location and context. As part of this tailoring, many design guidelines focus on specific types of streets. There are features that are the building blocks of a complete street such as bike lanes, pedestrian paths, landscaping, transit connections to active transportation paths, parking, etc., and each feature has design elements such as lane width, elevations, material type, and road or street furniture that define that feature. A framework with two examples is shown in Figure 2 that illustrates the relation between a street type, its geometry and features, and the design elements for the street and features. The data for the examples were taken from the City of LA design guide.

Based on the literature review conducted, Table 3 summarizes a range of different street typologies that are discussed in current complete street guidelines.

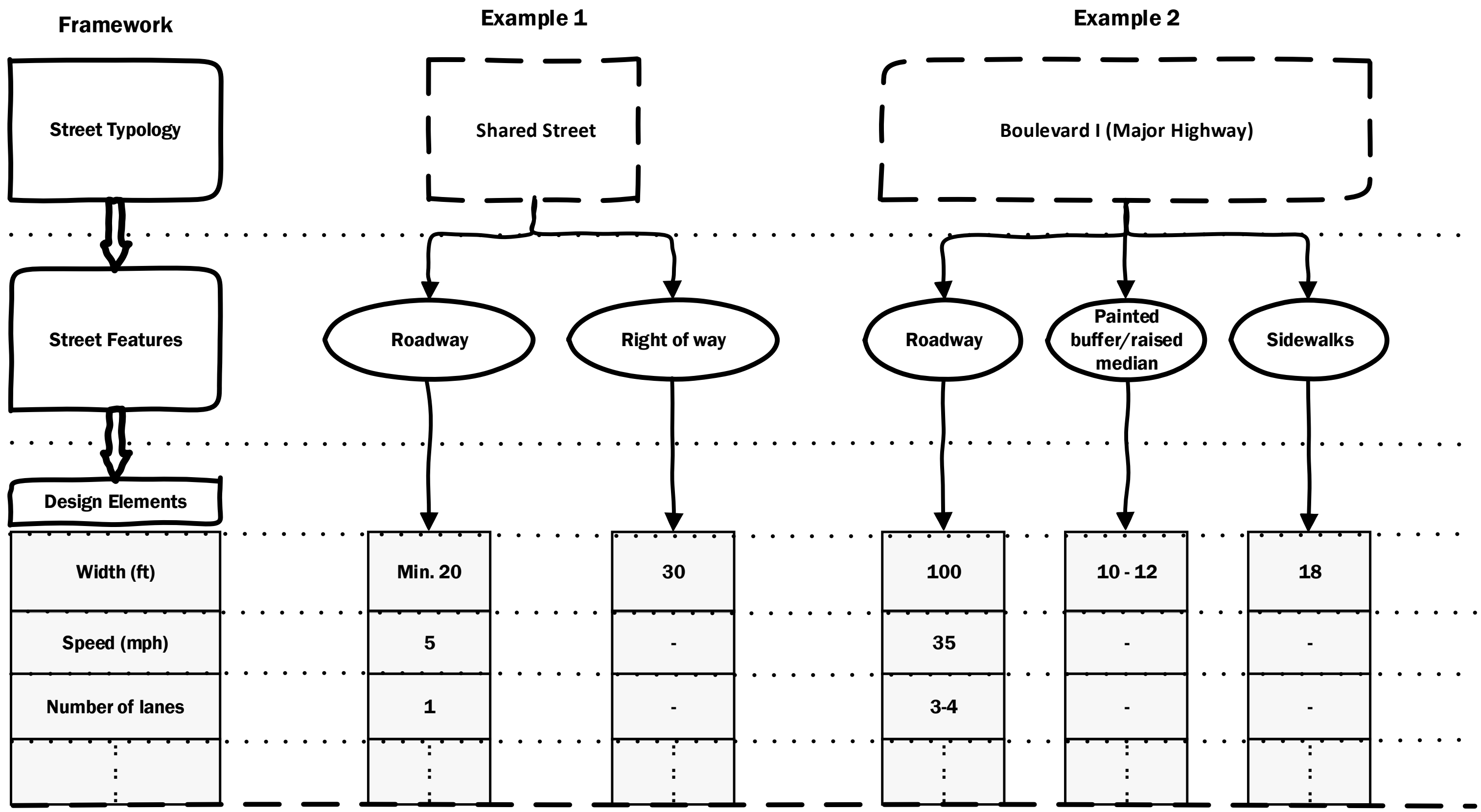

Figure 2. A Framework Illustrating Connectivity of Street Type, its Features and its Design Elements with Two Examples

Table 3. Street Typologies Reported in Different Complete Street Guidelines.

National Association of City Transportation Officials (NACTO) Urban Street Design Guide	City of LA	NACTO Global Street Design Guide	Florida DOT (FDOT)	Chicago DOT matrix	City of New Haven	Better Streets San Francisco	Southern Nevada Regional Transportation Commission	City of Philadelphia
• Downtown 1-way street • Downtown 2-way street • Downtown Thoroughfare • Neighborhood main street • Neighborhood street • Yield street • Boulevard • Residential Boulevard • Transit corridor • Residential Alley • Commercial Alley • Residential Shared Street • Commercial Shared Street	*Arterial Streets* • Boulevard I • Boulevard II • Avenue I • Avenue II • Avenue III *Non Arterial Streets* • *Collector* • Industrial collector • Industrial local • Local Street Standard • Local Street Limited *Hillside Streets* • Hillside collector • Hillside local • Hillside standard • Hillside Limited *Service road* • Access Roadway • One0way service road • Bi-directional service road *Other public right of ways*	• Pedestrian-Only Streets • Laneways and Alleys • Parklets • Pedestrian Plazas • Commercial Shared Streets • Residential Shared Streets • Residential Streets • Neighborhood Main Streets • Central One-Way Streets • Central Two-Way Streets • Transit Streets • Large Streets with Transit • Grand Streets • Elevated Structure Improvements • Elevated Structure Removal	• Natural • Rural • Rural Town • Suburban Residential • Suburban commercial • Urban general • Urban center • Urban Core	*Building form and function* • Residential • Mixed-use • Commercial center • Downtown • Institution or campus • Industrial • Parks • *Roadway form and function* • Thoroughfare • Connector • Main street • Neighborhood Street • Service Way • Pedestrian Way *Intersections and Crossings* • Signal (including 6-way intersections • Roundabout (traffic calming circle, mini-roundabout • All-way Stop • Stop, yield (1-way or 2-way)	• General Street • Boulevard • Slow Street • Pedestrian Only Street	*Commercial* Throughway Neighborhood Downtown *Residential* • Throughway • Neighborhood • Downtown *Other* • Industrial • Mixed-use *Special* • Parkway • Park Edge • Multi-way Boulevard • Ceremonial (Civic) • Alley • Shared Public way • Paseo (Pedestrian-only)	• Low and High-Speed Boulevards (conventionally arterials) • Avenue (conventionally collectors) • Street (conventionally local streets) • Alley/Lane *Special types* • Main Street • Drive • Transit Mall • Bike Boulevard • Festival Street • Shared Space	• High-Volume pedestrian • Civic/ceremonial street • Walkable commercial corridor • Urban Arterial • Auto oriented Commercial/Industrial • Park road • Scenic Drive • City neighborhood street • Low-density residential • Shared narrow • Local

National Association of City Transportation Officials (NACTO) Urban Street Design Guide	City of LA	NACTO Global Street Design Guide	Florida DOT (FDOT)	Chicago DOT matrix	City of New Haven	Better Streets San Francisco	Southern Nevada Regional Transportation Commission	City of Philadelphia
	• Shared Street • Pedestrian Walkway • Service Road • Alley	• Streets to Streams • Temporary Street Closures • Post-Industrial Revitalization • Waterfront and Parkside Streets • Historic Streets • Streets in Informal Areas		• Uncontrolled • Mid-block pedestrian crossing • Driveway (curb cuts) *Functional Requirement Overlays* • State route • County route • Truck route • Snow route • Strategic Regional Arterial • Mobility Priority Streets • Pedestrian Priority Street (P-street) • Bicycle Priority Street • Transit Priority Street • Historic Boulevard System • Transit-Oriented District (El stops) • Home Zone (shared street)				

As evident in Table 4, there are a number of ways of organizing typologies. The simplest can be seen in the City of New Haven, Florida DOT and City of Philadelphia guidelines. Their typologies have single attributes which are captured in their name. The typologies from the City of LA and the Global Street Design Guide have more nuance and break down typologies within major categories (i.e., a sub-types under arterials). The most comprehensive typology designation is from the Chicago Department of Transportation, which provides a comprehensive matrix of typologies based on the building forms and functions near the street, the street's function and services, the types of intersections with other routes, and overlays of warranted functional requirements, all tailored to the Chicago area context. These typologies may or may not be used (or be appropriate) elsewhere in the U.S depending upon the needs of society and design requirements of other agencies.

The National Urban Street Design Guide by NACTO covers a wide range of different street typologies that are viable candidates for transformation to a complete street. This source's typology designations were selected for use in this study because they are developed for broad application (rather than regional application) and cover a range of streets that would occur in cities in the U.S. with the intent to be generally applicable across the country. Each of these street types is summarized in the section below, along with complete street features that are likely to be compatible with the typology. These typologies cover the types of existing street geometries and complete street functions that were identified in different stakeholder meetings held in the initial stages of this project. The Global Street Design Guide, also from NACTO, is more comprehensive than the earlier Urban Street Design Guide, however many of its typologies that go beyond those in the Urban Street Design Guide are expected to be much less commonly used in urban areas in the U.S.

The next step in the development of the typologies used in this framework was to identify the specific features that are typically considered for inclusion in each type of complete street. The purpose of identifying the features is so that their life cycle inventories can be developed to calculate the environmental impact of their construction, and so that their potential influence on the social and environmental indicators developed later in the project can be considered. The features that can be included in each street type were taken from the NACTO Urban Pavement Design Guide. Those features were then cross-checked for same items in the San Francisco Better Streets Plan, and their dimensions and quantities were taken from standard plans and specifications for each feature from San Francisco. Each street type is described in Appendix A in terms of the conventional street type and potential conversion using the various possible features taken from the NACTO design guide.

Table 4. Summary of Complete Street Features Typically Considered in the NACTO Urban Street Design Guide. (NACTO 2013)

Existing Street Type	Raised Cycle Track (1-way)	Raised Cycle Track (2-way)	Buffered Cycle Track	Wide Side-walk	Island/ Median	Curb-extension	Planted furniture zone[1]	Parklet	Shelter/ Transit station	Lighting	Low-impact pavement	Street furniture	Textured and pervious pavements that are flush with the curb	Striping	Raised inter-section at sidewalk grade	Clear path
Downtown 1-Way Street Reconstruction	X			X	X	Bus Bulb										
Downtown 1-Way Street Alternative		X		X		Bus Bulb										
Downtown 2-Way Street					X	Bus Bulb								X		
Downtown Thoroughfare			X[2]		X											
Neighborhood Main Street					Pedes-trian safety island			X						X		
Neighborhood Street						Or raised crosswalk								X		
Yield Street							X									
Boulevard			X[3]		Median	X[4]										
Residential Boulevard		X			Median	X[4]										
Transit Corridor		X							X							
Residential Alley							X			X	X					

Existing Street Type	Raised Cycle Track (1-way)	Raised Cycle Track (2-way)	Buffered Cycle Track	Wide Side-walk	Island/ Median	Curb-extension	Planted furniture zone[1]	Parklet	Shelter/ Transit station	Lighting	Low-impact pavement	Street furniture	Textured and pervious pavements that are flush with the curb	Striping	Raised inter-section at sidewalk grade	Clear path
Commercial Alley											X			X[5]	X	
Residential Shared Street												X	X			X
Commercial Shared Street												X	X	X		X

Notes:

1. Bio swales/rain gardens, pervious strips
2. On both sides, buffered by parking lane
3. Buffered by boulevard medians
4. Or with midblock crossings to assist median access and use
5. Rumble strip

5. Environmental Life Cycle Assessment and Complete Streets Sensitivity Analysis Examples

Introduction

This chapter presents a framework for quantifying the environmental impacts of implementing complete streets (CS) guidelines using life cycle assessment (LCA) methodology, along with some results of its application in a sensitivity analysis that considers some common complete streets applications. In the sensitivity analysis, six types of urban streets were benchmarked and compared under two design scenarios:

- A conventional design using Section Four of the Sacramento County Office of Engineering Improvement Standard (Sacramento County 2009), which is an example of a standard currently in use for designing conventional streets, and
- A complete streets design using the Complete Streets Manual from the Department of Urban Planning of the City of Los Angeles, (City of LA 2014).

The sensitivity analysis also considered a range of changes in vehicle miles traveled for the street type in question and the surrounding network affected by the complete street. The change in vehicle miles traveled data was found in a report from the City of San Jose, as were the following two cases of vehicle speed changes on the complete street, which were also assumed to occur in the portion of traffic that moved to parallel routes in the surrounding network:

- The typical conventional design maximum speed, and
- The design maximum speed recommended for complete streets by NACTO.

Throughout this document, the Sacramento County Standard is referred to as SAC-DG (Sacramento Design Guide), and the design option for each urban street type under SAC-DG is referred to as Conv-Option (Conventional [Design] Option). Similarly, the manual developed by the City of Los Angeles will be referred to as LA-DG (LA Design Guide), and the design option for each street type under LA-DG is referred to as the CS-Option (Complete Street [Design] Option).

This chapter begins with a brief review of environmental LCA and the four phases for conducting an LCA study according to the International Organization for Standardization (ISO) standards, as implemented for pavement in the FHWA pavement LCA framework (Harvey et al. 2016) that serves as the main guideline for conducting LCA in subsequent sections. All study details are covered in the “Assumptions and Modeling Details” section, followed by results and discussion.

The limited sensitivity analysis to demonstrate the framework presented in this chapter provides a quantitative comparison of the environmental impacts of designing urban streets under conventional design guidelines versus complete streets guidelines and includes sensitivity to different assumptions. However, it should be noted that the scope of the LCA study in this chapter is limited to material production, transportation of materials to the site, construction activities, and changes in vehicle miles traveled and vehicle speed, and their effects on selected emissions from the production (well to pump) and combustion (pump to wheel) of vehicle fuel in the use stage. The assessment 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 in lieu of motorized vehicles.

All vehicles are assumed to burn gasoline and only passenger cars and light-duty trucks (SUVs) are considered, which means that consideration of any heavier freight vehicles is excluded.

A limitation of many complete street designs is that they do not consider existing use of a conventional street for freight vehicles (it can be said that they are "incomplete" in that sense). Any changes in freight vehicle routes, changes in speed and operation of freight vehicles, and changes to smaller freight vehicles that can operate on complete streets and any other logistical changes are not considered in this sensitivity analysis.

In addition to those impacts already mentioned, complete streets can have other important impacts not considered in the limited sensitivity analysis presented in this chapter. Additional case studies for field projects can include consideration of expansion of the system boundaries for LCA, which were limited by the scope and budget of this framework development project.

Brief Review of Environmental LCA

Life cycle assessment is a technique that can be used to analyze and quantify the environmental impacts of a product, system, or process. LCA provides a comprehensive approach to evaluating the total environmental burden of a product or process by examining all the inputs and outputs over the life cycle, from raw material production to end-of-life. Figure 3 shows a generic model of the life cycle stages for a product. This systematic approach identifies where the most relevant impacts occur and where the most significant improvements can be achieved while identifying potential trade-offs. ISO, through the 14040 series of standards , defines the process and rules for conducting an LCA (ISO 2006).

The general framework for conducting LCA studies as defined by ISO 14040 (2006) consists of four major phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation, as shown in Figure 4. The process begins with defining the goal of the study which determines the system boundary and scope of the study, study duration, and a suitable functional unit. The next step is the inventory phase where all the inputs and outputs to the system boundary within the life cycle are quantified. The inputs are normally in the form of input flows of raw materials and energy and output flows of waste and pollution (depending on the system boundary), emissions to air, water, and soil as well as the flow of product output. In the LCIA phase, the LCI results are classified and categorized into several environmental impact categories such as global warming, acidification, eutrophication, ozone layer depletion and more. The final step is the interpretation of the results to answer the questions defined during goal and scope definition.

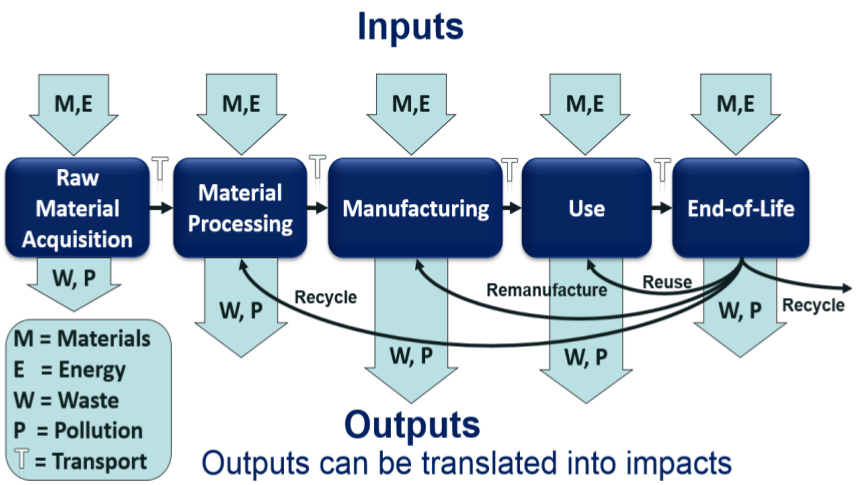

Figure 3. The General Life Cycle of a Production System (Kendall, 2012)

A current limitation of LCA is that the impacts are quantified globally and are not typically broken down by where they occur. This makes sense for impacts that are global in nature, such as global warming potential, but this limitation should be considered during interpretation of other impacts that may not be as important or may be more important depending on where they occur.

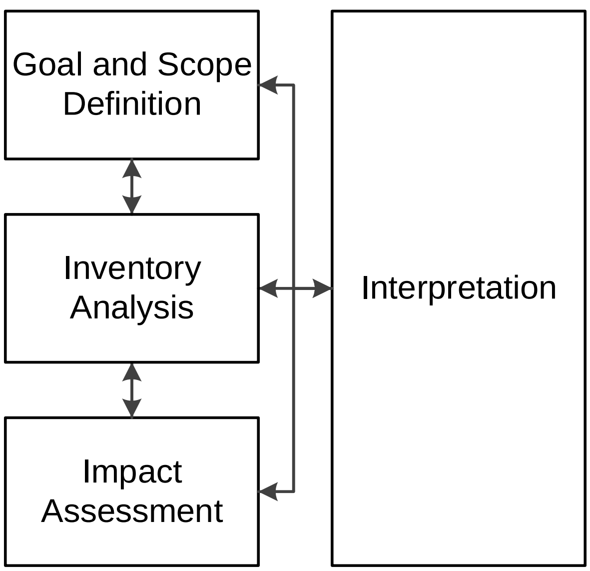

Figure 4. General Life Cycle Assessment Framework According to ISO 14040 (2006)

LCA can be used for a variety of purposes, such as (Harvey et al., 2014):

- Identifying opportunities to improve the environmental performance of products at various points in their life cycles,

- Informing and guiding decision-makers in industry, government, and non-governmental organizations,
- Selecting relevant indicators of environmental performance from a system-wide perspective
- Quantifying the environmental performance of a product or system.

Assumptions and Modeling Details

Six major urban street types identified in SAC-DG were chosen for this study and are listed in Table 5. The goal of the LCAs in this section is to benchmark the selected environmental impacts, primary energy demand, and material consumption of building various urban street types under the two different conventional (SAC-DG and LA-DG) and complete street design guidelines. The main audience for this work is city planners and local governments.

The system boundary for each street type includes material production, transportation of raw materials from extraction site to processing plant and from there to the construction site, and construction activities; this is referred to as a cradle-to-laid LCA. Throughout this chapter, the LCA results for these stages of the life cycle are referred to as MAC impacts (Material, transportation, And Construction).

An analysis period of 30 years was selected for conducting the LCA and calculating payback periods for offsetting the differences in environmental impacts due to complete streets (CS) designs compared with conventional designs. Further, a sensitivity analysis was conducted in which the assumed reductions in VMT for CS-Options were evaluated for offsetting the extra MAC emissions of CS-Options compared to conventional (Conv-)-Options. The functional unit for all cases in this chapter is considered as one block, except where stated otherwise.

The phase that follows goal and scope definition is the life cycle inventory (LCI) or the accounting phase of an LCA. LCI is the phase in which all the inputs (energy and materials) and outputs (emissions and waste emitted to air, water, and soil) are quantified. The first step is to quantify the amount of materials needed in each case during the analysis period. SAC-DG has detailed drawings for the cross-section of each conventional street type and other elements such as curb and gutters. SAC-DG drawings (Figure 5 below and Figure 39 to Figure 41 in Appendix B) were used to determine the dimensions (Table 5) needed to calculate the quantity of materials. Minimum aggregate base (AB) and asphalt concrete (AC) thicknesses were also taken from the same reference. Figure 6 and Figure 7 show design recommendations for thoroughfares by LA-DG and NACTO (2013), respectively (see Figure 42 to Figure 51 in Appendix B for other street types).

SAC-DG does not offer any recommendations for block length, but it does have requirements regarding maximum speed and minimum stopping sight distance. Due to lack of data availability and because this study is more focused on relative changes in environmental impacts of CS-Options versus Conv-Options, block length for each street type was considered as the minimum stopping sight distance multiplied by two.

Table 5. Conventional Street Dimensions (Sacramento County 2009)

Street Type	Minimum Conventional Asphalt Thickness (in)	Minimum Aggregate Base Thickness (in)	Pavement Width (ft)	Block Length (ft)
32-ft Minor Residential	3.0	10.0	26	300
38-ft Primary Residential	3.0	10.0	32	400
48-ft Collector	3.5	13.0	42	500
60-ft Major Collector	4.0	14.0	54	600
74-ft Arterial	5.5	20.5	56	720
96-ft Thoroughfare	6.5	23.0	78	860
Street Type	**Minimum Asphalt Thickness (in.)**	**Minimum Aggregate Base Thickness (in.)**	**Pavement Width (ft)**	**Block Length (ft)**
32-ft Minor Residential	3.0	10.0	26	300
38-ft Primary Residential	3.0	10.0	32	400
48-ft Collector	3.5	13.0	42	500
60-ft Major Collector	4.0	14.0	54	600
74-ft Arterial	5.5	20.5	56	720
96-ft Thoroughfare	6.5	23.0	78	860

SAC-DG and LA-DG use different terminologies for street types. Table 6 shows how the street types in the two guidelines are matched based on width and traffic levels.

Table 6. Street types in SAC-DG and their assumed equivalent categories in LA-DG

Sacramento County	City of LA
Minor Residential (32 ft)	Local Street Standard
Primary Residential (38 ft)	Collector
Collector (48 ft)	Avenue III (Secondary Highway)
Major Collector (60 ft)	Avenue II (Secondary Highway)
Arterial (74 ft)	Avenue I (Secondary Highway)
Thoroughfare (96 ft)	Boulevard I (Major Highway Class I)

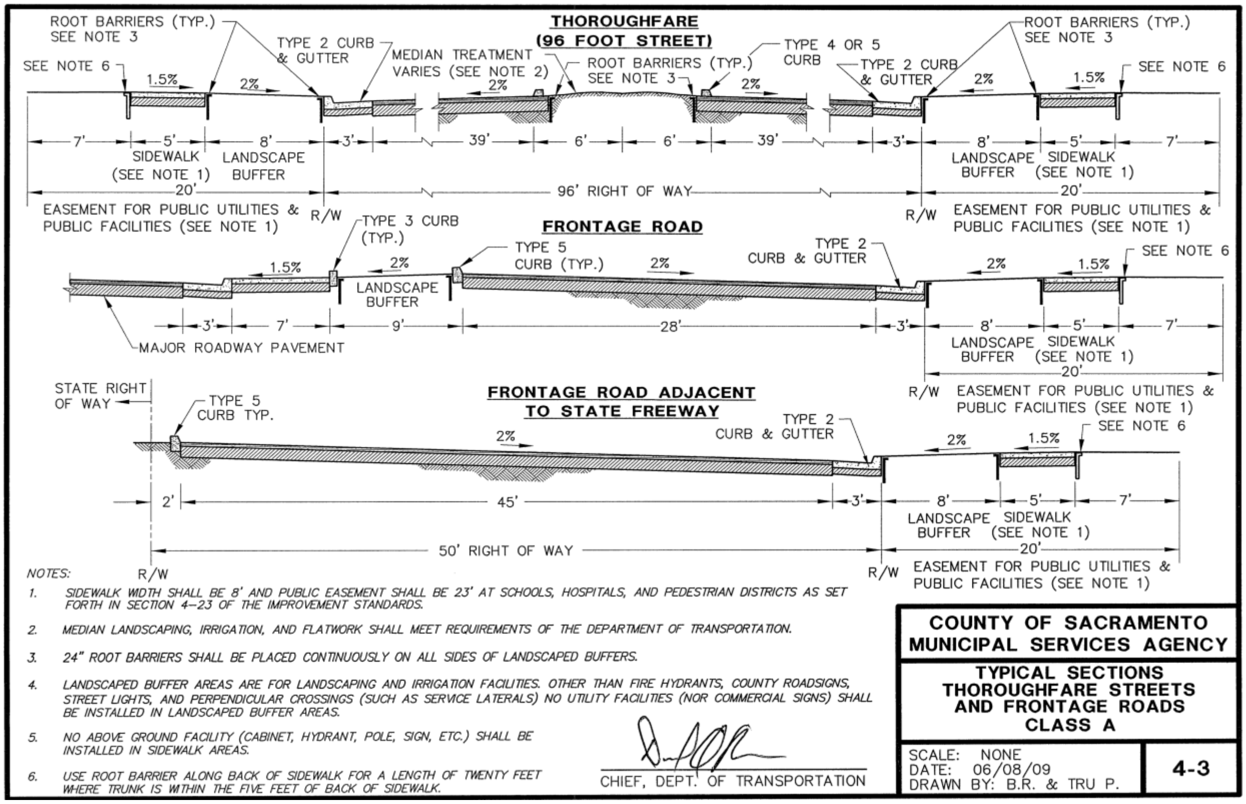

Figure 5. Cross Section of a Thoroughfare (Sacramento County 2009)

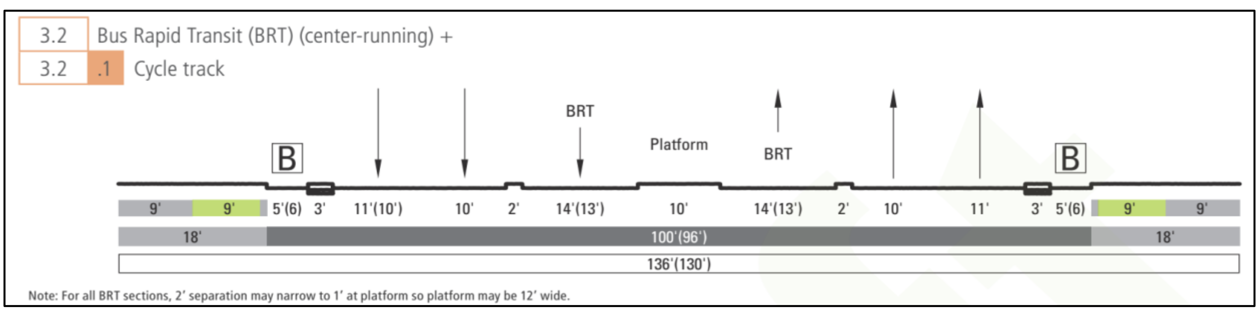

Figure 6. LA-DG Recommendation for Thoroughfare as a Complete Street (City of LA 2014)

Figure 7. NACTO Recommendation for Thoroughfare (from *Urban Street Design Guide*, by NACTO, pp. 13)

The next phase in LCA is impact assessment (LCIA). LCIA results were calculated using the TRACI 2.1 impact assessment methodology developed by the U.S. EPA (Bare 2012). A reduced set of TRACI impact indicators was used for this study. LCIs and LCIA values are available in the database with appropriate units (per kg of materials and mixes, per ton-km of materials transported, or per lane-km of construction activities). Full details of all the assumptions and data sources used for developing the UCPRC LCI Database can be found in the UCPRC LCI Documentation report (Saboori et al., 2018). Table 17 in Appendix C shows the list of materials and values of selected LCIA impact categories and primary energy demand (PED) for each. Table 18 provides similar data for different surface treatments used in pavement projects in which the functional unit for surface treatment is one lane-kilometer (ln-km), and the system boundary includes material production, transportation, and construction impacts (the values in the table are MAC values). A few items, such the additional paint and plantings used in complete streets, were directly taken from GaBi LCA software (GaBi 2016) and are not reported in the UCPRC LCI documentation; these items are designated with (GaBi) in their titles.

The impact indicators considered in this report are:

- Global Warming Potential (GWP): in kg of CO_{2e}.
- Photochemical Ozone Creation Potential (POCP): in kg of O_{3e} (a measure of smog formation).
- Human Health (Particulate): in kg of $PM_{2.5}$ (particulate matters smaller than or equal to 2.5 micrometers in diameter).

- Total Primary Energy Demand (PED): in MJ.
- Primary Energy Demand (Non-Fuel): in MJ.

Non-Fuel PED is also referred to as “feedstock energy” and represents the energy stored in material that can be recovered for combustion later if need be. The feedstock energy in asphalt binder (as a petroleum product) is a typical example: even though it is not a common practice to recycle binder out of pavement to combust it for energy purposes because of the cost and high emissions, the primary energy stored in the binder can theoretically be recovered for this purpose. On the contrary, the energy used in various combustion processes in the system boundary cannot be recovered. Therefore, the PED (Non-Fuel) should be reported separately (Harvey et al. 2016).

Table 7 shows a complete list of all the CS elements recommended in LA-DG which are sorted into four categories:

- Intersections and Crossings
- Off-Street Non-Vehicular Treatments and Strategies
- Roadways
- Sidewalk Area

LCI and LCIA of the materials and surface treatments presented in Table 17 and Table 18 (in Appendix B) were used to calculate the LCI and LCIA for the LA-DG CS elements shown in Table 7. The results are presented in Table 19 in Appendix B.

For each element (either conventional or CS) a service life was assumed and used to determine the number of times that each will be treated with a typical maintenance, rehabilitation, or reconstruction treatment during the 30-year analysis period. Although the assumptions used in this study are generally more conservative than those in actual practice, it was assumed that the entire conventional street and complete street infrastructure would be replaced at the end of their service life. If any items have remaining service life at the end of the analysis period, a linearly pro-rated salvage value was calculated and credited to the item.

Results and Discussion

Appendix B presents detailed LCA results for each street type designed under SAC-DG (Table 20 to Table 25) conventional street design, and Appendix C presents similar results under LA-DG (Table 26 to Table 31) complete street design. In this section, the summary and comparison of all results are presented. For each street type, Table 7 shows MAC impacts (absolute values) under different impact categories for Conv-Option and CS-Option. Table 8 presents the absolute change in each impact category when switching from the Conv-Option to the CS-Option.

Figure 8 shows the breakdown of total GWP between CS elements and conventional elements. In all CS cases, conventional elements of urban streets, meaning the pavement, curbs and gutters, etc., claim 90 percent or more of total MAC GWP. CS elements in thoroughfares have the maximum share of total GWP among all street types, 10 percent, while CS elements of arterials claim the lowest share, 0.7 percent.

As stated earlier, comparing different street types with each other is not part of the goal of this study, and it does not add much value since functionalities are different. Furthermore, comparing the same street type under two design methods by just looking at the absolute values of impacts is not very beneficial as these numbers are directly proportional to the length of each block. This approach would have been suitable if the goal was to minimize total emissions or reduce project-level emissions by a certain amount (where absolute values of emissions are important). However, for this specific research, because the goal is to conduct a preliminary comparison between the two designs and get a first-order estimate of changes in impacts, calculating relative values seems most appropriate.

Table 7. Absolute Values of Various Impacts Categories for the Two Design Options for the Materials, Transportation and Construction (MAC) phases: Conventional (Conv) and Complete Streets (CS)

Impacts of Conv-Option					
Street Type	**GWP (kg CO_2e)**	**POCP (kg O_3e)**	**PM2.5 (kg)**	**PED (Total) (MJ)**	**PED (Non-Fuel) (MJ)**
32 ft. Minor Red.	4.80E+04	5.43E+03	2.59E+01	4.66E+05	3.34E+05
38 ft. Primary Red.	1.09E+05	1.34E+04	5.95E+01	1.16E+06	1.37E+06
48 ft. Collector	1.67E+05	2.14E+04	9.09E+01	1.87E+06	2.47E+06
60 ft. Major Collector	2.65E+05	3.47E+04	1.45E+02	3.05E+06	4.51E+06
74 ft. Arterial	4.62E+05	6.10E+04	2.53E+02	5.37E+06	7.99E+06
96 ft. Thoroughfare	8.21E+05	1.11E+05	4.52E+02	9.81E+06	1.62E+07
Impacts of CS-Option					
Street Type	**GWP (kg CO_2e)**	**POCP (kg O_3e)**	**PM2.5 (kg)**	**PED (Total) (MJ)**	**PED (Non-Fuel) (MJ)**
32 ft. Minor Red.	5.06E+04	5.62E+03	2.72E+01	4.81E+05	2.94E+05
38 ft. Primary Red.	1.14E+05	1.38E+04	6.19E+01	1.20E+06	1.35E+06
48 ft. Collector	1.70E+05	2.49E+04	4.68E+02	1.85E+06	2.45E+06
60 ft. Major Collector	2.87E+05	3.66E+04	1.57E+02	3.21E+06	4.42E+06
74 ft. Arterial	4.59E+05	6.07E+04	2.51E+02	5.34E+06	7.97E+06
96 ft. Thoroughfare	8.13E+05	1.07E+05	4.47E+02	9.38E+06	1.42E+07

Table 8. Absolute Change in MAC Impacts (Impacts of CS-Option Minus Impacts of Conv.-Option)

Street Type	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
32-ft Minor Residential	2.57E+03	1.90E+02	1.33E+00	1.48E+04	-3.91E+04
38-ft Primary Residential	4.48E+03	3.76E+02	2.44E+00	3.08E+04	-1.95E+04
48-ft Collector	2.65E+03	3.54E+03	3.77E+02	-1.91E+04	-2.09E+04
60-ft Major Collector	2.26E+04	1.95E+03	1.23E+01	1.60E+05	-8.33E+04
74-ft Arterial	-2.33E+03	-3.16E+02	-1.45E+00	-2.69E+04	-2.55E+04
96-ft Thoroughfare	-8.10E+03	-4.41E+03	-5.92E+00	-4.30E+05	-2.02E+06

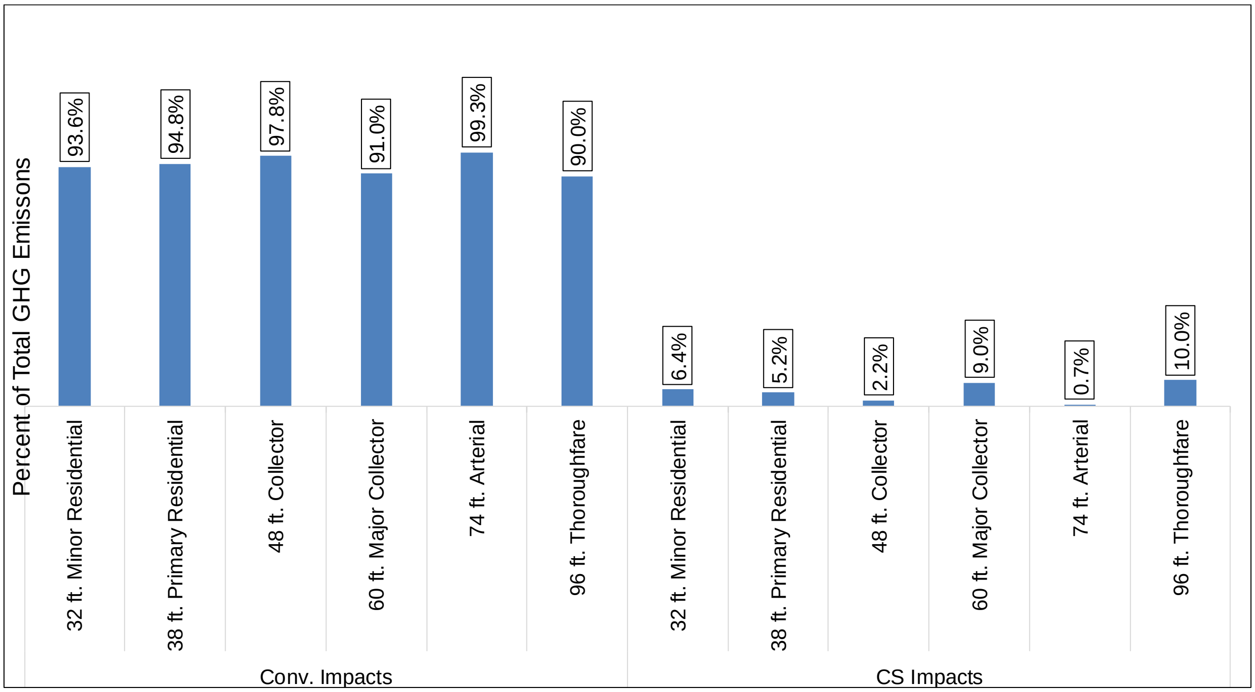

Figure 8. Breakdown of materials and construction (MAC) GWP of complete streets between their conventional (Conv.) elements and complete street (CS) elements

Table 9 shows the relative change in MAC impacts. The table shows the percent increase in MAC impacts (in different impact categories) when switching from the Conv-Option to the CS-Option. GWP, POCP, and PM2.5 all increase for residential and collector streets, ranging between a 1.6 to 8.5 percent increase in GWP, a 0.8 to 5.6 percent increase in POCP (smog formation) and a 1.5 to 8.5 percent increase in particulate matter. However, for arterials and thoroughfares, switching from the Conv-Option to the CS-Option results in impact reductions across all categories, ranging between 0.5 to 1.0 percent decrease in GWP, 0.5 to 4.0 percent decrease in POCP (smog formation) and 0.6 to 1.3 percent decrease in particulate matter. These changes 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 designs for these types. These changes in the impact indicators are nearly all less than +/- 10 percent, reflecting the fact that the conversion to a complete street involves relatively small changes in the amounts and types of materials used on a complete street versus a conventional street. PED (Non-Fuel) is the only category in which all street types show a decrease in impacts when switching to CS-Options, with reductions ranging from 0.3 to 12.4 percent. This decrease is mostly because CS elements replace asphalt pavement that has high PED (Non-Fuel) values compared to other items. As mentioned, PED (Non-Fuel) has no environmental impact and is a measure of use of a non-renewable resource (oil).

Table 9. Percent Change in MAC Impacts (CS-Conv.)/Conv.

Street Type	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
32-ft Minor Residential	5.4%	3.5%	5.1%	3.2%	-11.7%
38-ft Primary Residential	4.1%	2.8%	4.1%	2.6%	-1.4%
48-ft Collector	1.6%	0.8%	1.5%	0.7%	-2.1%
60-ft Major Collector	8.5%	5.6%	8.5%	5.3%	-1.8%
74-ft Arterial	-0.5%	-0.5%	-0.6%	-0.5%	-0.3%
96-ft Thoroughfare	-1.0%	-4.0%	-1.3%	-4.4%	-12.4%

Sensitivity Analysis and Conclusions

Change in VMT

Reducing vehicle miles traveled by facilitating active modes of transportation (biking and walking) is a major goal of CS design guidelines. In this section, a sensitivity analysis that considers a range of changes in VMT is shown. The analysis was performed to provide both an example quantification of the environmental impacts/savings due to such changes, and an idea of the variables influencing the results. The results were then combined with the materials and construction LCA results of the previous section to see the relative sensitivities of MAC, assumed speed change, and assumed VMT change on the model outputs. The results indicate the importance of 1) always including sensitivity to these variables in the framework, and 2) collecting data to use with models to quantify the range of possible values.

To calculate the emissions due to changes in VMT, the environmental impacts of fuel combustion in vehicles during use stage under each design scenario were calculated first. The following assumptions were made for this purpose.

- The assumed daily traffic (number of vehicles/day) values were taken from SAC-DG for each street type.

- The environmental impacts of fuel consumption were calculated in two separate stages:
  - Gasoline production, which includes all the upstream impacts: crude oil extraction, transportation to the refinery plant, processes conducted at the refinery, and transportation to the filling station. These data were collected from the GaBi life cycle assessment software (GaBi 2016) using the process titled "US: Gasoline mix (regular) at filling station ts." The sum of all the upstream contributions is called the "well-to-pump" impact.
  - Tailpipe emissions, also called "pump-to-wheel" emissions, are due to combustion of fuel by the vehicle. The EMFAC2017 Web Database, developed by the California Air Resources Board, was used for this stage (EMFAC2017 Web Database). The emission rates of light-duty autos (LDA, or passenger cars) and light-duty truck type 1 (LDT1, or sports utility vehicles, SUVs) vehicles in Sacramento county in 2018 were extracted. Results were reported only for gasoline vehicles. It was assumed that 60% of the vehicles are passenger cars and 40% are light duty trucks. This assumption does not consider changes in VMT of freight vehicles and buses, and is therefore only a first-order estimate.
  - To calculate well-to-pump impacts, the total amount of fuel used for each vehicle-speed scenario was needed and, as EMFAC does not report fuel consumption values, US EPA's MOtor Vehicle Emission Simulator (*MOVES*) was run to get fuel consumption rates versus speed for all the vehicle speed combinations *(MOVES* website).
  - The modeling only considered constant speeds and did not include changes in the drive cycles because *EMFAC* does not have detailed drive cycle data. In addition, two design speeds were considered for complete streets: design speeds for conventional streets and the reduced speeds recommended by NACTO in their Urban Street Design Guide (NACTO, 2013)

Table 10 shows the assumptions made for traffic volume and speed for each street type, and Table 11 shows the well-to-wheel impacts of vehicle fuel consumption during the use stage for the conventional design scenarios.

Table 10. Traffic Assumptions Made for Traffic Levels and Speeds

Street Type	Traffic (Vehicles per Day)	Conventional Design Speed (mph)
32-ft Minor Residential	1,000	25
38-ft Primary Residential	5,000	30
48-ft Collector	10,000	35
60-ft Major Collector	15,000	40
74-ft Arterial	30,000	45
96-ft Thoroughfare	50,000	50

Table 11. Well-to-Wheel Impacts of Vehicle Fuel Combustion during the 30-Year Analysis Period for Conventional Design Scenarios

Street Type	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
32-ft Minor Residential	3E+05	1E+01	3E+03	4E+06	0E+00
38-ft Primary Residential	2E+06	1E+02	2E+04	3E+07	0E+00
48-ft Collector	4E+06	2E+02	5E+04	6E+07	0E+00
60-ft Major Collector	8E+06	4E+02	8E+04	1E+08	0E+00
74-ft Arterial	2E+07	9E+02	2E+05	2E+08	0E+00
96-ft Thoroughfare	4E+07	2E+03	4E+05	5E+08	0E+00

There is no reliable and widely accepted model for estimating VMT reduction due to implementation of CS elements for different street types, as was discussed in Chapter 3. While some studies report as much as a 15 percent reduction in VMT (Smart Growth America 2015) other studies show mixed results with a high level of variability. For example, Figure 9 shows the histogram of percent reduction in daily traffic in different streets in San Jose after implementing a road diet (Nixon et al. 2017). The San Jose study measured VMT changes on the complete street and on adjacent streets, so the changes measured can be considered to represent the network of parallel alternative routes around the complete street, not just the complete street itself.

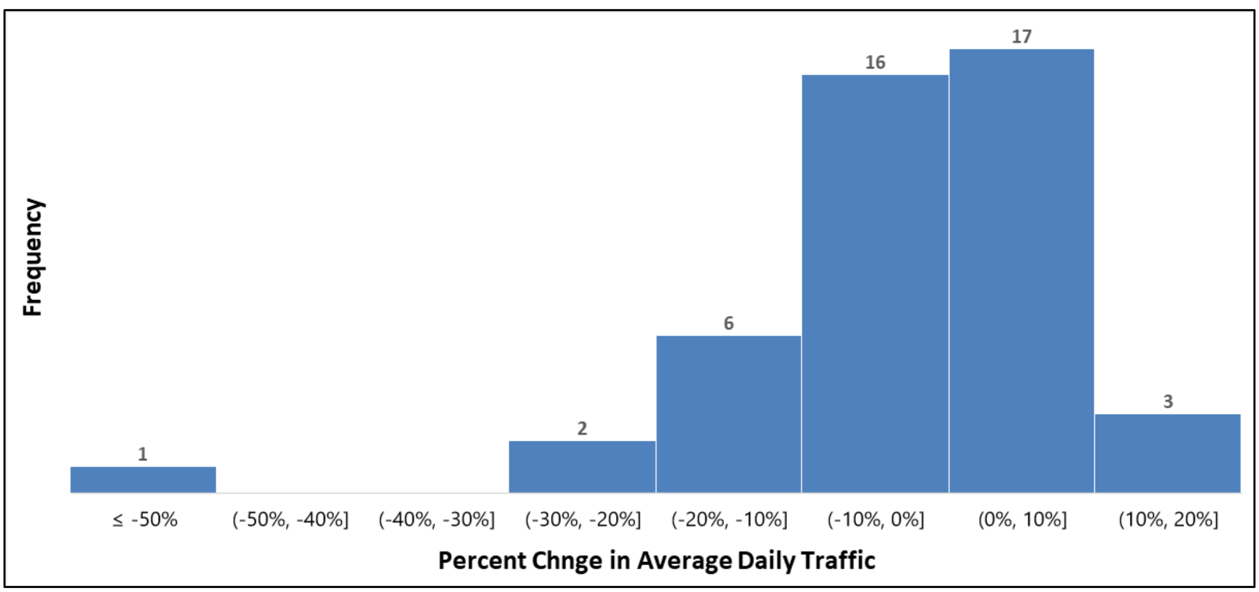

Figure 9. Histogram of Changes in Daily Traffic After Implementing Road Diets on Conventional Streets in San Jose (Nixon et al. 2017)

Therefore, it was decided to select a range of changes in VMT and to run the model for each case to gain a better understanding of the sensitivity of the results to changes in traffic. The model was run for five cases of VMT change for each street type, and the assumptions were made based on the San Jose report that these VMT changes were for the complete street and the streets around it, combined. The change in VMT ranged between -15 percent to +5 percent. Any changes in congestion were not considered.

Figure 10 and Figure 11 compare the difference in GHG emissions of MAC and well-to-wheel for the CS-Option versus the Conv-Option for minor residential and thoroughfare streets across the range of changes in VMT levels. These two street types have the lowest and highest traffic and slowest and fastest traffic speeds, respectively, and therefore show the range of impacts of VMT and speed change. Defining the total life cycle impacts as the summation of MAC and well-to-wheel impacts during the life cycle, the figures show that relatively small changes in VMT can result in major changes in total life cycle GHG emissions. This is because well-to-wheel impacts are initially one to two orders of magnitude larger than MAC impacts (compare the values in Table 7 and Table 11); therefore, any small change in traffic patterns drives the net change in total impacts. Figure 12 and Figure 13 show the cumulative GHG emissions with time for the same two street types,highlighting the payback period for each case of change in VMT. While it takes at least two years to fully offset the extra MAC impacts of CS-Options with reductions in well-to-wheel impacts for the best case scenario of 15 percent reduction in VMT, this payback can never be realized if the VMT does not change or increases. For thoroughfares, the situation is different, as the MAC of the CS-Option is actually lower than the MAC of the Conv-Option. So, as long there is no increase in VMT, implementation of the CS option results in reduction of total impacts.

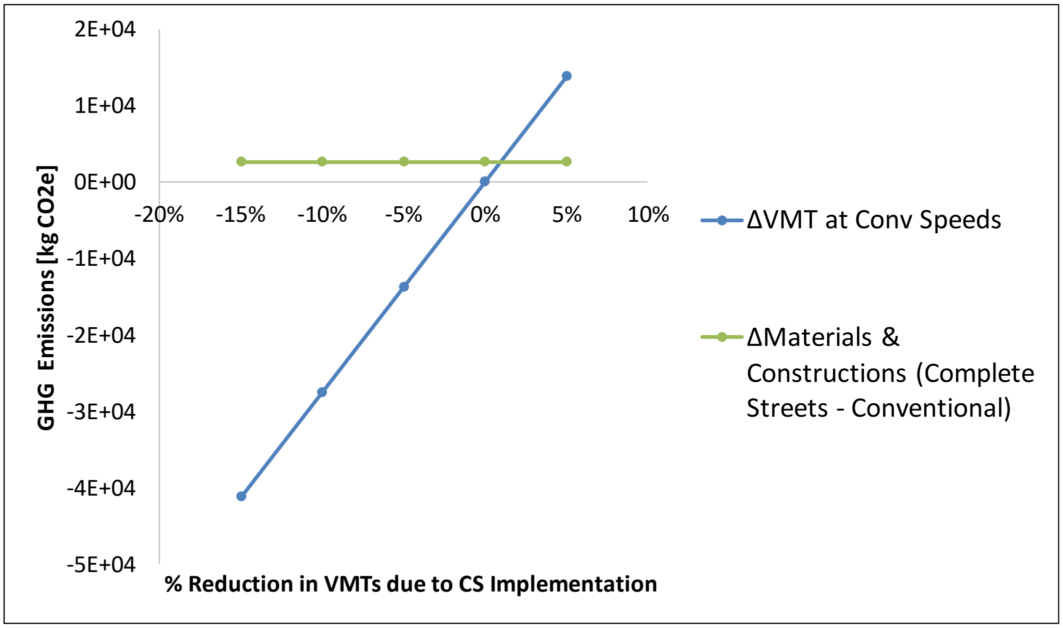

Figure 10. Difference in Well-to-Wheel and MAC GWP [kg CO2e] Impacts (CS-Conv) during the Analysis Period (30 years) for 32-ft Minor Residential Only Considering Changes in VMT for Well-to-Wheel

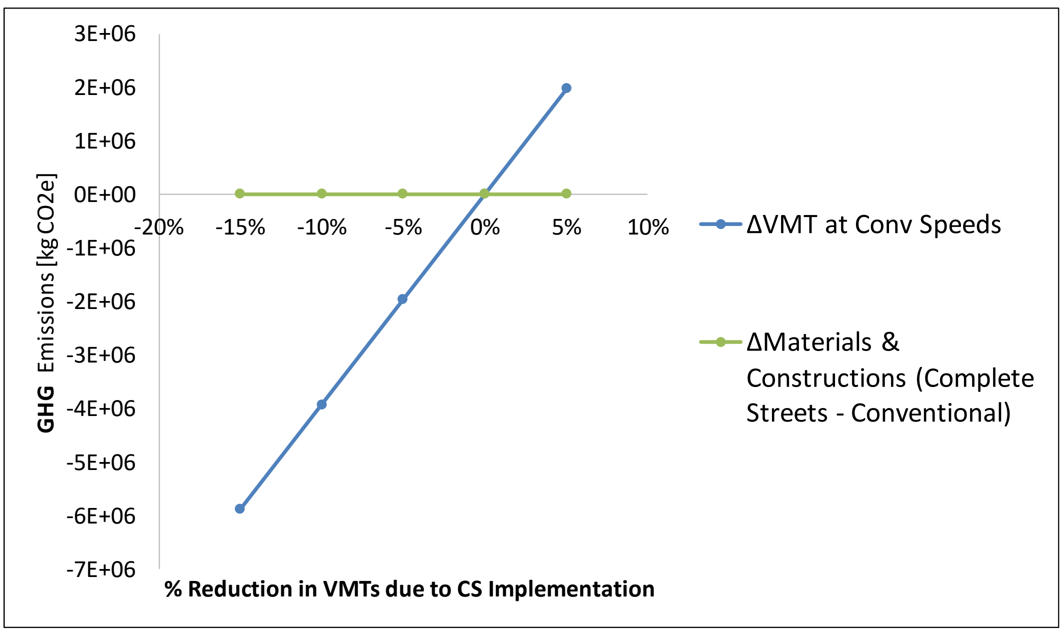

Figure 11. Difference in Well-to-Wheel and MAC GWP [kg CO2e] Impacts (CS-Conv) during the Analysis Period (30 years) for 96-ft Thoroughfare Only Considering Changes in VMT for Well-to-Wheel

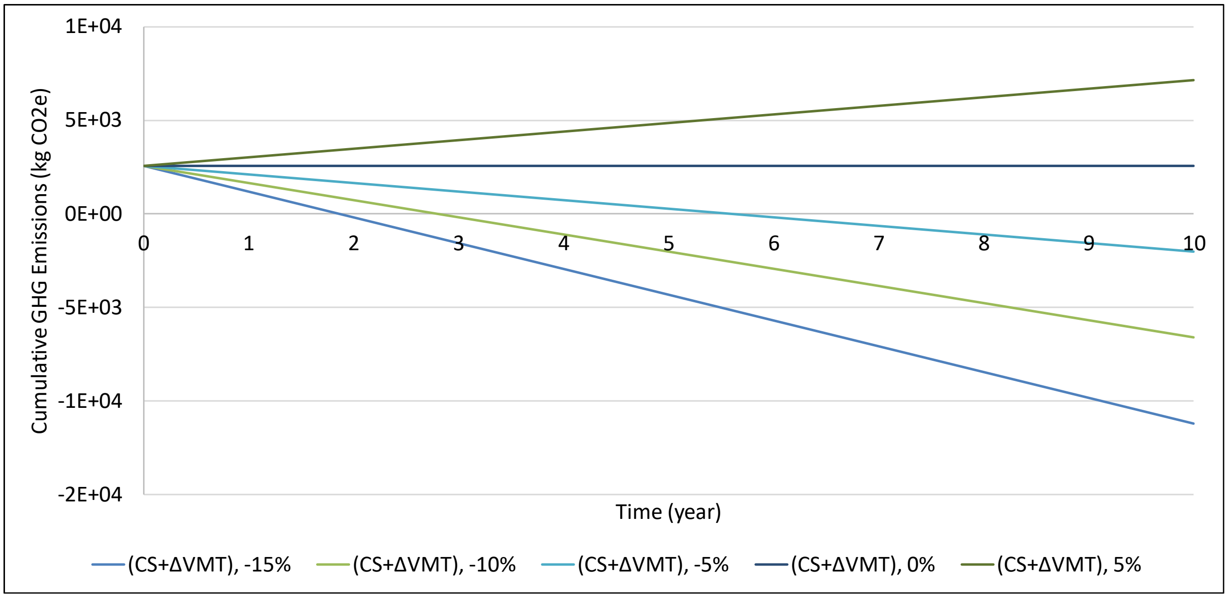

Figure 12. Cumulative GHG Emissions for 32-ft Minor Residential Assuming Only Changes in VMT

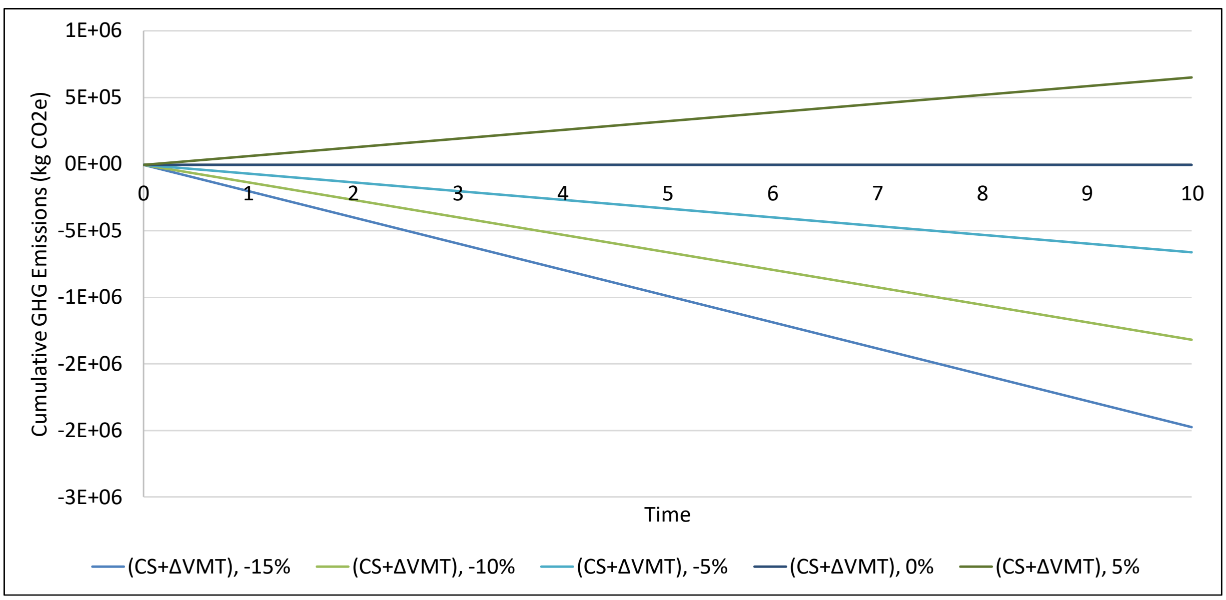

Figure 13. Cumulative GHG Emissions for 96-ft Thoroughfare Assuming Only Changes in VMT

Changes in Traffic Speed

In addition to reducing VMT and encouraging active modes of transportation, urban designers prefer using traffic calming designs that reduce traffic speed to increase safety and make active transportation modes more attractive to the public. In this section, the impact of such measures is quantified by considering the effects of reduced speed on vehicle fuel consumption using the lower speed limits recommended in the NACTO design guide (NACTO 2013). Table 12 shows the conventional design speed limits and the speed limits recommended by NACTO. Reducing traffic speed can improve safety, and potentially increase mode change from vehicles to active transportation as discussed in Chapter 3, however, it can have negative impacts on the fuel efficiency of vehicles. Figure 14 shows the changes in vehicle fuel efficiency, expressed as miles per gallon (mpg) or miles travelled per gallon of fuel, versus speed for passenger cars and light duty trucks based on data collected from the *MOVES* model *(MOVES* website). Figure 15 and Figure 16 show similar trends by plotting tailpipe global warming potential and PM 2.5 emissions based on data collected from the EMFAC model (EMFAC2017 Web Database).

The sensitivity analysis for changes in VMT presented in the previous section was repeated for the design speeds recommended by NACTO and the results are plotted in Figure 17 and Figure 18 for minor residential streets and thoroughfares, respectively. As the results in the figures show, reductions in traffic speed can have significant impacts on the well-to-wheel emissions of the traffic during the use stage. For minor residential streets, reduction of design speeds from 25 to 20 miles per hour results in an increase in well-to-wheel impacts for complete street versus conventional options across all values of change in VMT. This is because within the speed range of residential streets, any speed reduction results in dramatic decreases in fuel efficiency and increases in tailpipe emissions, and the resulting increased emissions cannot be offset by even a 15 percent reduction in VMT.

However, the opposite is true for thoroughfares because when design speed is changed from the conventional value of 50 miles per hour (mph) to the NACTO recommended speed of 45 mph for thoroughfares, the fuel consumption of passenger cars decreases to its minimum value across all speeds (45 mph is an optimal speed for fuel consumption according to the model). Therefore, for the case of the thoroughfare, the speed limit reduction further intensifies the reduction of well-to-wheel impacts due to VMT reduction. Figure 19 which shows well-to-wheel GHG emissions (kg CO_2e per mile) for a traffic mix of 60 percent passenger cars and 40 percent light-duty truck type 1 vehicles, can be used to identify the speed range in which a traffic speed reduction results in lowered GHG emissions and avoids the unintended consequence of increased GHG emissions due to reduced speed.

Table 12. Conventional Design Speed Limits and NACTO Recommended Values for Different Street Types

Street Type	Traffic (Vehicles per Day)	Conventional Design Speed (mph)	NACTO Design Speed (mph)
32-ft Minor Residential	1,000	25	20
38-ft Primary Residential	5,000	30	25
48-ft Collector	10,000	35	25
60-ft Major Collector	15,000	40	30
74-ft Arterial	30,000	45	35
96-ft Thoroughfare	50,000	50	45

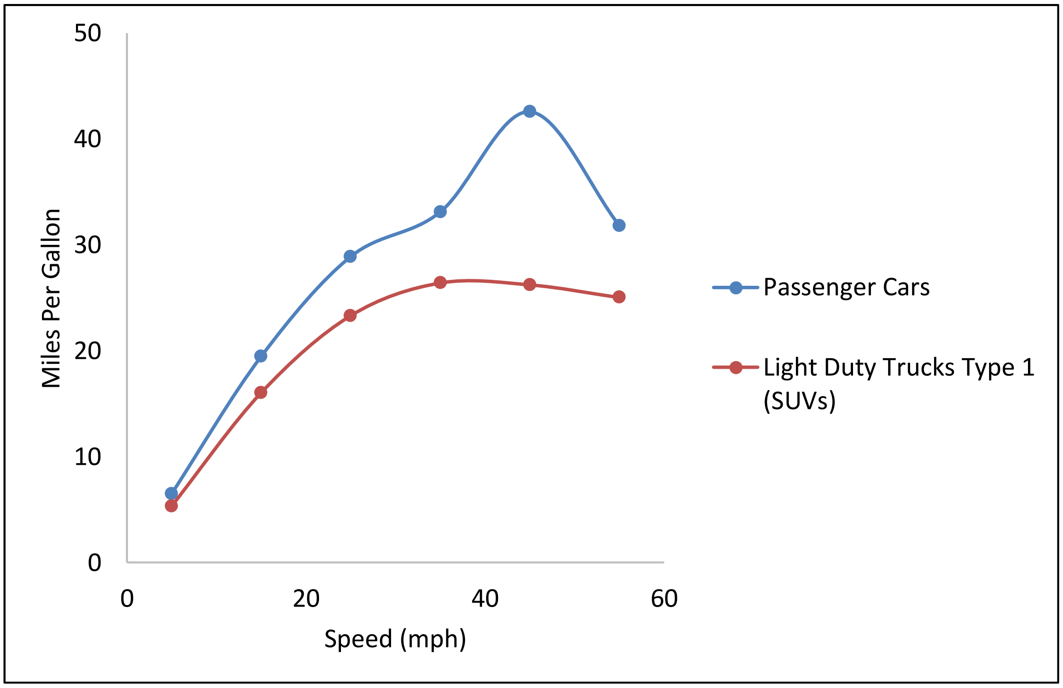

Figure 14. Changes in MPG with Speed Based on US EPA's MOVES Data

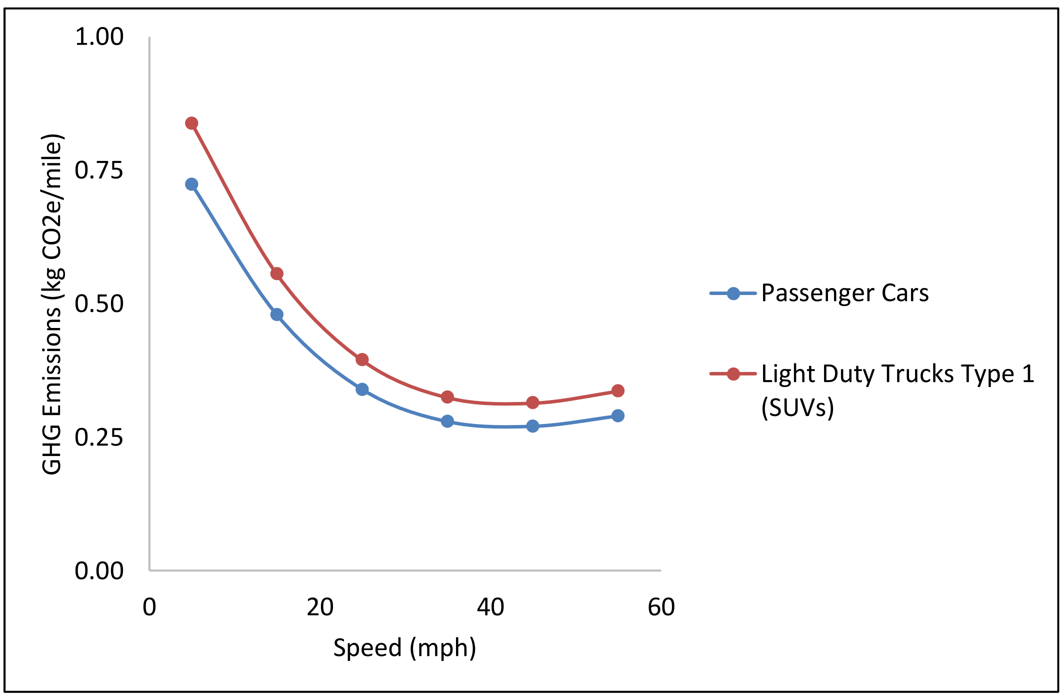

Figure 15. Changes in Tailpipe GHG Emissions Based on EMFAC Model

NCST

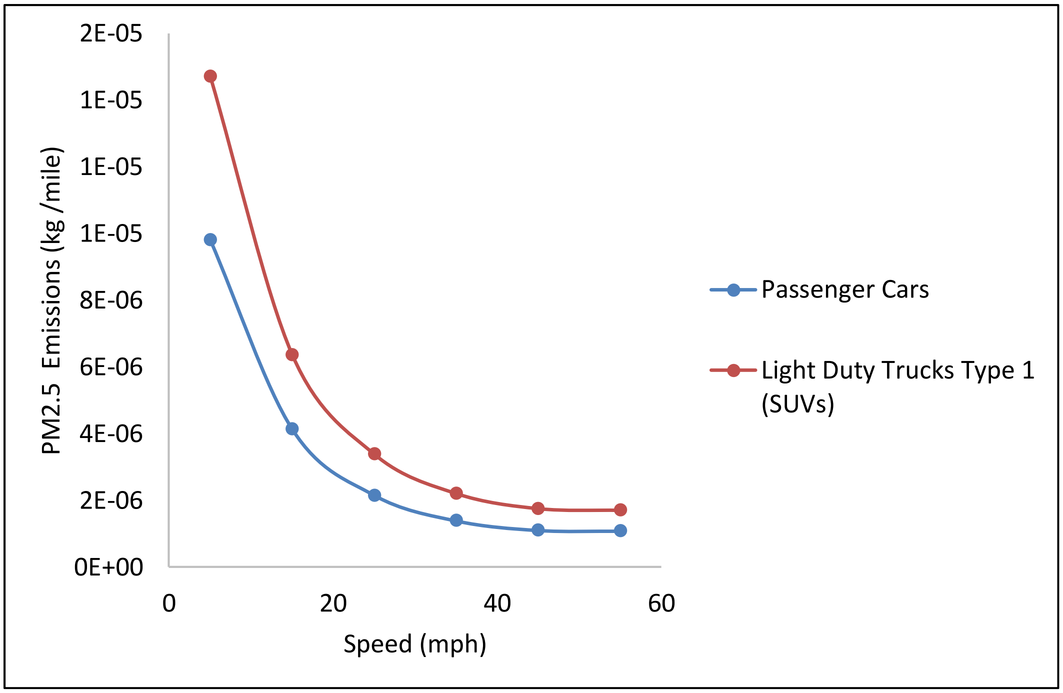

Figure 16. Changes in Tailpipe PM2.5 Emissions Based on EMFAC

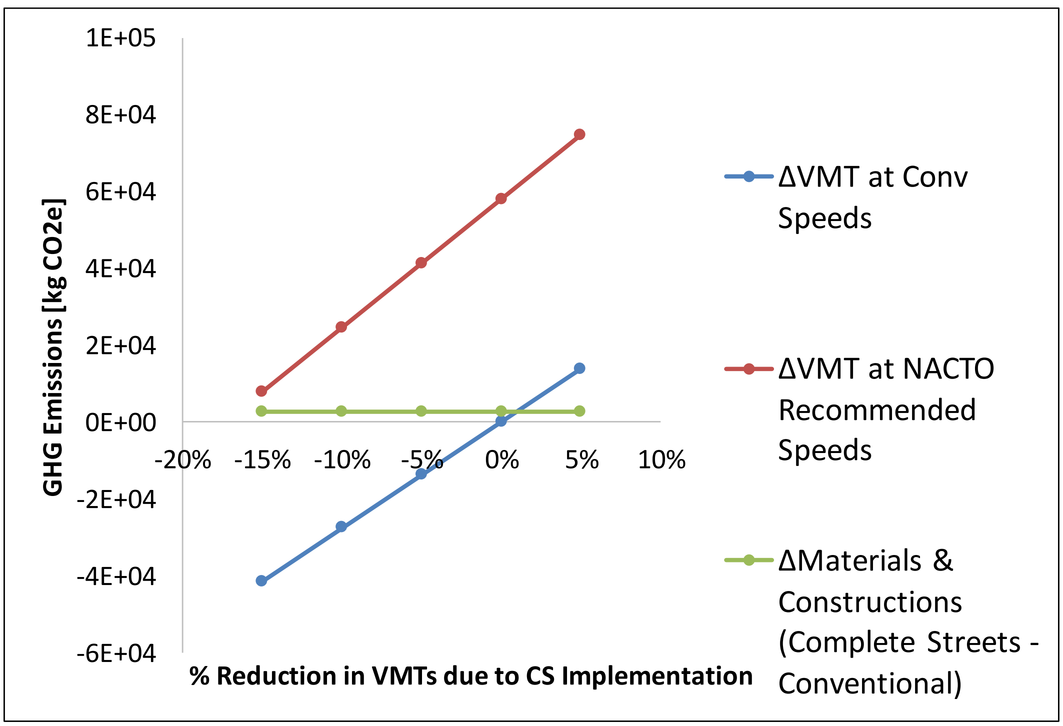

Figure 17. Difference in Well-to-Wheel and MAC GWP [kg CO2e] Impacts (CS-Conv) during the Analysis Period (30 years) for 32-ft Minor Residential Considering Changes in Both VMT and Traffic Speed for Well-to-Wheel Impacts

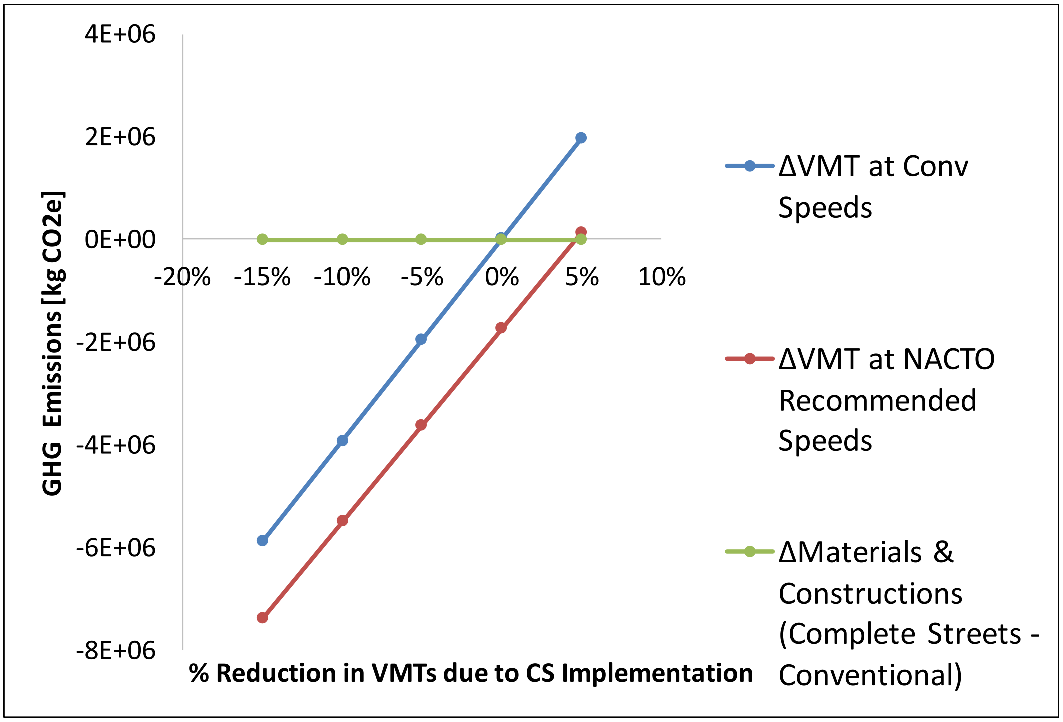

Figure 18. Difference in Well-to-Wheel and MAC GWP [kg CO2e] Impacts (CS-Conv) during the Analysis Period (30 years) for 96-ft Thoroughfare Considering Changes in Both VMT and Traffic Speed for Well-to-Wheel Impacts

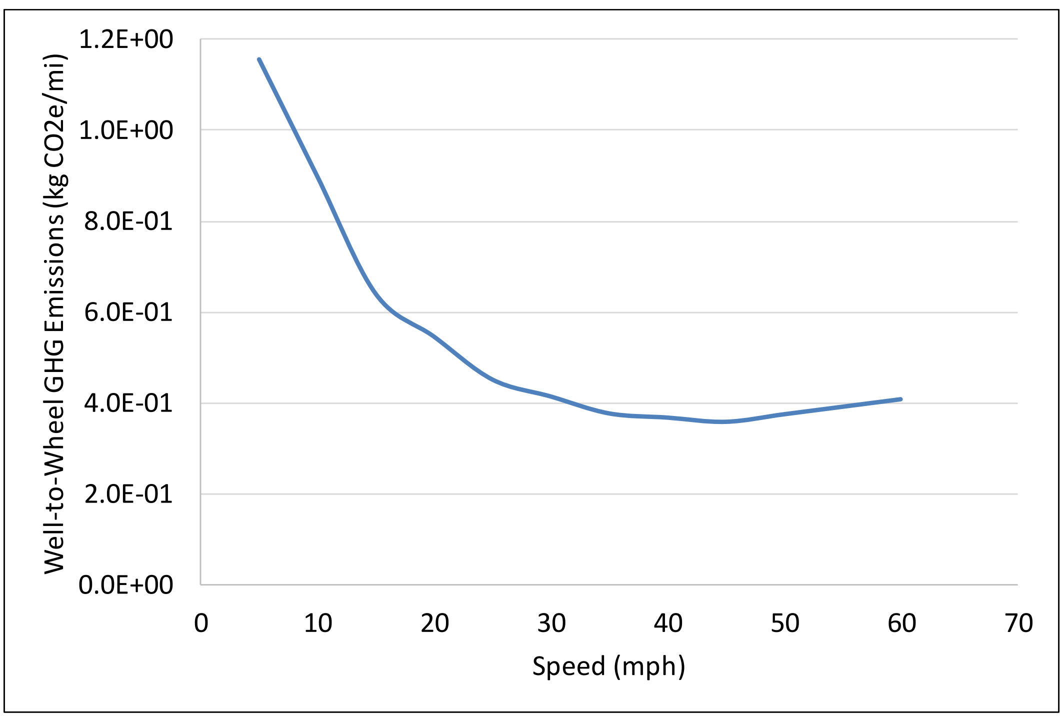

Figure 19. Well-to-Wheel GHG Emissions versus Speed for a Mix of 60% Passenger Cars and 40% Light Duty Trucks Type 1

Summary and Preliminary Conclusions

A preliminary set of rudimentary assumptions was used to demonstrate the use of LCA to consider the full life cycle environmental impacts of conversion of several types of conventional streets to complete streets.

The importance of objective and reliable models for changes in traffic volume and congestion from the implementation of complete streets and comparison with conventional streets cannot be overstated. The full system impacts of complete streets on environmental impact indicators, considering materials, construction and traffic changes, are driven by changes in reduction in VMT and changes in the operation of the vehicles with regard to speed and drive cycle changes caused by congestion, if it occurs. To avoid situations where well-intended efforts might result in greater environmental impacts, utilization of life cycle assessment should be used as a robust and objective methodology that consider the full life cycle of the alternatives. Each LCA study should use 1) high-quality data, 2) a correct definition of the system boundary, and 3) include a thorough investigation, identification, and quantification of possible significant unintended consequences.

The initial results indicate that application of the complete streets networks to streets where there is little negative impact on vehicle drive cycles from speed change will have the most likelihood of causing overall net reductions in environmental impacts.

The results also indicate that there is a range of potential VMT changes to which environmental impacts are more sensitive than they are to the effects of the materials and construction phases, and that changes in vehicle speed have different effects on environmental impacts depending on the context of their implementation, including the street type. These results indicate that the effects on environmental impacts due to implementing a complete street should be analyzed on a project-by-project basis, and that the effects will not always be positive. This preliminary conclusion leads to recommendations that this type of analysis be performed on a project-by-project basis, that the analysis include the surrounding network, and that a sensitivity analysis should also be included.

6. Social and Economic Indicators and Performance Measures

Introduction and Background

As funding for complete streets increases and the use of complete streets is encouraged to improve desirable social outcomes, appropriate indicators and performance measures will be 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 to provide practical performance measures for use in:

- Measuring pre-complete street performance,
- Predicting changes due to the complete street project, and
- Measuring post-deployment performance.

These indicators are intended for use in evaluating a project, and for comparing projects.

Limitations of indicators with respect to urban and rural applications

The indicators that were adapted in this study are focused on urban applications. They are not necessarily applicable to rural complete streets projects. They need to be evaluated for rural projects as they have been done in this study for urban projects. New indicators may need to be developed for rural projects.

Life cycle assessment and social life cycle assessment

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 streets interventions.

LCA has been adopted by the pavement field to systematically and objectively assess 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. The approach used for environmental LCA for this study was reported in Chapter 5.

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). The United Nations supported a multi-year project to develop such indicators, though its results are not applicable to complete streets projects (Andrews et al. 2009, UNEP 2013), as was discussed in Chapter 2, and as highlighted in observations from a workshop on the use of the UN S-LCA approach as reported in Chapter 3. 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 study and are discussed in this chapter. Most of these performance parameters are outside the framework of LCA and are intended to address a wide range of social and economic outcomes from a complete streets project.

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 project, 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. The intention of the work presented in this chapter is to identify a comprehensive set of social indicators that can be used as performance measures for complete streets 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.

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 and to be used in comparisons between projects that consider equity.

Consideration of equity

Background

Equity can be defined from a moral and sociological point of view as "fairness" to all people and removing inequality that comes from bias. The 1999 President's Report on Sustainable Development (President's Council, 1999) included a goal for equity that defined it as ensuring “that all Americans are afforded justice and have the opportunity to achieve economic, environmental, and social well-being.”

In this study, the review of performance indicators for complete streets is focused on evaluating them with regard to whether or not they contribute to increasing opportunities to achieve economic, environmental and social well-being, in particular for those who do not currently have many opportunities. At the same time, transportation and its supporting infrastructure can have major negative impacts on quality of life. Transportation infrastructure, as well as the lack of transportation infrastructure, can also have either positive or negative impacts on the opportunity for human and economic development. All of these need to be considered in social performance indicators.

The current wave of climate change and climate readiness legislation sets aside funding for complete streets projects in disadvantaged neighborhoods to address cumulative disparate impact from past practices of divestment, social exclusion and unequal public infrastructure investment. Disadvantaged neighborhoods reflect historical and spatial patterns of segregation and divestment and the resulting disparate impacts.

California Senate Bill 1 (SB 1) states that "it is the intent of the Legislature that the Department of Transportation and local governments are held accountable for the efficient investment of public funds to maintain the public highways, streets, and roads, and are accountable to the people through performance goals that are tracked and reported." The California Transportation Commission’s 2019 Active Transportation Program Guidelines include the goal of ensuring “… that disadvantaged communities fully share in the benefits of the program” (CTC 2018, pg 1) and states that “SB 99 specifies that at least 25% of funds [from the Active Transportation Program] must benefit disadvantaged communities in each of the program components.” (CTC 2018, pg 8).

Complete streets may offer an array of advantages that can help create healthy, vibrant places, and could be an important tool for local governments to meet legislative mandates for reducing GHGs and other environmental goals through sustainable community strategies, such as California Senate Bill 375. Complete streets projects can provide ways for environmental interventions at the local level while bringing economic stability and growth and building social cohesion through “placemaking.” Placemaking is a process of creating urban spaces that promote healthy social interaction and physical activity based on local (neighborhood level) desires, needs and decision-making, and that retain those characteristics over the long-term by being properly maintained and managed so that they can be continually used by all residents.

Spatial scales for considering equity

“Opportunity locations” or “opportunity destinations” can be defined as places that develop economic, environmental, and social well-being, and transportation is needed that allows people to access them. The inequalities that occur in public infrastructure in terms of opportunity destinations and the transportation infrastructure to get to them are most typically grouped on a spatial scale of neighborhoods. Neighborhoods can be defined both demographically and by physical boundaries. Historically in California (and across most of human history) the demographic and physical boundaries have been interactive, with physical boundaries often used to enforce or define human defined demographic boundaries based on race, ethnicity and/or social class and income levels. The inequalities of opportunity have well-known symptoms: poverty, low school achievement, youth crime, and high unemployment

Inequity can be lost when considered on a regional scale because of blending of statistics across disparate neighborhoods. On the other hand, inequity can lose its meaning when looked at for individuals because opportunities for individuals are defined by the neighborhood they are in and what they have access to in those neighborhoods.

The approach of performance measures in some of the studies reviewed in the literature is to focus on the symptoms of inequity rather than underlying problems that can cause it. Underinvestment in civil infrastructure can be one of the underlying contributors because it is a major cause of inequality of opportunity. This can include inequality of facilities such as parks, schools, medical care, jobs, fresh food, child care, community centers, libraries, major retail and entertainment, and places of worship in the neighborhood as well as the infrastructure to connect to these destinations in terms of transit routes, stops and centers, and active transportation routes. Another important type of destination is inter-neighborhood transportation connection points, in particular for disadvantaged neighborhoods which have often been defined by physical barriers to connection with locations of opportunity that are in adjacent or otherwise reasonably reachable neighborhoods.

Social indicators are needed that measure availability of civil infrastructure locations of opportunity and then access to it provided by transportation, for this study including those with complete street features. This is in contrast to making the complete street the focus of the indicator and measuring how much access it provides without considering if there are locations to be accessed. Access to these types of infrastructure is defined by the time, cost and effort needed to get to them from where people live, and by the cost of using them. Well-designed indicators should serve as diagnostic tests to help identify the underlying problems creating lack of opportunity. They should also be designed so that they avoid unintended negative consequences such as prioritizing transportation projects in neighborhoods because they are rich with locations of opportunity compared with those that are opportunity location-poor.

If successful, the social indicators should be able to identify restorative strategies that may include complete streets, and resulting regenerative effects. They should also create positive circular economic effects where conditions are created for long-term sustainability of the neighborhoods from an environmental, economic and social perspective to begin reversal of cumulative disadvantages from lack of investment.

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 recent 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 20, 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 20 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.

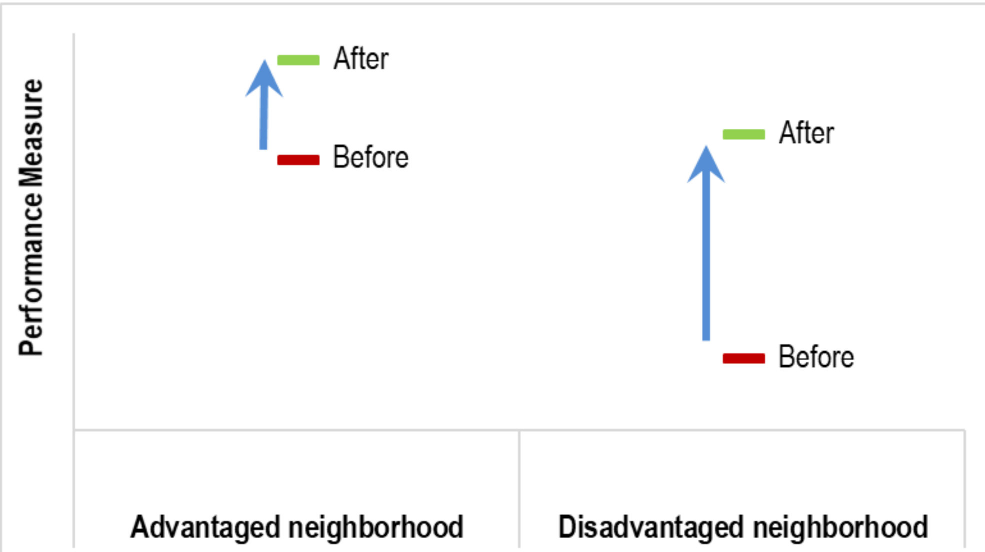

Figure 20. Evaluation of a Performance Measure for an Advantaged versus a Disadvantaged Neighborhood

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 21 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.

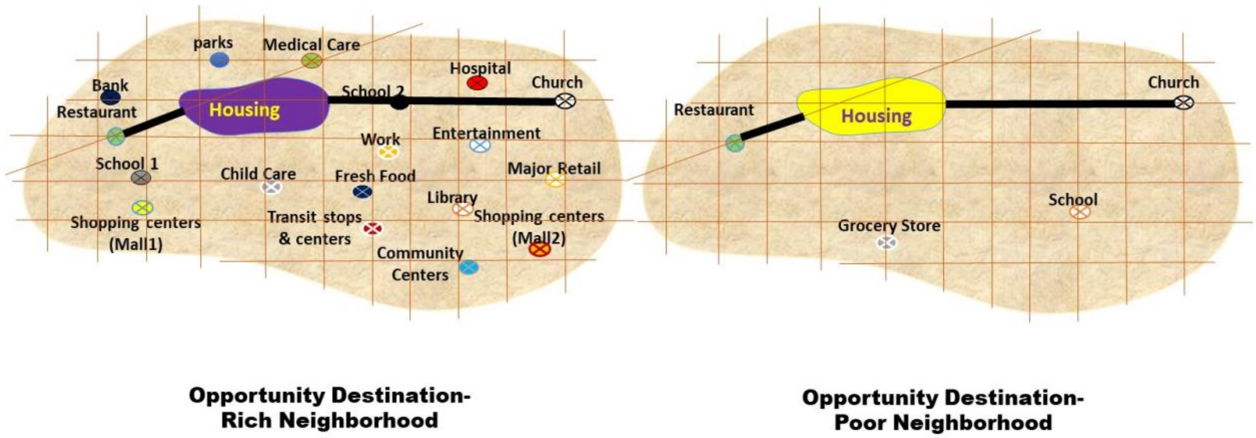

Figure 21. Consideration of Opportunity Destination Density in Two Neighborhoods when Considering Accessibility Measures

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 22. 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.

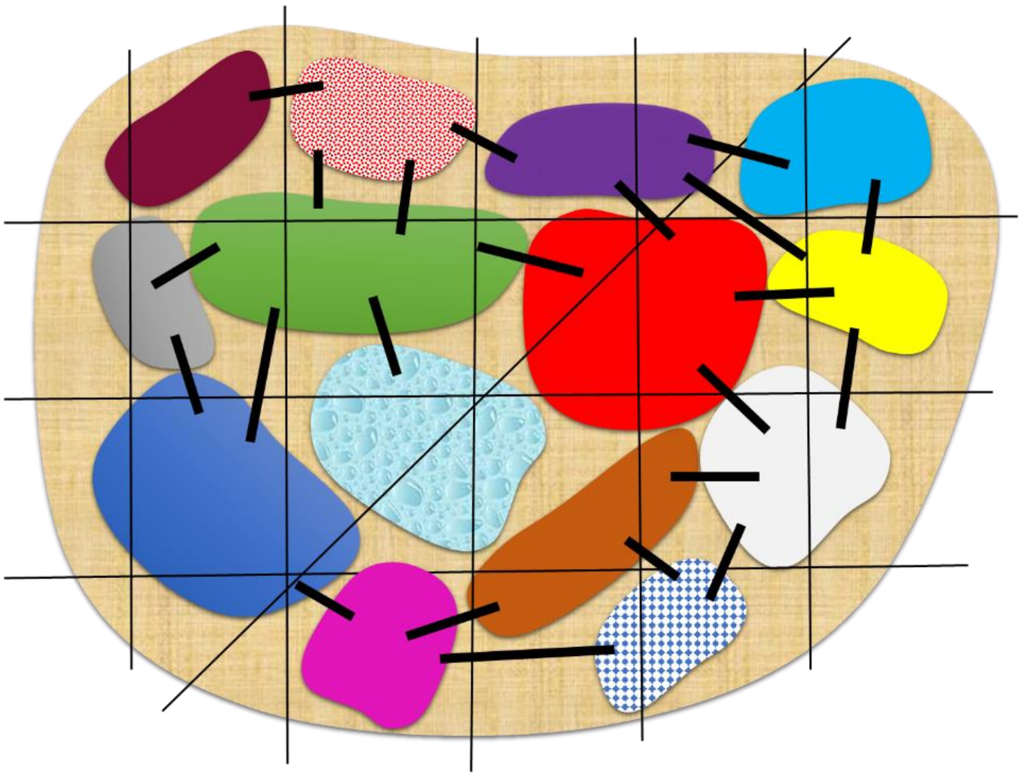

Figure 22. Consideration of Active Transportation and Transit-Active Transportation Connectivity between Neighborhoods

Other Considerations

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 23. 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.

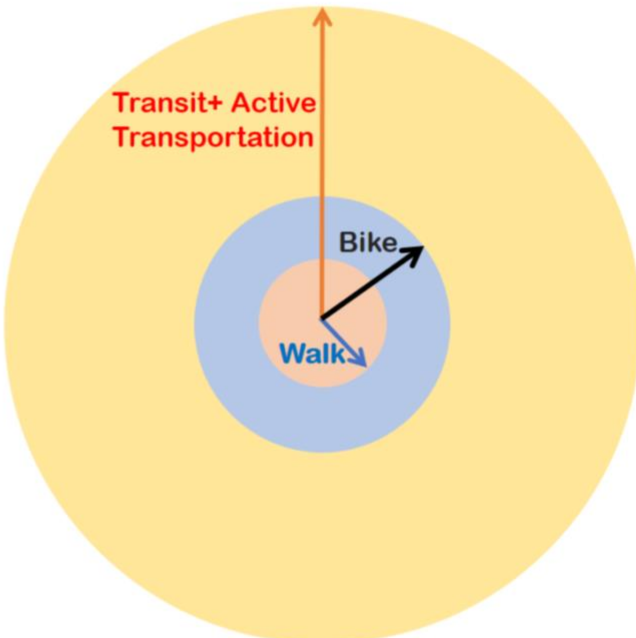

Figure 23. The Ability of Mixed Mode Travel Including Transit and Active Transportation to Improve Travel

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.

Goal and Approach

The goal of this research 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 (FHWA 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. Table 13 illustrates the categories of LCA performance measures proposed by this study, and the corresponding categories in the FHWA and Caltrans (FHWA 2016, Caltrans 2017)

The performance measures for transportation projects can be divided into two main categories, social and environmental. The environmental impact indicators proposed in the complete streets LCA framework are listed in Table 13, and were described in detail in Appendix F. They are shown in Table 13 as a reminder that 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 13, did not consider specific environmental indicators, but instead considered broad categories (e.g., environmental, sustainability).

As shown in Table 13, 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 (FHWA 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 13. Summary of FHWA, Caltrans and proposed categories for social performance measures (Harvey et al., 2016; FHWA 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 13. For the same reason, and again to check that a comprehensive set of measures is proposed in each impact category, Table 14 shows the performance measures proposed by Caltrans and FHWA, and in cases where the terminology differed, Table 14 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 14. 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

Caltrans Performance Measures	FHWA Performance Measures
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**
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

Next, the final selected performance measures used in the framework of this study are shown in Table 15, organized by the selected goal/value category. As noted by FHWA (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 15 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 report, a brief description of each performance measure, the data resources required, calculation methods derived from FHWA guidance, and example studies are provided.

Table 15. 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 Appendix F. Included in the appendix are discussions regarding how some performance measures were redefined for this project after the review for the equity and other considerations discussed elsewhere in this chapter. These performance measures will be reviewed by stakeholders as part of the case studies planned after submission of this report.

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 (Table 15).

For several categories, one or more indicators were created based on the complete street characteristics. For instance, "access to schools" was a new performance measure which 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.

Each of the indicators was viewed from an equity point of view by evaluating how the indicator would rank the same project in a historically advantaged neighborhood with a richness of publicly supported destinations, such as schools, libraries, churches, parks, medical services, and shopping centers, and connecting services including active transportation and transit connections versus a historically disadvantaged neighborhood that has few such destinations. These evaluations are described in the detailed descriptions of the indicators in Appendix F. 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 (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.

Several indicators were revised, such as the connectivity index which was revised to consider perceived safety of the connections, and several were removed after that review, as described in Appendix F. The same process will be used for a second review after trying the indicators on several projects. Consideration of equity will be aided by baselining neighborhood-scale conditions such as historical levels of public investment, inclusion in infrastructure plans, political capacity of neighborhoods, sales tax revenues produced by neighborhood and constraints to accessing social goods. 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.

7. Summary of LCA Framework for Complete Streets and Planning for Case Studies

Summary

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

- Development of a problem statement for application of LCA to the evaluation of complete streets projects and identification of research/data gaps that need to be filled
- Writing of a goal and scope statement for this study to fill those gaps
- Review of the literature for background on complete streets, complete streets guidelines and LCA of complete streets
    - The literature shows no previous application of LCA to evaluate complete streets projects
- Data collection from discussions and interviews from a wide range of stakeholders and participants in complete streets funding, planning, and advocacy
    - The conclusions were that social indicators and consideration of equity in their definition and use are concerns for many advocates for complete streets user groups as well as those responsible for delivering them
    - 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 for planning is warranted
    - 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
    - Estimation of mode choice change from vehicles to active transportation is still difficult; the important variables are known but methods of predicting change are still in development
    - The results provided ideas for social impact indicators that would be of value
- Summary of complete streets typologies
    - The results permit quantification of environmental impacts of materials, construction and maintenance of complete streets for comparison with conventional streets
- Application of LCA to calculate environmental impacts for complete streets
    - The environmental LCA framework was applied to the conversion of a range of conventional street types to become complete streets. Maintenance was considered in addition to the initial impacts of conversion. It was generally found that the conversion to complete streets for smaller, lower-traffic volume streets increased impacts due to the use of materials and construction over the life cycle, and was about the same for larger high traffic volume streets.

    - Sensitivity analysis based on a range of measured network changes in VMT after implementation of a complete street indicated that the environmental impacts are highly dependent on the change in VMT, and are not always for the better.
    - Sensitivity analysis based on comparison of the change in traffic speeds from those for each type of conventional street to recommended reduced traffic speeds on each type of complete street indicated that the effects on environmental impacts were highly dependent on the street type. When the change of speed brought it closer to the optimal speed for fuel consumption, generally around 45 mph, then there were beneficial changes in impacts (that is, reduced impacts). This occurred for larger streets with higher conventional speeds. For residential and smaller streets, the change in speed was to a value farther below the optimal speed for fuel consumption, which resulted in detrimental changes in impacts (increased impacts).
    - The effects of VMT change and speed change were generally much larger than those from materials and construction to convert the street to a complete street, although the materials and construction changes were not insignificant.
    - The effects of complete streets on freight logistics were not considered and could also be important. More information is needed to be able to consider the effects on freight logistics and the resulting environmental impacts.
- Adaption of social and economic indicators and performance measures
    - The indicators adapted and evaluated in this study are primarily for urban projects. The indicators need to be evaluated for rural applications, and there may be a need to develop new indicators for rural projects.
    - 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 from interviews
    - 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

Planning for Case Studies

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 will be based on project design for those that have not yet been constructed or completed. Where case study projects have been completed, projects will be evaluated based on performance before and after project completion.

There are two goals for the case studies:

- Evaluate the framework in terms of its practicality, which will primarily be centered around data collection, and the usefulness and reasonableness of the results, where they can be calculated. The results will be used to improve the framework.
- Where the framework is sufficiently able to function, evaluate the outcomes from complete streets projects. Projects will be evaluated on two levels:
    - The complete streets project itself
    - The complete streets network when fully implemented, if the project is part of the planned network

Case studies will be solicited in different parts of California, including urban and rural locations, and in more and less advantaged neighborhoods so that the equity aspects of the framework can also be evaluated.

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Appendix A. Qualitative Description of Types and Complete Street Conversion

Downtown 1-way Street

Conventional Design

One-way downtown streets with 2-4 lanes that do not carry much traffic result in underutilized space. Such roadways are mainly designed for 15-minutes peak traffic periods. Bicyclists are often at higher risk cycling in such wide, fast-moving traffic zones. Depending on the motorized and non-motorized traffic load, downtown 1-way streets space can be well utilized in complete street designs.

Transformation Opportunities

The roadway area dedicated to vehicle traffic can be narrowed down, and bicycle and transit lanes can easily be incorporated at reasonably low costs. In cases where 1-way streets carry heavy bus traffic, curbsides or offsets can be converted to bus only lanes (colored for identification). Preferably, the left curbside can be converted to a raised bicycle track (colored for identification) and the other side can accommodate the bus lane. This alternative can reduce the risk for bicyclist accidents. Furthermore, during the off-peak traffic hours, curbsides can also be designed to accommodate vehicle parking. In case downtown 1-way streets accommodate a high density of pedestrians, roadway area can be used to expand sidewalks. These features are shown in Figure 24.

Figure 24. NACTO Recommendations for Downtown 1-Way Street (From *Urban Street Design Guide*, by NACTO, pp. 9)

Downtown 2-way Street

Conventional Design

Downtown 2-way streets are typically the hardest to reconfigure as these not-too-wide streets are mainly designed to accommodate traffic, pedestrians, bicyclists, parking and transit. Freight delivery at peak hours further worsens the congestion situation. During traffic peak hours, such streets are high risks for everyone.

Transformation Opportunities

In order to utilize the space efficiently, standalone color-identified bicycle lanes can be added to the curbsides and bicycle signals should be installed. Dedicated bus waiting areas or bus bulbs can also be constructed at the start of the street. Right turn signals should be activated for the traffic approaching the street so that vehicles avoid queuing behind the bus blocking the intersection. A parallel parking lane also be accommodated beside the bicycle lane. Proper road markings and signs are also required to be installed. Freight delivery should be planned at off-peak traffic hours in order to avoid conflicts and traffic congestion. These features are shown in Figure 25.

Figure 25*.* NACTO Recommendations for Downtown 2-Way Street (From *Urban Street Design Guide*, by NACTO, pp. 11)

Downtown Thoroughfare

Conventional Design

Downtown thoroughfares are commonly wide 6 to 8 lane, 2-way streets that may run through the downtown and may also connect to other neighborhoods and/or centers. Left turns are major head on collision risks for vehicles and crossing pedestrians. For safety reasons, bicyclists prefer riding on sidewalks. Bicyclists in the street and buses experience delays due to parking encroachment, freight and traffic.

Transformation Opportunities

Depending on the traffic volumes passing through the street, restricted left turn lanes for bicyclists should be added. Dedicated bike and parallel parking lanes designed for downtown 2-way streets may also be incorporated. In case of high bicyclist volume, dedicated right turn bicycle lanes may be reserved. Under normal traffic and bicycle volume conditions, right turn lanes may act as a mixing zone (accommodating both bicycles and vehicles). A 6-foot pedestrian safety island may also be constructed between the right turn lane and second lane near the intersection. These features are shown in Figure 26.

Figure 26. NACTO Recommendations for Downtown Thoroughfare (From *Urban Street Design Guide*, by NACTO, pp. 13)

Neighborhood Main Street

Conventional Design

Neighborhood main streets accommodate businesses and experience high volumes of pedestrians, transit, bicyclists and frequent vehicle parking. In 4-lane (two way each direction) roadway configurations, the left turn poses high rear end collision risks.

Transformation Opportunities

So-called "road diets" can help reduce collision risks, and by converting 4 traffic lanes to 3 traffic lanes with the center lane available for vehicle and bicycle left turn bays (the road diet), more space is created that can be utilized for dedicated bicycle lanes and parking spaces. Part of the center lane can act as road diet for turning vehicles whereas the rest can be converted to a median. Plants could be installed in the median, and pedestrian safety islands can also be retained. For low traffic streets, parklets may also be created beside the curb. If the street carries high bicyclist volumes, bicycle boxes can be created that are marked space for bicycle left turns in front of the traffic red light. Such street installations also help local businesses making streets safe and attractive. Freight loading and unloading space can also be assigned however, NACTO recommends that freight vehicles should operate in such streets during off-peak traffic hours. These features are shown in Figure 27.

Figure 27. NACTO Recommendations for Neighborhood Main Street (From *Urban Street Design Guide*, by NACTO, pp. 15).

Neighborhood Street

Conventional Design

These streets are mainly residential neighborhoods that provide access to local schools, stores and other neighborhood destinations. The street space is mostly underutilized and wide lanes encourage vehicles to run at higher speeds increasing the risk of crashes/accidents.

Transformation Opportunities

1-way neighborhood streets can be narrowed down, and a left bike lane can be added. Cross walks and curb extensions can be raised. Parking spaces near the curbs may also be accommodated. These features are shown in Figure 28.

Figure 28. NACTO Recommendations for Neighborhood Street (From *Urban Street Design Guide*, by NACTO, pp. 16).

Yield Street

Conventional Design

2-way yield street design is suitable for a residential area where traffic is expected to move at slow speeds. The design of such a street mainly depends on traffic, parking space utilization, flush curbs and other street features.

Transformation Opportunities

Such residential streets should be attractive, safe and inviting places to walk or provide access to other places. Driveways grade and sidewalks should be maintained. Sidewalks can also accommodate plant furniture. Installation of signs and road markings are essential. Curb extensions can also help in reducing traffic speeds in such streets if required. These features are shown in Figure 29.

Figure 29. NACTO Recommendations for Yield Street (From *Urban Street Design Guide*, by NACTO, pp. 17).

Boulevard

Conventional Design

Boulevards are wide and large streets that handle multi-operation. Boulevards separate higher speed throughway traffic from slow moving or parking traffic in the outer lanes (sometimes called frontage roads) in a residential or commercial street. As the boulevards are large and wide, special attention is required at the intersections. Poorly designed intersections create a sense of confusion and become unsafe for all the users. Due to high traffic volumes and heavy congestions on these streets, many have been redesigned to increase vehicle traffic throughput; however, some cities have restored original multi-mode design features.

Transformation Opportunities

Frontage roads should be stop or traffic signal controlled. Such roads can also help accommodate back-in angled parking spaces near the curbs as well for local businesses and/or residents. Frontage road lanes that mix slow and parking vehicles with bicyclists and transit vehicles picking up and dropping passengers can be created. This can avoid rear-end collision risks and helps through traffic to pass without affecting other users. The medians between the frontage and throughway lanes can be converted to seating and walking paths. These features are shown in Figure 30 and Figure 31.

Figure 30. NACTO Recommendations for Boulevard (From *Urban Street Design Guide*, by NACTO, pp. 18).

Figure 31. NACTO Recommendations for Boulevard (From *Urban Street Design Guide*, by NACTO, pp. 19).

Residential Boulevard

Conventional Design

Residential boulevards were typically designed to let traffic pass quickly by providing enough lanes to limit congestion. Residential boulevards are often unattractive for people to walk and space is underutilized. Such boulevards have relatively low traffic relative to the number of lanes and wide and extra lanes tend to encourage drivers to drive fast, increasing the risk of accidents in residential areas.

Transformation Opportunities

Transformation options include redesigning medians to accommodate walking paths, plants and seating areas. Midblock crossings or curb extensions are necessary for safety reasons because of the long distances that must be crossed by pedestrians and bicyclists at intersections. A raised bicycle path between the median and roadway can also be constructed. Curbside parking can be added, if not already present. In cases where residents have off-street parking, curbside parking can be reduced by adding curbside extensions, or expanded sidewalks. These features are shown in Figure 32.

Figure 32. NACTO Recommendations for Residential Boulevard (From *Urban Street Design Guide*, by NACTO, pp. 21).

Transit Corridor

Conventional Design

Transit corridors not only accommodate buses, traffic, bicycles and pedestrians, but also may include light rail. Transit corridors may promote economic growth and businesses nearby if designed and utilized properly.

Transformation Opportunities

Transit corridors deign should be oriented towards pedestrian safety. Curbside raised bicycle lanes or center 1-way or 2-way bicycle tracks should be considered in order to accommodate bicyclists. High quality transit services and median transit lanes can help reduce congestion, attract passengers to use transit and are much safer. Transit waiting areas should be properly designed keeping in mind peak hour demand. Installing transit fare collection units, or more sophisticated fare collection and well-designed boarding areas can also avoid delays. These features are shown in Figure 33 and Figure 34.

Figure 33. NACTO Recommendations for Transit Corridor (From *Urban Street Design Guide*, by NACTO, pp. 22).

Figure 34. NACTO recommendations for Transit Corridor (From *Urban Street Design Guide*, by NACTO, pp. 23).

Residential/Green Alley

Conventional Design

Residential alleys provide run behind houses in residential areas. The majority of residential alleys are either vehicle-free or subject to very low traffic and are mostly not maintained making them unattractive.

Transformation Opportunities

NACTO refers to residential alleys as "green streets" once they are transformed. Constructing permeable pavements is another alternative that not only serves as a hardscape but also acts as a stormwater drainage and stormwater quality management system. Signs should be properly installed if the alley also lets traffic pass through as well. Proper lighting, including use of efficient "one-demand" lighting triggered by motion sensors, is another necessity for residential alleys for the safety of public and residents. Bicyclists may share the alley with pedestrians. Organization of local residents or neighborhood associations to maintain the alleys can be considered. The pavement does not need to be built for heavy vehicles if the alley is not used for waste collection or other services requiring heavy vehicles. If the residential alleys are used for waste collection vehicles, consideration must be given to accommodation of garbage trucks, which are heavy, when designing the pavement. Permeable pavements can be used for both light and heavy-duty load requirements to improve drainage and stormwater quality. Design for human thermal comfort may be a consideration depending on the climate, and amount of shading from trees and buildings. These features are shown in Figure 35.

Figure 35. NACTO Recommendations for Green Alley (From *Urban Street Design Guide*, by NACTO, pp. 24).

Commercial Alley

Conventional Design

Commercial alleys run behind buildings in commercial areas and primarily serve businesses for deliveries and waste collection. They are often considered unclean and unsafe; however, they could be transformed.

Transformation Opportunities

Like residential alleys, the pavement does not need to be built for heavy vehicles if the alley is not used for waste collection or deliveries requiring heavy vehicles. If the commercial alleys are used for waste collection, freight delivery vehicles or access by fire trucks, the pavement must be designed to carry these heavy axle loads. Same shared space rules for bicyclists apply to the commercial alleys as were discussed for other streets. Special consideration for safety should be given in case freight trucks access this space. Permeable pavements can be used for both light and heavy-duty load requirements to improve drainage and stormwater quality. Design for human thermal comfort may be a consideration depending on the climate, and amount of shading from trees and buildings. These features are shown in Figure 36.

Figure 36. NACTO recommendations for Commercial Alley (From *Urban Street Design Guide*, by NACTO, pp. 25).

Residential Shared Street

Conventional Design

These streets are mainly low volume residential streets. In the U.S., many of these streets were designed without sidewalks, thus, bicyclists, pedestrians and vehicles share the roadway. The sidewalks, when present, are mostly narrow which can be a hazard for pedestrians, especially when bicyclists are also using them for safety reasons, and can be difficult to use by wheelchairs.

Transformation Opportunities

These streets should be designed in a way that prioritizes pedestrians and bicyclists, while still accommodating motorized vehicles. Bike stands, benches, street and plant furniture, may help to define shared spaces. Shared street signs and yield to pedestrians' signs should be installed. Wide streets may allow parking for the residents in the design. The shared streets should be constructed in a way so that snow-plowing is easier (in case of cold snowy winters), materials are durable, and drainage is provided either in the center of the street or along the flush curb. Pervious materials may be used to build the streets, improving flood control and storm water management. Design for human thermal comfort may be a consideration depending on the climate, and amount of shading from trees and buildings. Most of these features are shown in Figure 37.

Figure 37. NACTO recommendations for Residential Shared Street (From *Urban Street Design Guide*, by NACTO, pp. 27).

Commercial Shared Street

Conventional Design

Commercial shared streets are locations where vehicle traffic is low speed, and there are high volumes of pedestrians during rush hours and lunch hours. Commercial shared streets need to allow freight trucks to load and unload goods for businesses. Vehicles searching for on-street parking create congestion. The sidewalks are typically not wide enough to carry peak volumes of pedestrian traffic and they will often spill into the street creating the potential for unsafe conditions. Freight vehicles will often partially block sidewalks where there is inadequate room to park and unload.

Transformation Opportunities

Shared streets maintain access for vehicles operating at low speeds and are designed to permit easy loading and unloading for trucks at designated hours. They are designed to implicitly slow traffic speeds using pedestrian volumes, design, and other cues to slow or divert traffic. Bike stands, benches, street and plant furniture, also helps define the shared space. Shared street signs should be installed, and designated freight loading and unloading zone may be marked. Car traffic and/or freight traffic may be prohibited during certain hours of the day. A transit mall may be considered for transit access to the pedestrians. Permeable pavements can be used for heavy duty load requirements in areas where they will not interfere with buildings to improve drainage and stormwater quality. Design for human thermal comfort may be a consideration depending on the climate, and amount of shading from trees and buildings. Some of these features are shown in Figure 38.

Figure 38. NACTO Recommendations for Commercial Shared Street (From *Urban Street Design Guide*, by NACTO, pp. 29).

Caveat to All Street Type Summaries

All the recommendations by NACTO are intended to improve accommodation of all travel modes and improve safety for existing streets that are currently primarily designed or configured for motorized traffic only. The specific features and their implementation summarized in this document were prepared to be able to define and estimate performance indicators for LCA and do not cover the full range of features, nor the potential approaches to implementation that are possible or desirable in a given context. Other context-appropriate solutions can be proposed for each street type depending on the prevailing circumstances, and county/city or state rules and regulations.

The NACTO guide specifically calls out the use of recycled and lower impact materials for only a few of the street types. The use of lower impact materials can and should be considered for all street types and features. It should also be noted that the use of LCA to determine the impacts of materials and designs is one of the purposes of the framework being built in this study. The use of LCA will help determine whether a design strategy or material actually produces a lower impact and can be used with cost studies to determine the benefit/cost trade-offs of alternative designs.

The NACTO guide specifically calls out the use of permeable pavements and recycled or low-impact materials for only a few of the street types summarized in this document. The use of permeable pavements can be considered for a wider range of street types and implementation schemes than the NACTO guide suggests.

Appendix B. Geometric and Functional Requirements of Each Standard

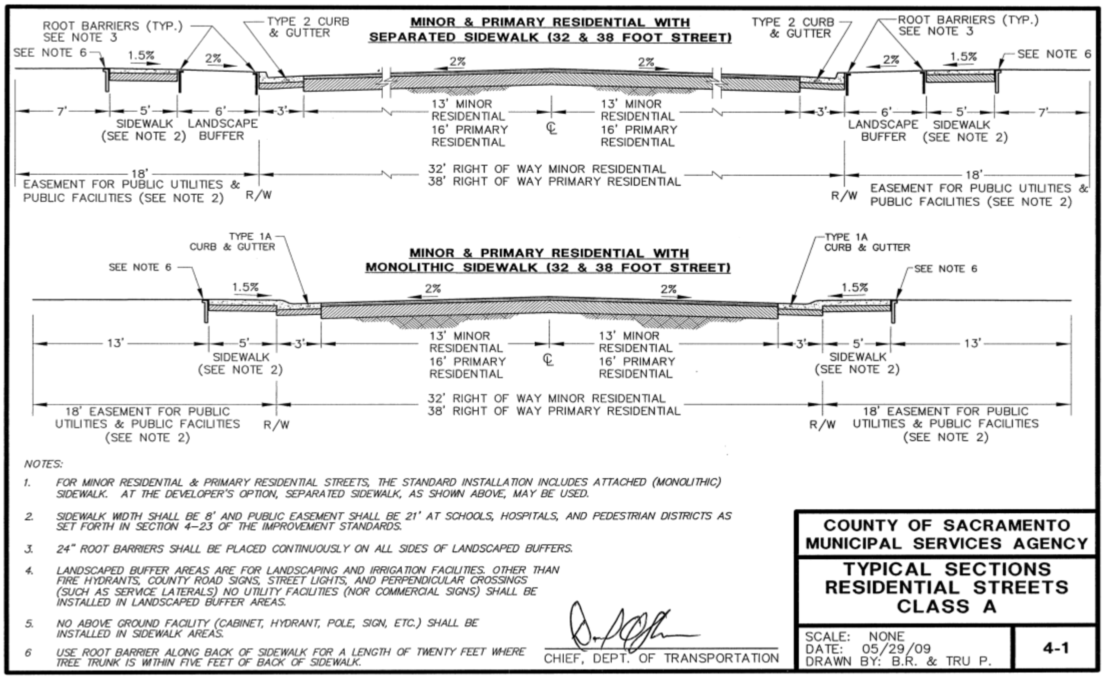


Figure 39. Cross section of Minor and Primary Residential (Sacramento County, 2009)

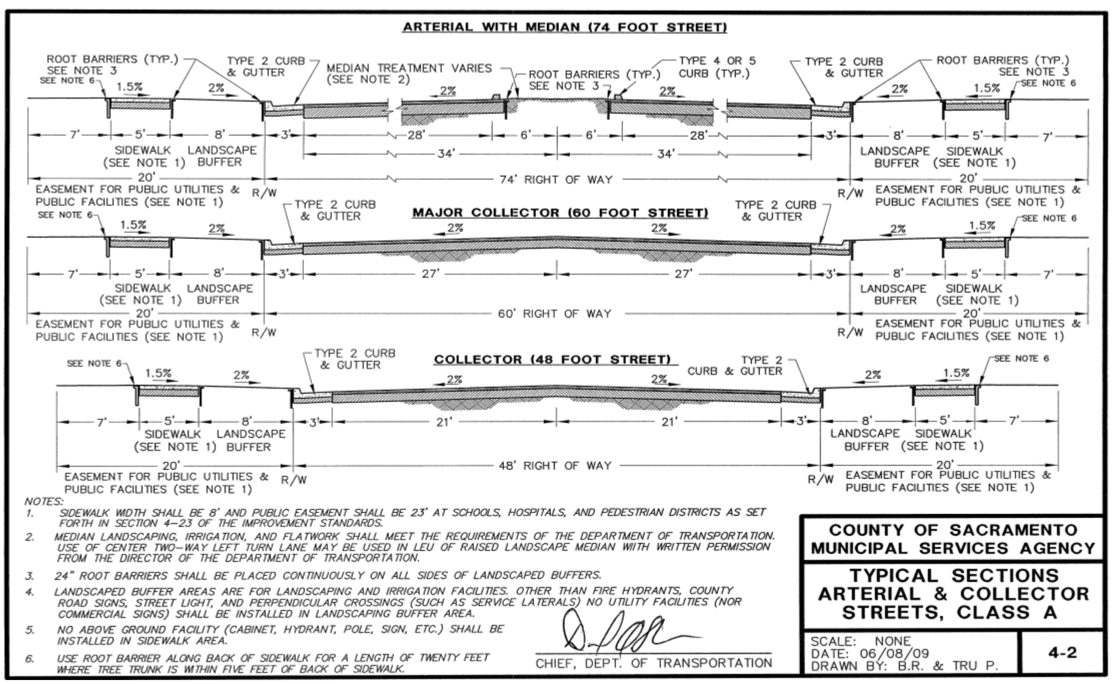


Figure 40. Cross Section of Collector, Major Collector, and Arterial Streets (Sacramento County, 2009)

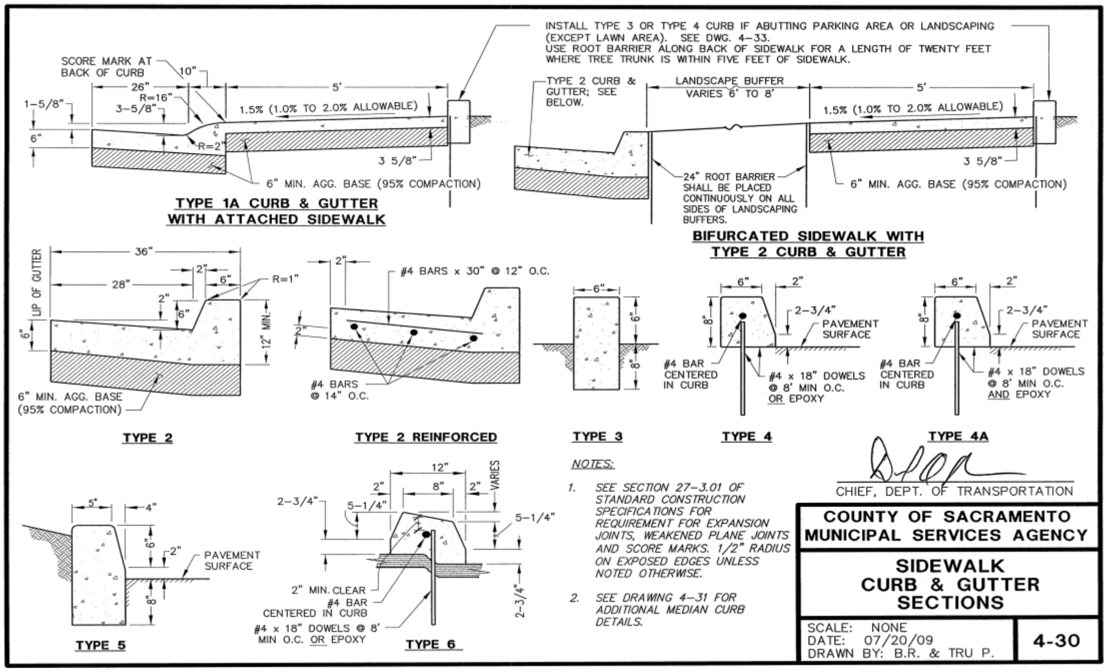


Figure 41. Cross section of Sidewalk, Curb, and Gutter (Sacramento County, 2009)

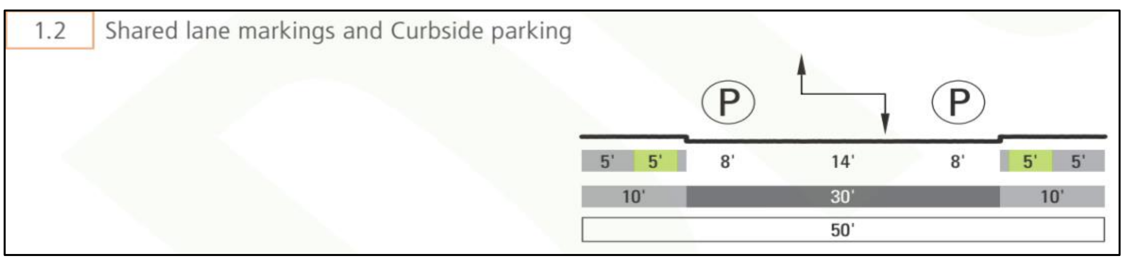


Figure 42. LA-DG Recommendation for Minor Residential Street (City of LA, 2014)

Figure 43. NACTO Recommendation for Minor Residential Street (From *Urban Street Design Guide*, by NACTO, pp. 17)

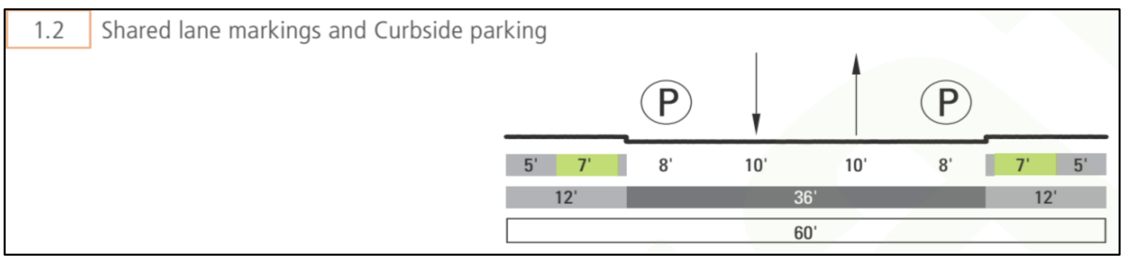


Figure 44. LA-DG Recommendation for Primary Residential Street (City of LA, 2014)

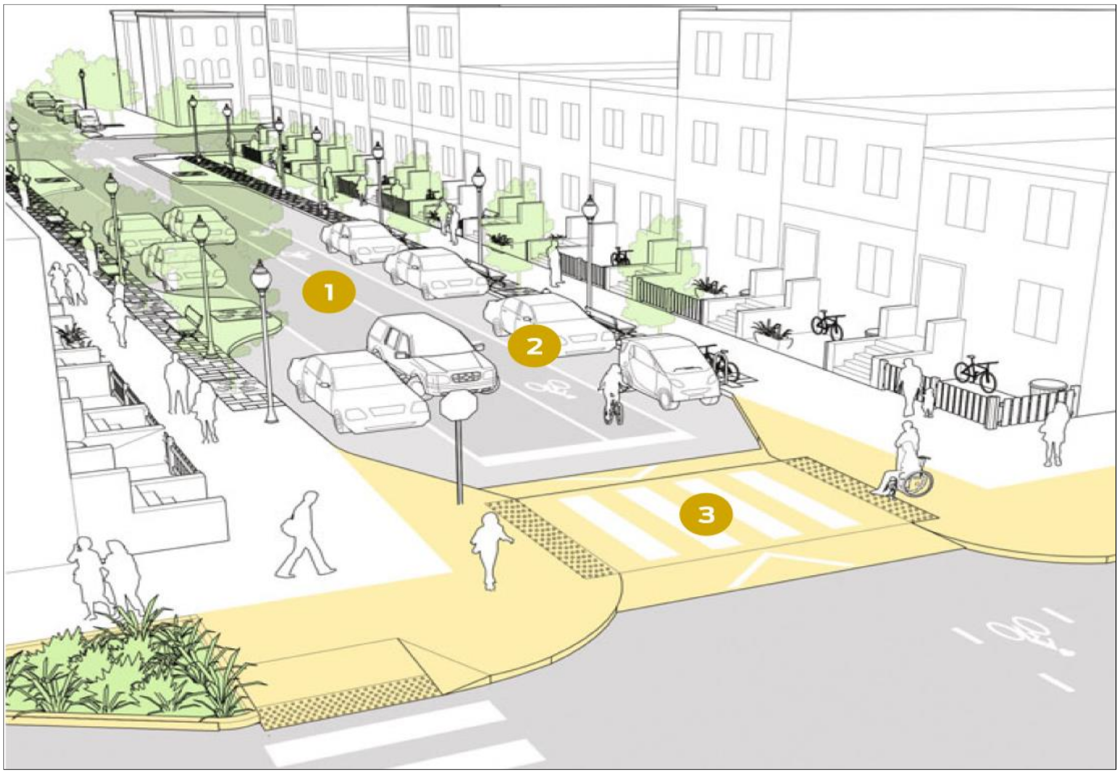


Figure 45. NACTO Recommendation for Primary Residential Streets (From *Urban Street Design Guide*, by NACTO, pp. 16)

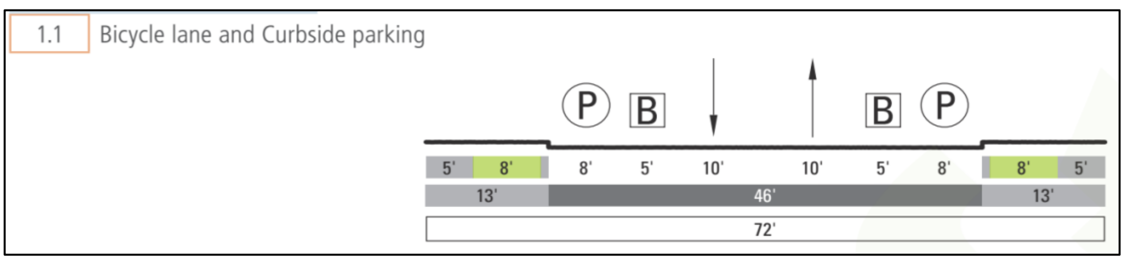


Figure 46. LA-DG Recommendation for Collector Street (City of LA, 2014)

Figure 47. NACTO Recommendation for Collector Street (From *Urban Street Design Guide*, by NACTO, pp. 11).

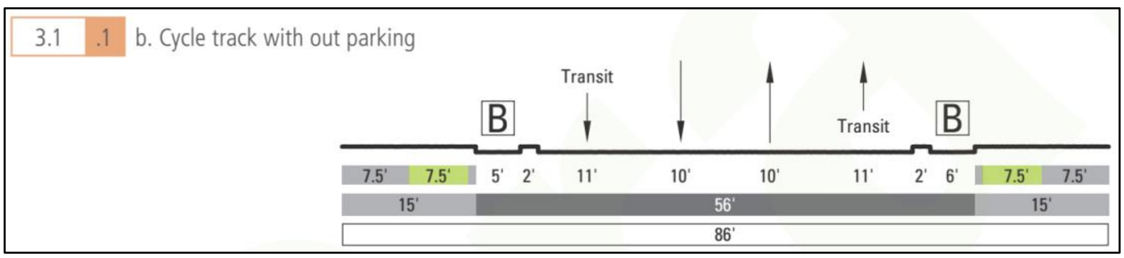


Figure 48. LA-DG Recommendation for Major Collector Street (City of LA, 2014)

Figure 49. NACTO recommendation for Major Collector Street (From *Urban Street Design Guide*, by NACTO, pp. 15).

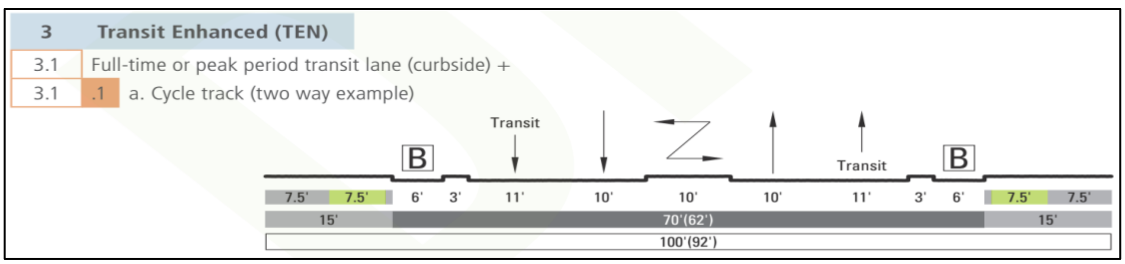


Figure 50. LA-DG Recommendation for Arterial Street (City of LA, 2014)

Figure 51. NACTO Recommendation for Major Arterial Street (From *Urban Street Design Guide*, by NACTO, pp. 13).

Table 16. Complete Streets Elements Defined for Various Streets Types in the City of LA (2014) CS Design Guide

Intersections & Crossings	Off-Street Non-Vehicular Treatments & Strategies	Roadways	Sidewalk Area
Accessible Pedestrian Signal	Bicycle Channel Ramps for Stairways	Back-In Angle Parking	Bicycle Parking
Advance Yield Markings	Coastal Paths	Bicycle Corral	Bikeshare Stations
Bicycle Box	Fencing for Bike Paths	Bicycle Lane	Building Entries
Bicycle Green Wave	Grade-Separated Undercrossing & Overcrossing	Bus Pad	Bus Bulb
Bicycle Loop Detector	Multi-Purpose Path Constructed within New Transit Corridor	Chicane	Bus Stop Location
Bicycle Pavement Markings approaching an Intersection	Multi-Purpose Paths (Class I)	Commercial Loading	Esplanade
Bicycle Pavement Markings through an Intersection	Multi-Purpose Paths in Existing Active Rail Corridor	Landscaped Median	Outdoor Dining
Bicycle-Only Left Turn Pocket	Multi-Purpose Paths in River & Utility Corridor	Lane Narrowing	Parking Meters & Pay Stations
Bicycle-Only Signal	Programming & Temp. Treats.	Lane Reconfiguration / Road Diet	Parklets
Corner Bulb-out		Median Bus Boarding Island	Portable Signage & Sidewalk
Crossing Refuge Island		Median Bus Lane / Busway	Public Art
Crosswalk Markings		Neckdown	Public Seating
Curb Radius		Offset Bus Lane	Sidewalk Equestrian Trails
Curb Ramp		On-Street Carshare Parking	Storm water Treat. & Mgmt.
Decorative Pavement Materials		Peak-hour Bus Lane	Street Lighting
Diverter		Pedestrian Pl	Street Trees & Landscaping
Driveways		Protected Bicycle Lane	Signage & Wayfinding
Exclusive Pedestrian Phase		Shared Bicycle-Bus Lane	Utilities & other infrastructure
Leading Pedestrian Interval		Shared Lane Marking (Sharrow)	Waste & Recycling Receptacles
Mini-Roundabout		Speed Feedback Sign	
Pedestrian Beacon			
Raised Crosswalk			
Shorter Signal Cycle Length			
Split Phasing			
Traffic Mini-Circle			
Transit Signal Prioritization			
Two-Stage Turn Queue Box			

Appendix C. LCA Results for Materials, Surface Treatments, and Complete Street Elements

Table 17. LCI and PED Values Used for the Materials Used in this Study

Item	Function Unit	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Aggregate, Crushed	1 kg	3.43E-03	6.53E-04	1.59E-06	6.05E-02	0.00E+00
Aggregate, Natural	1 kg	2.36E-03	4.04E-04	9.54E-07	4.31E-02	0.00E+00
Bitumen	1 kg	4.75E-01	8.09E-02	4.10E-04	4.97E+01	4.02E+01
Bitumen Emulsion (Residual Bitumen)	1 kg	5.07E-01	8.23E-02	4.17E-04	5.09E+01	4.02E+01
Blast Furnace Slag (Ground)	1 kg	1.03E-01	1.13E-02	1.16E-04	1.97E+00	0.00E+00
Crumb Rubber Modifier (CRM)	1 kg	2.13E-01	6.90E-03	1.05E-04	3.47E+01	3.02E+01
Diesel Burned in Equipment	1 gal.	1.19E+01	5.27E+00	9.37E-03	1.65E+02	0.00E+00
Dowel & Tie Bar	each	3.69E+00	1.30E-01	1.39E-03	4.87E+01	0.00E+00
Electricity	1 MJ	1.32E-01	4.28E-03	2.54E-05	2.92E+00	0.00E+00
Limestone	1 kg	4.44E-03	2.11E-04	8.24E-08	7.84E-02	0.00E+00
Natural Gas Combusted	1 m3	2.41E+00	5.30E-02	1.31E-03	3.84E+01	0.00E+00
Paint (GaBi)	1 kg	1.04E-02	1.28E-01	9.51E-07	1.68E-02	0.00E+00
Paraffin (Wax)	1 kg	1.37E+00	7.57E-02	4.70E-04	5.46E+01	0.00E+00
Polypropylene Fibers	1 kg	2.33E+00	8.65E-02	5.53E-04	8.39E+01	0.00E+00
PCA*, Accelerator	1 kg	1.26E+00	5.71E-02	1.88E-04	2.28E+01	0.00E+00
PCA*, Air Enterainer	1 kg	2.66E+00	8.68E+00	2.55E-03	2.10E+00	0.00E+00
PCA*, Plasticizer	1 kg	2.30E-01	1.34E-02	5.57E-05	4.60E+00	0.00E+00
PCA*, Retarder	1 kg	2.31E-01	4.23E-02	9.81E-05	1.57E+01	0.00E+00
PCA*, Superplasticizer	1 kg	7.70E-01	4.55E-02	2.33E-04	1.83E+01	0.00E+00
PCA*, Waterproofing	1 kg	1.32E-01	4.00E-02	6.74E-05	5.60E+00	0.00E+00
Portland Cement, Regular	1 kg	8.72E-01	7.28E-02	4.99E-04	5.94E+00	0.00E+00
Portland Cement, with 19% Slag	1 kg	7.04E-01	2.60E-02	1.78E-04	3.40E+00	0.00E+00
Portland Cement, with 50% Slag	1 kg	4.45E-01	1.76E-02	1.23E-04	2.75E+00	0.00E+00
Quicklime	1 kg	1.40E+00	3.52E-02	7.11E-04	7.88E+00	0.00E+00
Reclaimed Asphalt Pavement (RAP)	1 kg	7.16E-03	1.39E-03	2.70E-06	1.02E-01	0.00E+00
RC*, BPA	1 kg	3.73E+00	1.61E-01	9.92E-04	9.08E+01	0.00E+00
RC*, Polyester Styrene	1 kg	4.40E+00	2.08E-01	5.10E-03	9.17E+01	0.00E+00
RC*, Polyurethane	1 kg	2.34E+00	1.02E-01	9.24E-04	5.15E+01	0.00E+00
RC*, Styrene Acrylate	1 kg	1.56E+00	6.34E-02	4.92E-04	3.66E+01	0.00E+00
Styrene Butadiene Rubber (SBR)	1 kg	4.13E+00	1.29E-01	4.48E-04	1.03E+02	0.00E+00

* PCA: Portland Cement Admixture, RC: Reflective Coating

Table 18. LCIA and PED Values for 1 ln-km of Various Surface Treatments Applied in Construction of Urban Streets, with Typical Service Lives and Thicknesses

Item	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	Item	Function Unit
Aggregate, Crushed	1.44E+04	2.55E+03	5.49E+00	2.22E+05	0.00E+00	15	15
BCOA*	2.04E+05	2.11E+04	1.13E+02	1.60E+06	0.00E+00	15	10
BCOA (High SCM*)	8.40E+04	1.16E+04	4.78E+01	7.88E+05	0.00E+00	15	10
BCOA (Low SCM)	1.31E+05	1.32E+04	7.09E+01	1.10E+06	0.00E+00	15	10
Cape Seal	7.17E+03	1.58E+03	5.40E+00	1.35E+05	3.75E+05	6	NA
Chip Seal	4.93E+03	1.03E+03	3.70E+00	9.41E+04	2.69E+05	6	NA
Curb Type 5	2.54E+04	2.35E+03	1.39E+01	1.96E+05	0.00E+00	15	NA
Fog Seal	1.29E+03	2.69E+02	1.05E+00	2.56E+04	8.42E+04	3	NA
HMA (mill and fill)	3.81E+04	5.34E+03	2.35E+01	4.48E+05	1.22E+06	10	7.5
HMA (overlay)	3.35E+04	4.23E+03	2.14E+01	3.82E+05	1.22E+06	10	7.5
Paint (area)	6.36E-03	7.82E-02	5.81E-07	1.03E-02	0.00E+00	3	NA
Paint (linear)	4.84E-04	5.96E-03	4.43E-08	7.82E-04	0.00E+00	3	NA
Pavers	9.74E+04	1.17E+04	1.17E+02	9.77E+05	0.00E+00	15	NA
PCC	2.65E+05	2.46E+04	1.45E+02	2.05E+06	0.00E+00	20	17.5
PCC (High SCM)	1.16E+05	1.59E+04	6.57E+01	1.08E+06	0.00E+00	20	17.5
PCC (Low SCM)	1.88E+05	1.94E+04	1.02E+02	1.49E+06	0.00E+00	20	17.5
Permeable HMA	8.42E+04	1.16E+04	4.93E+01	1.40E+06	2.25E+06	10	27
Permeable PCC	2.51E+05	2.46E+04	1.36E+02	2.01E+06	0.00E+00	15	30
Permeable RHMA	8.96E+04	1.25E+04	5.40E+01	1.51E+06	2.70E+06	10	27
Planting (GaBi)	1.08E+02	2.24E+01	1.37E-01	1.61E+03	0.00E+00	5	NA
RC*, Bisphenol A (BPA)	1.06E+04	5.38E+02	2.91E+00	2.55E+05	0.00E+00	2	NA
RC, Polyester Styrene	1.24E+04	6.68E+02	1.43E+01	2.58E+05	0.00E+00	2	NA
RC, Polyurethane	8.88E+03	4.71E+02	3.58E+00	1.94E+05	0.00E+00	2	NA
RC, Styrene Acrylate	5.98E+03	3.27E+02	1.99E+00	1.39E+05	0.00E+00	2	NA
RHMA (mill and fill)	3.65E+04	5.08E+03	2.28E+01	3.78E+05	1.31E+06	10	5
RHMA Concrete (overlay)	3.25E+04	4.06E+03	2.09E+01	3.21E+05	1.31E+06	10	5
Sand Seal	2.67E+03	6.57E+02	1.98E+00	4.84E+04	1.18E+05	6	NA
Slurry Seal	2.24E+03	5.52E+02	1.71E+00	4.11E+04	1.06E+05	6	NA

* BCOA: Bonded Concrete Overlay on Asphalt, SCM: Supplementary Cementitious Materials, RC: reflective coating

Table 19. LCI and PED of MAC of Each of the CS Elements Used in This Study

CS Element	Serv. Life (yrs.)	Material Used	L* (m)	W* (m)	Area (m2)	Thick . (cm)	Vol. (m3)	Quantity (kg/m3) (kg/m2) (kg/m)	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Buffered Cycle Track	3	Paint (area)	1.00	1.00	1.00	NA	NA	0.61	1.72E-06	2.11E-05	1.57E-10	2.78E-06	0.00E+00
Coloring Lanes	3	Paint (area)	1.00	1.00	1.00	NA	NA	0.61	1.72E-06	2.11E-05	1.57E-10	2.78E-06	0.00E+00
Curb Extension	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00
Curb Type 5	15	PCC	1.00	NA	NA	NA	NA	149	2.54E+01	2.35E+00	1.39E-02	1.96E+02	0.00E+00
Island	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00
Planted Furniture Zone	5	Planting	1.00	1.00	1.00	NA	NA	1300	1.08E-02	2.24E-03	1.37E-05	1.61E-01	0.00E+00
Raised Bicycle Buffer	10	HMA (overlay)	1.00	NA	NA	NA	NA	9	4.67E-01	5.90E-02	2.99E-04	5.33E+00	1.70E+01
Raised Cycle Track	10	HMA (overlay)	1.00	1.00	1.00	NA	NA	122	6.13E+00	7.75E-01	3.93E-03	7.00E+01	2.23E+02
Raised Middle Lane	10	HMA (overlay)	1.00	1.00	1.00	NA	NA	122	6.13E+00	7.75E-01	3.93E-03	7.00E+01	2.23E+02
Raising the Intersection*	10	HMA (overlay)	1.00	1.00	1.00	NA	NA	244	1.23E+01	1.55E+00	7.85E-03	1.40E+02	4.45E+02
Shelter/Transit station	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00
Striping	3	Paint (linear)	1.00	NA	NA	NA	NA	0.05	4.84E-07	5.96E-06	4.43E-11	7.82E-07	0.00E+00
Pervious Pavement	10	Permeable HMA	1.00	1.00	1.00	100.0	1.00	2400	8.43E+01	1.16E+01	4.94E-02	1.40E+03	2.25E+03
Widening Sidewalk	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00

* L: Length, W: Width, Raising the Intersection to Sidewalk Grade

Appendix D. LCA Results for Conventional Streets

In all the tables below:

- # of App: Number of treatment application during the analysis period
- SL: Service Life
- SV: Salvage value at the end of analysis period (expressed as % of service life)
- T: Thickness
- W: Width

Table 20. Itemized Impacts of The Conv. Option During the Analysis Period for a Minor Residential 1 Block)

Total	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	9.18E+03	1.16E+03	5.88E+00	1.05E+05	3.34E+05	10.0	7.6	3	0%	3.70	1	Street Top Layer	19.1%
Aggregate, Crushed	4.39E+03	7.77E+02	1.67E+00	6.77E+04	0.00E+00	15.0	25.4	2	0%	3.70	1	Street AB	9.1%
PCC	1.54E+04	1.43E+03	8.44E+00	1.19E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	32.1%
Aggregate, Crushed	1.30E+03	2.30E+02	4.96E-01	2.01E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	2.7%
Planting	2.13E+01	1.20E+01	7.31E-02	8.59E+02	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	1.55E+04	1.44E+03	8.50E+00	1.20E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	32.3%
Aggregate, Crushed	2.17E+03	3.84E+02	8.27E-01	3.34E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	4.5%

Table 21. Itemized Impacts of the Conv. Option During the Analysis Period for A Primary Residential 1 Block)

Total	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	3.76E+04	4.76E+03	2.41E+01	4.30E+05	1.37E+06	10.0	7.6	3	0%	3.70	3	Street Top Layer	34.5%
Aggregate, Crushed	1.80E+04	3.19E+03	6.86E+00	2.77E+05	0.00E+00	15.0	25.4	2	0%	3.70	3	Street AB	16.5%
PCC	2.40E+04	2.22E+03	1.31E+01	1.85E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	22.0%
Aggregate, Crushed	2.02E+03	3.59E+02	7.72E-01	3.12E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.9%
Planting	3.31E+01	1.86E+01	1.14E-01	1.34E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	2.42E+04	2.24E+03	1.32E+01	1.87E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	22.1%
Aggregate, Crushed	3.37E+03	5.98E+02	1.29E+00	5.20E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	3.1%

Table 22. Itemized Impacts of the Conv. Option During the Analysis Period for a Collector (1 Block)

Total	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	6.79E+04	8.59E+03	4.35E+01	7.76E+05	2.47E+06	10.0	8.9	3	0%	3.70	3	Street Top Layer	40.6%
Aggregate, Crushed	3.62E+04	6.41E+03	1.38E+01	5.58E+05	0.00E+00	15.0	33.0	2	0%	3.70	3	Street AB	21.6%
PCC	2.83E+04	2.62E+03	1.55E+01	2.18E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	16.9%
Aggregate, Crushed	2.39E+03	4.23E+02	9.10E-01	3.68E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.4%
Planting	3.91E+01	2.19E+01	1.34E-01	1.58E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	2.85E+04	2.63E+03	1.56E+01	2.20E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	17.0%
Aggregate, Crushed	3.98E+03	7.04E+02	1.52E+00	6.13E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	2.4%

Table 23. Itemized Impacts of the Conv. Option During the Analysis Period for a Major Collector (1 Block)

Total	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	1.24E+05	1.57E+04	7.95E+01	1.42E+06	4.51E+06	10.0	10.2	3	0%	3.70	4	Street Top Layer	46.8%
Aggregate, Crushed	6.23E+04	1.10E+04	2.37E+01	9.60E+05	0.00E+00	15.0	35.6	2	0%	3.70	4	Street AB	23.5%
PCC	3.51E+04	3.25E+03	1.92E+01	2.71E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	13.3%
Aggregate, Crushed	2.96E+03	5.25E+02	1.13E+00	4.57E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.1%
Planting	4.85E+01	2.73E+01	1.66E-01	1.96E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	3.54E+04	3.27E+03	1.94E+01	2.73E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	13.4%
Aggregate, Crushed	4.94E+03	8.75E+02	1.88E+00	7.62E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	1.9%

Table 24. Itemized Impacts of the Conv. Option During the Analysis Period for an Arterial (1 Block)

Total	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	2.20E+05	2.78E+04	1.41E+02	2.51E+06	7.99E+06	10.0	14.0	3	0%	3.70	5	Street Top Layer	47.7%
Aggregate, Crushed	1.18E+05	2.08E+04	4.48E+01	1.81E+06	0.00E+00	15.0	52.1	2	0%	3.70	5	Street AB	25.5%
Planting	1.21E+02	6.78E+01	4.14E-01	4.87E+03	0.00E+00	5.0	NA	6	0%	3.66	2	Landscape	0.0%
Curb Type 5	2.63E+04	2.43E+03	1.44E+01	2.03E+05	0.00E+00	15.0	NA	2	0%	3.66	1	Curb around Median	5.7%
PCC	4.37E+04	4.04E+03	2.39E+01	3.38E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	9.5%
Aggregate, Crushed	3.69E+03	6.53E+02	1.41E+00	5.69E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	0.8%
Planting	6.04E+01	3.39E+01	2.07E-01	2.44E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	4.40E+04	4.07E+03	2.41E+01	3.40E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	9.5%
Aggregate, Crushed	6.15E+03	1.09E+03	2.34E+00	9.48E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	1.3%

Table 25. Itemized Impacts of the Conv. Option During the Analysis Period for a Thoroughfare (1 Block)

Total	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	4.47E+05	5.65E+04	2.86E+02	5.11E+06	1.62E+07	10.0	16.8	3	0%	3.70	6	Street Top Layer	61.1%
Aggregate, Crushed	2.23E+05	3.96E+04	8.52E+01	3.44E+06	0.00E+00	15.0	58.4	2	0%	3.70	6	Street AB	30.6%
Planting	1.47E+02	8.24E+01	5.03E-01	5.92E+03	0.00E+00	5.0	100.0	6	0%	3.66	2	Landscape	0.0%
Curb Type 5	3.18E+04	2.95E+03	1.74E+01	2.46E+05	0.00E+00	15.0	NA	2	0%	3.66	1	Curb around Median	4.4%
PCC	5.31E+04	4.91E+03	2.91E+01	4.10E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	7.3%
Aggregate, Crushed	4.48E+03	7.94E+02	1.71E+00	6.91E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	0.6%
Planting	7.34E+01	4.12E+01	2.52E-01	2.96E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	5.35E+04	4.95E+03	2.93E+01	4.13E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	7.3%
Aggregate, Crushed	7.47E+03	1.32E+03	2.85E+00	1.15E+05	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	1.0%

* SL: Service Life

T: Thickness

# of App.: Number of treatment application during the analysis period

W: Width

SV: Salvage value at the end of analysis period (expressed as % of service life)

Appendix E. LCA Results for Complete Streets

In all the table below:

- # of App: Number of treatment application during the analysis period
- %Conv rep. by CS* Percent of surface area normally covered by Conv. options that is now covered by CS elements
- L: Length
- Mat: Material
- SL: Service Life
- SV: Salvage value at the end of analysis period (expressed as % of service life)
- T: Thickness
- W: Width

Table 26. Itemized Impacts of the CS Element During the Analysis Period for a Minor Residential (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block *	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App *	SV *	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Coloring Lanes	3	Paint (area)	1	90	2.13	192	0%	NA	NA	192	10	0 %	3.30E-03	4.06E-02	3.02E-07	5.33E-03	0.00E+00
Curb Extension	15	PCC on AB	2	8	2.44	20	100%	NA	NA	39	2	0 %	3.25E+03	3.27E+02	1.73E+00	2.75E+04	0.00E+00

Table 27. Itemized Impacts of the CS Element During the Analysis Period for a Primary Residential (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block *	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App *	SV *	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Coloring Lanes	3	Paint (area)	1	140	2.13	299	0%	NA	NA	299	10	0 %	5.13E-03	6.32E-02	4.69E-07	8.29E-03	0.00E+00
Curb Extension	15	PCC on AB	3	8	2.44	20	100%	NA	NA	59	2	0 %	4.88E+03	4.91E+02	2.59E+00	4.13E+04	0.00E+00

Table 28. Itemized Impacts of the CS Element During the Analysis Period for a Collector (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block *	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App *	SV *	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Coloring Lanes	3	Paint (area)	2	165	2.13	352	0%	NA	NA	704	10	0 %	1.21E-02	1.49E-01	1.11E-06	1.95E-02	0.00E+00
Shelter/Transit station	15	PCC on AB	1	15	3.00	45	100%	NA	NA	45	2	0 %	3.75E+03	3.77E+02	1.99E+00	3.17E+04	0.00E+00

Table 29. Itemized Impacts of the CS Element During the Analysis Period for a Major Collector (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block *	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App *	SV *	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Coloring Lanes	3	Paint (area)	2	205	1.68	344	0%	NA	NA	687	10	0 %	1.18E-02	1.45E-01	1.08E-06	1.91E-02	0.00E+00
Curb Extension	15	PCC on AB	4	8	2.44	20	100%	NA	NA	78	2	0 %	6.51E+03	6.54E+02	3.46E+00	5.50E+04	0.00E+00
Planted Furniture Zone	5	Planting	1	185	0.91	169	100%	NA	NA	169	6	0 %	1.09E+01	2.28E+00	1.39E-02	1.63E+02	0.00E+00
Curb Type 5	15	PCC	1	372	NA	NA	0%	NA	NA	372	2	0 %	1.89E+04	1.75E+03	1.03E+01	1.46E+05	0.00E+00
Coloring Lanes	3	Paint (area)	2	205	3.35	687	0%	NA	NA	1375	10	0 %	2.36E-02	2.91E-01	2.16E-06	3.81E-02	0.00E+00
Raised Bicycle Buffer	10	HMA (overlay)	2	205	NA	NA	0%	NA	NA	410	3	0 %	5.74E+02	7.26E+01	3.68E-01	6.56E+03	2.09E+04

Table 30. Itemized Impacts of the CS Element During the Analysis Period for an Arterial (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block *	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App *	SV *	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Coloring Lanes	3	Paint (area)	2	255	1.68	427	0%	NA	NA	855	10	0 %	1.47E-02	1.81E-01	1.34E-06	2.37E-02	0.00E+00
Raised Bicycle Buffer	10	HMA (overl ay)	2	255	NA	NA	0%	NA	NA	510	3	0 %	7.14E+02	9.03E+01	4.58E-01	8.16E+03	2.59E+04
Coloring Lanes	3	Paint (area)	2	255	3.35	855	0%	NA	NA	1710	10	0 %	2.94E-02	3.62E-01	2.69E-06	4.75E-02	0.00E+00
Shelter/Tra nsit station	15	PCC on AB	1	8	3.00	24	100%	NA	NA	24	2	0 %	2.00E+03	2.01E+02	1.06E+00	1.69E+04	0.00E+00
Island	15	PCC on AB	1	4	1.00	4	100%	NA	NA	4	2	0 %	3.34E+02	3.35E+01	1.77E-01	2.82E+03	0.00E+00

Table 31. Itemized Impacts of the CS Element During the Analysis Period for a Thoroughfare (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block *	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App *	SV *	GWP (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
Coloring Lanes	3	Paint (area)	2	310	1.68	520	0%	NA	NA	1039	10	0 %	1.79E-02	2.20E-01	1.63E-06	2.88E-02	0.00E+00
Raised Bicycle Buffer	10	HMA (overl ay)	5	310	NA	NA	0%	NA	NA	1550	3	0 %	2.17E+03	2.75E+02	1.39E+00	2.48E+04	7.89E+04
Coloring Lanes	3	Paint (area)	2	310	3.96	1228	0%	NA	NA	2457	10	0 %	4.22E-02	5.19E-01	3.86E-06	6.82E-02	0.00E+00
Shelter/Tra nsit station	15	PCC on AB	1	310	3.05	945	100%	NA	NA	945	2	0 %	7.88E+04	7.92E+03	4.19E+01	6.66E+05	0.00E+00
Island	15	PCC on AB	2	3	1.00	3	100%	NA	NA	6	2	0 %	5.00E+02	5.03E+01	2.66E-01	4.23E+03	0.00E+00

Appendix F. Complete Street Social Performance Measures

Accessibility

Access to Community Destinations

Description

Access to community destinations reflects the proximity of pedestrian, bicycle, and transit infrastructure and services to origins and destinations. Specific destinations which are part of the analysis should be defined by transportation agencies. Parks, grocery stores, medical centers, child and senior day care centers, businesses with a certain number of employees, high-density residential locations, bike share stations, bus stops, community centers, community colleges, community services, government offices, major tourist destinations, major retail and entertainment, office buildings, places of worship, public libraries, retirement homes, transit centers, and universities and colleges are types of community destinations (FHWA 2016). Access to schools has been set aside as separate from this general category.

Data Collection and Methodologies

The assessment should consist of counting how many community destinations there are within a reasonable travel time or distance (active transportation or combination of active and transit transportation) of a complete street project. When comparing projects in different neighborhoods, this indicator should be tested for applicability with regard to an equitable comparison before it is used. In particular, this indicator should not be used for comparison between projects unless they have a similar number of destinations within some pre-determined range. If the neighborhoods do not have similar numbers of community destinations (potentially broken down by types) within a reasonable travel time or distance if the complete streets project is built or a complete streets network that it is included in were built, it is an indication that use of this indicator will lead toward selection of projects in areas that are already advantaged in terms of the richness of destinations. This would indicate that investment to increase the number of destinations would be first step towards more equity between the neighborhoods, and complete streets and transit can be included in those destination development projects to provide active transportation access.

The assessment should also look at the change in the number of community destinations that become accessible with the building of the complete street project and the complete street network it is a part of. Comparisons of the change of in the number of destinations made accessible can potentially provide a more equitable result instead of the number of destinations made accessible.

FHWA Measurement Guidance

According to FHWA guideline, the following measures can be used for evaluating access to community destinations by travel time substitution for distance (e.g., 20 minutes for ½ mile). In all cases the bicycling, walking, and transit routes must be functional for children and disabled persons to be counted (FHWA 2016).

- "Proportion of residences within a ½-mile walking distance or 2-mile biking distance or combined bike or walk and transit trip of 20 minutes to specific key destinations, such as parks or day care centers.
- Proportion of residences within ½-mile walking distance or 2-mile biking distance or combined bike or walk and transit trip of 20 minutes to specific key destinations along a completed pedestrian or bicycle facility that is functional for children and disabled persons.
- Proportion of residences with access to a predefined set of "community destinations" within a 20-minute walk or 20-minute bike ride on routes that are that functional for children and disabled persons or combined bike or walk and transit trip of 20 minutes.
- Percent of the network complete for pedestrians and bicyclists within ½ mile and 2 miles or combined bike or walk and transit trip of 20 minutes respectively of each designated destination.
- Number of destinations that can be accessed within a ½ mile along a walking network functional for disabled persons from a given point on the network.
- Number of destinations within 3 miles along a bicycling network from a given point on the network." (FHWA 2016, pg 39)

FHWA also suggests the following data sources for calculating the access to community destination indicator (FHWA 2016):

- Local parcel data.
- GIS data on schools, parks, healthcare centers, and other daily destinations.
- NAICS coded employment data, available from the U.S. Bureau of Labor Statistics.
- GIS data on transportation network for all modes.
- Optional: Demographic data from the U.S. Census Bureau.

Some Example Studies:

- BLS (employment data from the U.S. Bureau of Labor and Statistics) data finder website which has their own indicators and definition for those indicators, help find the relationship between each two indicators defined in this website. (BLS, 2017).
- The "Access to destinations" report by M. Iacono et al. (2008) published by the Minnesota Department of Transportation is another helpful reference. This report has used available travel survey data for the Twin Cities region to find out the relationship

between actual travel behavior and mean distance to numerous services. It also has examined several types of destinations and estimated distance decay models for auto and non-auto travel modes. The models' applicability for several types of travel and development of accessibility measures for connecting this information are part of this study. (Iacono et al. 2008).

- Data sources that were used in the Minnesota DOT report are the travel behavior inventory (TBI), transit on-board survey, trail user survey, and non-motorized pilot program (NMPP) survey. The last three data sources are based on surveying. Distance decay functions are used to relate the number of trips to distance for various combinations of mode and trip purpose, as well as to help as a substitution for travel cost. The study of distance decay functions is a good starting point for understanding travel behavior of each mode. Equation 1 shows the distance decay function for each mode and activity combination.

$$P_{mk} = \alpha \exp(\beta x) \qquad \textit{Eq (1)}$$

Where P_{mk} indicates the percentage of trips of mode m and purpose k at a specific distance x. Dividing the number of trips in each interval by the total number of trips by a given mode for a certain purpose computed the percentage of the trips for each mode. If the percentage would be used instead of the number of trips as the dependent variable, it does not influence the impedance parameter, β. Because, it only reflects a scale transformation of the decay function while the value of the α parameter is scaled consequently.

Moreover, travel time as an impedance variable is a second set of functions used to check against the accuracy of the distance decay functions in estimating trip distance. However, limitations of the sample and self-reported travel time data (the travel behavior inventory data in this study) are the shortcoming of using travel time data. In addition, the function f_{ij} that represents the cost of travel as an impedance to interaction is specified as in Equation 2:

$$f_{ij} = \exp(-bCij) \qquad \textit{Eq (2)}$$

Where f_{ij} represents the cost of travel as an impedance to interaction, b as a non-negative parameter, and C as a generalized cost that can be replaced with distance or travel time.

Another possible application of the distance decay function is the study of multimodal, multipurpose accessibility to estimate the various mode-purpose combinations which illustrates the way that the negative exponential function and gravity-type accessibility measure can produce an accessibility equation (Equation 3):

$$A_i = \frac{\sum_{j+1} E_j exp(-\beta x)}{E} \qquad \textit{Eq (3)}$$

Where Ai denotes the accessibility at zone i, Ej represents a measure of opportunities ("employment" can be used here) at zone j, and E denotes all available opportunities in the region. A caveat is that these types of measures have not often been evaluated for non-motorized modes.

- The Minnesota report gives us a model that can be used for the access to community destination indicator. However, sample size, focusing on home-based trips, no multi-stop trip chains, and estimation of distance decay functions are the limitation this study faced. Moreover, this report only considers mode and trip purpose while criteria such as age, income level, household structure, ethnicity, etc. are not considered (Iacono et al., 2008)
- One of the most important tools for tracking how the nation’s travel patterns change across time and places is the American Community Survey (ACS) used in “Modes Less Traveled—Bicycling and Walking to Work in the United States report” by Brian McKenzie. This report highlights the geographic, social, and economic dimensions which affect use of bicycle and walking trips (Mckenzie 2014).
- This report also considers the effect of different parameters on walking and bicycling modes such as those that are a function of geography, like the size of regions and cities, residential community type, age, sex, race and ethnicity, and household income. In addition, average travel time for bicycling, walking and other modes is evaluated. The estimates based on ACS sample give the approximation of the actual values and represent the entire U.S. resident household and group quarters population. Hence, the difference between an estimate based on a sample and the corresponding value and the estimate based on the entire population (as from a census) lead to sampling error and can be measured in the form of margins of error for all evaluations (Mckenzie 2014).

Access to Schools

Description

Access to schools reflects the proximity of pedestrian, bicycle, and transit infrastructure and services to origins and destination (which in this case are the 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 (Evenson et al. 2010). In all cases the bicycling, walking, transit and combined active transportation/transit routes must be functional for children and disabled persons to be counted. The transit trips include consideration of the transit level of service (i.e., total trip time considering out-of-transit waiting time).

Data Collection and Methodologies

The assessment should consider whether a school is accessible to the populations of students and staff 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. When comparing projects in different neighborhoods, this indicator should be tested for applicability with regard to an equitable comparison before it is used. In particular, this indicator should not be used for comparison between projects in different neighborhoods unless the schools are accessible even if they are completely connected by the complete streets/transit project or a complete streets/transit network. If it is not a high number, this would suggest that investment in neighborhood schools closer to student residences should be a first step towards more equity between the 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.

The assessment should also look at the change in the number of students and staff who can access the school with the building of the complete street/transit project and the complete street/transit network it is a part of. Comparisons of the change number of students and staff who have access can potentially provide a more equitable result instead of the number of students and staff who have access.

FHWA Measurement Guidance

According to the FHWA guideline, the following measures can be used for evaluating access to school by travel time substitution for distance (e.g., 20 minutes for ½ mile) (FHWA 2016).

- "Proportion of children and school employees attending school with access to biking/walking path that is functional for children and disabled persons within a ½-mile walking distance or 2-mile biking distance or combined bike or walk and transit trip of 20 minutes to schools.
- Proportion of children and school employees within ½-mile walking distance or 2-mile biking distance to school along a completed pedestrian or bicycle facility on routes that are that functional for children and disabled persons or combined bike or walk and transit trip of 20 minutes.
- Proportion of children and school employees with access to school within a 20-minute walk or 20-minute bike ride or combined bike or walk and transit trip of 20 minutes.
- Percent of the network complete for pedestrians and bicyclists within ½ mile and 2 miles respectively of each designated school.
- Number of schools that can be accessed within a ½ mile along a walking network from a given point on the network.
- Number of schools within 3 miles along a bicycling network from a given point on the network." (FHWA 2016, pg 39)

The FHWA also suggests following data sources for access to school indicator:

- Local parcel data.
- GIS data on schools.

- GIS data on transportation network for all modes.
- Optional: Demographic data from the U.S. Census Bureau.

Some Example Studies

Other appropriate data sources and references are similar to the "access to community destination" performance measure:

- BLS (employment data from the U.S. Bureau of Labor and Statistics) data finder website which has their own indicators and definition for those indicators, help find the relationship between each two indicators defined in this website. (BLS, 2017)
- The "Access to destinations" report by M. Iacono et al. published by the Minnesota Department of Transportation is another helpful reference. This report has used available travel survey data for the Twin Cities region to find out the relationship between actual travel behavior and mean distance to numerous services. It also has examined different types of destinations and estimated distance decay models for auto and non-auto travel modes. The models' applicability for several types of travel and development of accessibility measures for connecting this information are part of this study. (Iacono et al. 2008).
- Data Sources which have been used in the Minnesota DOT report are travel behavior inventory (TBI), transit on-board survey, trail user survey, and non-motorized pilot program (NMPP) survey while the last three data sources have been based on surveying. Distance decay functions are used to relate the number of trips to distance for various combinations of mode and trip purpose as well as help as a substitution for travel cost. The study of distance decay functions is a good starting point for understanding travel behavior of each mode. Equation 4 shows the distance decay function for each mode and activity combination.

  $$P_{mk} = \alpha \exp(\beta x) \qquad \text{Eq (4)}$$

  Where Pmk indicates the percentage of trips of mode m and purpose k at a specific distance x. Dividing the number of trips in each interval by the total number of trips by a given mode for a certain purpose computed the percentage of the trips for each mode. If the percentage would be used instead of the number of trips as the dependent variable, it does not influence the impedance parameter, β. Because, it only reflects a scale transformation of the decay function while the value of the α parameter is scaled consequently.

  Moreover, travel time as an impedance variable is a second set of functions used to check against the accuracy of the distance decay functions in estimating trip distance. However, limitations of the sample and self-reported travel time data (the travel behavior inventory data in this study) are the shortcoming of using travel time data. In addition, the function fij that represents the cost of travel as an impedance to interaction is specified as equation 5.

$fij = exp(-bCij)$ *Eq (5)*

Where fij represents the cost of travel as an impedance to interaction, b as a non-negative parameter, and C as a generalized cost that can be replaced with distance or travel time.

Another possible application of the distance decay function is the study of multimodal, multipurpose accessibility to estimate the various mode-purpose combinations which illustrates the way that the negative exponential function and gravity-type accessibility measure can produce an accessibility equation (equation 6):

$$A_i = \frac{\sum_{j+1} E_j exp(-\beta x)}{E}$$ *Eq (6)*

Where Ai denotes the accessibility at zone i, Ej represents a measure of opportunities (“employment” can be used here) at zone j, and E denotes all available opportunities in the region. A caveat is that these types of measures have not often been evaluated for non-motorized modes.

- The Minnesota report gives us a model that can be used for the access to school destination indicator. However, sample size, focusing on home-based trips, no multi-stop trip chains, and estimation of distance decay functions are the limitation this study faced. Moreover, this report only considers mode and trip purpose while criteria such as age, income level, household structure, ethnicity, etc. are not considered (Iacono et al. 2008).

Complete Street Performance Measures: Jobs

Access to Jobs

Description

Access to jobs illustrates the ability of pedestrian, bicycle, and transit infrastructure and services to provide access to places of employment. Transportation investment can have an impact on communities since it offers people accessibility to a greater number and greater variety of employment opportunities (FHWA 2016). This indicator can be used separately from the Access to Community Destinations indicator.

Data Collection and Methodologies

Access to jobs is particularly important for disadvantaged neighborhoods with low car 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. The evaluation should then identify the number of places of employment within 30-45 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. If the neighborhoods do not have similar numbers of places of employment within 30-45 minutes even if there was a complete streets/transit network, use of this indicator will lead toward 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.

The use of this indicator should also look at the change in the number of jobs that become accessible 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 equitable result instead of the number of jobs made accessible.

FHWA Measurement Guidance

Travel time between home and potential employers is a limiting factor that influences job choice. To measure the total number of jobs that may be accessed in less than 30 or 45 minutes using walking, bicycling, and transit, data on housing, employment, and the transportation network should be used. Another significant criterion in commute calculations is cost (FHWA 2016).

FHWA suggests the following data sources for access to jobs indicator:

- GIS data on transportation network for all modes.
- U.S. Census demographic and jobs data.
- U.S. Bureau of labor and statistics.
- Local transportation costs (e.g., fuel prices, transit fares).

Some Example Studies

- BLS (employment data from the U.S. Bureau of Labor and Statistics) data finder website which has their own indicators and definition for those indicators, help find the relationship between each two indicators defined in this website (BLS, 2017)
- The “Access to destinations” report by M. Iacono et al. published by the Minnesota Department of Transportation is another helpful reference. This report has used available travel survey data for the Twin Cities region to find out the relationship between actual travel behavior and mean distance to numerous services. It also has examined different types of destinations and estimated distance decay models for auto and non-auto travel modes. The models’ applicability for several types of travel and development of accessibility measures for connecting this information are part of this study (Iacono 2008).

Data Sources which have been used in the Minnesota DOT report are travel behavior inventory (TBI), transit on-board survey, trail user survey, and non-motorized pilot program (NMPP) survey while the last three data sources have been based on surveying. Distance decay functions are used to relate the number of trips to distance for various combinations of mode and trip purpose as well as help as a substitution for travel cost. The study of distance decay functions is a good starting point for understanding travel behavior of each mode.

The methodology is similar to that for Access to Community Destinations and Access to Jobs.

Job Creation

Description

Job creation estimates the number of jobs that are expected to change in the neighborhood or region in which the complete street/transit project is built related to modifications in infrastructure and policies for pedestrian and bicycle travel. Transportation investment can influence local employment in temporary construction jobs and permanent jobs. Permanent jobs are defined as occupations that exist after completing construction for employers locating to the project area (FHWA 2016).

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 on 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.

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. Data Collection and Methodologies

The first step towards equity evaluation between alternative complete streets/transit projects using the job creation performance measure is to calculate the number of jobs created by the construction project by measuring the direct number of temporary construction jobs, retail sales tax findings by tracking new employers and the associated number of permanent jobs attracted to the project area, and collecting employment data by review Census and BLS data to track change in employment over time.

From an equity point of view, prioritization of jobs considering disadvantaged neighborhoods and young people trying to enter the economy should be:

1. Full-time jobs with benefits over part time jobs with no benefits
2. Jobs only requiring a high school diploma or high school and/or vocational training, preferably with relatively high wages

3. Entry level jobs with benefits, that only require a high school diploma and/or vocational training
4. Entry level jobs requiring college or professional degrees
5. Jobs requiring college or professional degrees

If the first step shows inequities in this indicator for advantaged neighborhoods versus disadvantaged neighborhoods and people engaged in their careers versus people trying to enter the economy, investments that creating or support creation of jobs in the neighborhood and are accessible by active transportation and transit should be the next step. 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 (Table 7).

Job creation should be looked at in terms of the change in jobs from the complete streets/transit development between projects in advantaged and disadvantaged neighborhoods rather than the total number of jobs after completion.

Another important consideration when identifying job creation would be connectivity by active transportation and/or active-transportation combined with transit between a neighborhood and adjacent neighborhoods. This type of connectivity facilitates people coming into a neighborhood to create more economic opportunity for its businesses, and facilitates people in a disadvantaged neighborhood being able to access jobs in adjacent neighborhoods.

<u>FHWA Measurement Guidance</u>

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.

Recent research shows that while pedestrian and bicycle infrastructure projects create 11–14 jobs per $1 million of expenditures, highway infrastructure projects create 7 jobs per $1 million of spending (FHWA 2016).

The methods below are suggested to measure job creation by the 2016 FHWA guidebook (FHWA 2016):

- "Number of jobs created by construction project – measure the direct number of temporary construction jobs.
- Retail sales tax findings – track new employers and associated number of permanent jobs attracted to the project area.

- Employment data – review Census and BLS data to track change in employment over time" (FHWA 2016, pg 63)

FHWA suggests following data sources for access to job creation indicator:

- U.S. Census jobs data.
- Employment data from the U.S. Bureau of labor and statistics (BLS).
- Local municipality employment data

Some Example Studies

- BLS (employment data from the U.S. Bureau of Labor and Statistics) data finder website which has their own indicators and definition for those indicators, help find the relationship between each two indicators defined in this website (BLS, 2017)
- Data from Studies that have evaluated previous projects is available for top-down estimates. "Pedestrian and bicycle infrastructure: a national study of employment impacts" report by Heidi Garrett-Peltier published by the Political Economy Research Institute at the University of Massachusetts is another useful resource. The data for this report were collected from 11 cities and 58 separate projects in the United States from departments of transportation and public works departments. 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 (Garrett-Peltier 2011).
- The results of Garret-Peltier's report depict that these various transportation infrastructure projects created 9 in-state jobs for each $1 million of spending in addition to 3 jobs considering out-of-state effects. Another significant result is that bicycle-only infrastructure such as building or refurbishing bike lanes had the highest level of job creation: 11.4 jobs per $1 million spent on the project were created by bicycle-only infrastructure while pedestrian-only infrastructure (such as sidewalks and pedestrian crossings) and multi-use trails created 10 jobs for each $1 million. These results also help decision makers to ponder the economic aspects along with the environmental, safety, and health benefits due to local job creation potential of these projects. (Garrett-Peltier 2011).
- Table 32 and Table 33 illustrate direct and indirect job creation from bicycle, pedestrian, and road infrastructure for the top 20 industries and the national average employment impacts by project type, respectively (Garrett-Peltier 2011).

Table 32. Top 20 Industries: Direct and Indirect Job Creation from Bicycle, Pedestrian, and Infrastructure (Garrett-Peltier 2011)

Construction of other new nonresidential structures
Cut stone and stone product manufacturing
Concrete product manufacturing (not including ready-mix concrete or concrete pipes)
Ready-mix concrete manufacturing
Greenhouse, nursery, and floriculture production
Architectural, engineering, and related services
Asphalt paving mixture and block manufacturing
Other support services (includes traffic maintenance)
Concrete pipe, brick, and block manufacturing
Sign manufacturing
Plastics product manufacturing (other than pipes, bottles, packaging materials)
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 nonresidential structures
Accounting, tax preparation, bookkeeping, and payroll services

Table 33. National Average Employment Impacts by Project Type (Garrett-Peltier 2011)

Project Type	Road	Bicycle	Pedestrian	Off-Street Trail	Number of Projects	Direct Jobs per $1 Million	Indirect Jobs per $1 Million	Induced Jobs per $1 Million	Total Jobs per $1 Million
Total, all projects					58	4.69	2.12	2.15	8.96
Bicycle infrastructure only		√			4	6	2.4	3.01	11.41
Off-street multi-use trails				√	9	5.09	2.21	2.27	9.57
On-street bicycle and pedestrian facilities (without road construction)		√	√		2	4.2	2.2	2.02	8.42
Pedestrian infrastructure only			√		10	5.18	2.33	2.4	9.91
Road infrastructure with bicycle and pedestrian facilities	√		√		13	4.32	2.21	2	8.53
Road infrastructure with pedestrian facilities	√		√		9	4.58	1.82	2.01	8.42
Road infrastructure only (no bike or pedestrian components)	√				11	4.06	1.86	1.83	7.75

- The employment impacts of various categories of transportation infrastructure for two cities (Anchorage, Alaska and Santa Cruz, California) are presented in Table 34 and Table 35. In addition to specific site or street names for these projects, the type of the project (e.g., "Road Infrastructure with Pedestrian Facilities") and list an A, B, or C after the category name (if more than one project of this type is listed in a city) are listed in these tables (Garrett-Peltier 2011).

Table 34. The Employment Impacts of Various Categories of Transportation Infrastructure for Anchorage, Alaska (Garrett-Peltier 2011)

Transportation Infrastructure Category	Road	Bicycle	Pedestrian	Off-Street Trail	Direct Jobs per $1 Million	Indirect Jobs per $1 Million	Induced Jobs per $1 Million	Total Jobs per $1 Million	Total Jobs (Avg by Type)
Pedestrian infrastructure only			√		5.6	1.9	2.07	9.57	
Road infrastructure with bicycle and pedestrian facilities	√	√	√		3.9	1.3	1.44	6.64	
Road infrastructure with pedestrian facilities - a	√		√		5.5	1.6	1.96	9.06	9.1
Road infrastructure with pedestrian facilities - b	√		√		5.7	1.8	2.07	9.57	
Road infrastructure with pedestrian facilities - c	√		√		5.2	1.6	1.88	8.68	
Road infrastructure only	√				7.2	1.9	2.51	11.61	
Average all projects					5.52	1.68	1.99	9.19	

Table 35. The Employment Impacts of Various Categories of Transportation Infrastructure for Santa Cruz, California (Garrett-Peltier 2011).

Transportation Infrastructure Category	Road	Bicycle	Pedestrian	Off-Street Trail	Direct Jobs per $1 Million	Indirect Jobs per $1 Million	Induced Jobs per $1 Million	Total Jobs per $1 Million	Total Jobs (Avg by Type)
Bicycle infrastructure only		√			4.1	2.3	2.14	8.54	
On-street bicycle and pedestrian facilities		√	√		3.5	2.2	1.91	7.61	
Pedestrian infrastructure only – a			√		5.6	2.9	2.85	11.35	10.35
Pedestrian infrastructure only – b			√		4.1	2.9	2.34	9.34	
Road infrastructure only – a	√				2.2	1.5	1.24	4.94	5.07
Road infrastructure only - b	√				2.3	1.6	1.31	1.31	
Average all projects					3.63	2.23	1.97	7.83	

- The "Active transportation health and economic impact study" reported by the Southern California Association of Governments (SCAG) gives an indication of the wider economic impacts in terms of public health and economic benefits from building and maintaining active transportation infrastructure. To demonstrate how transportation contributes to economic competitiveness, travel demand modeling results of this study are integrated with the REMI (Regional Economic Models, Inc.) economic impact model. The data used in this model is from a wide range of economic and transportation topical areas and includes key econometric estimates, and integrates inter-industry transactions, long run equilibrium features, and regional characteristics (SCAG 2016).

During the forecast period (2016-2040), estimation for job creation is 11.5 jobs per year. It also is attributable to labor productivity from improved health outcomes as well as the construction of active transportation infrastructure (

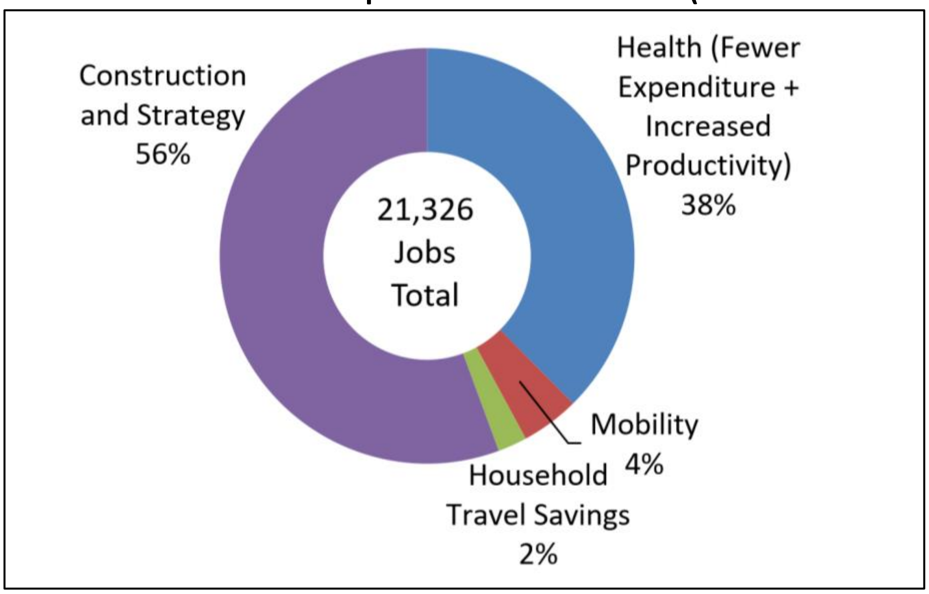
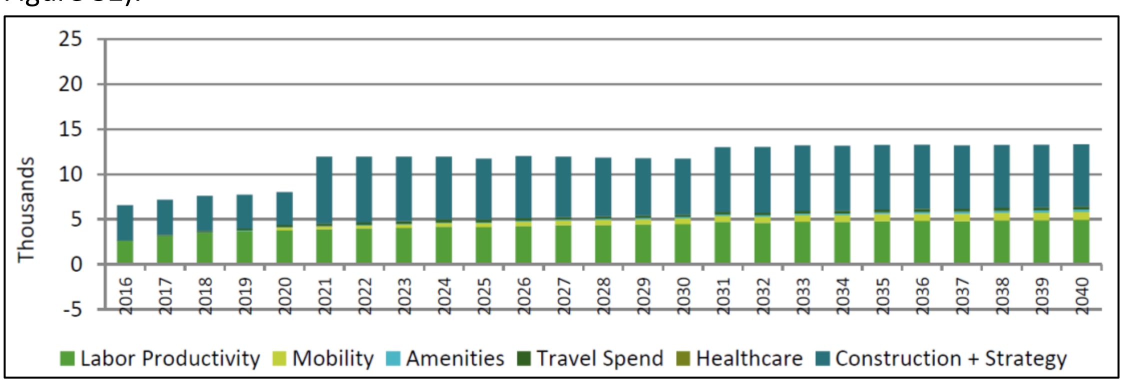


Figure 52).



- Figure 53 shows the most significant expected changes over time when additional infrastructure construction spending begins in 2021 (SCAG 2016).

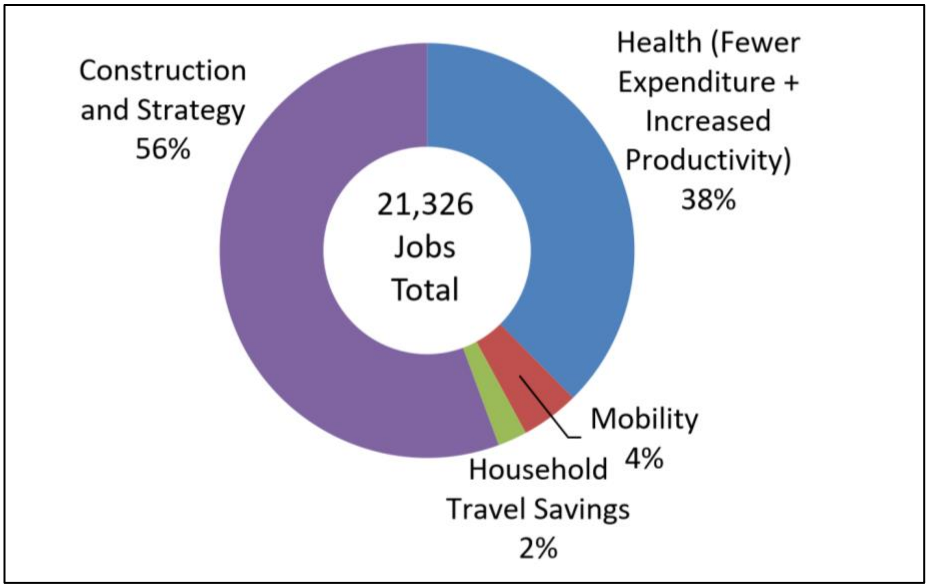


Figure 52. "Employment Gains per $1 Billion in AT-RTP (Regional Transportation Plan) Spending" (Fig Recreated from SCAG 2016).

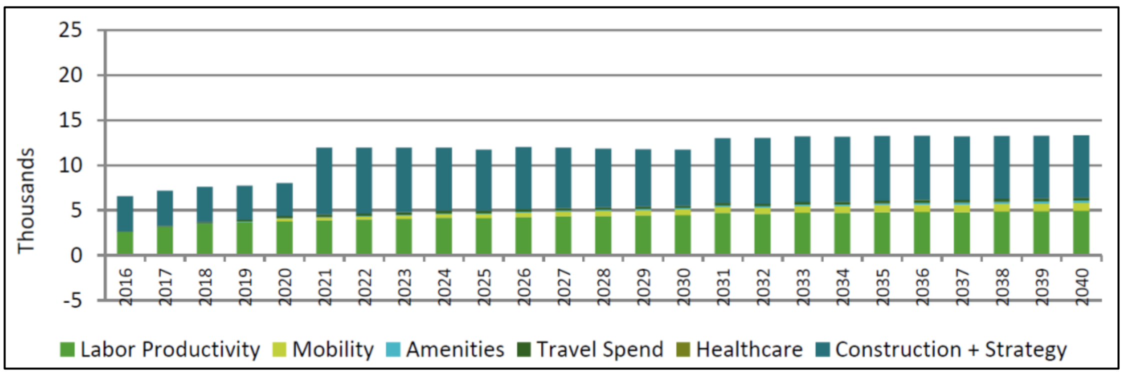


Figure 53. "Employment gains from active transportation, thousands, 2016- 2040" (SCAG 2016, pg 27).

- Job creation by different active transportation economic drivers can be seen in Table 36.This table shows 11.7 jobs per $1 million of RTP (Regional Transportation Plan) active transportation spent when spending on construction and programmatic strategies. It includes both direct construction jobs and more general jobs created by the construction workers (by increased spending). Healthier workers who are more productive create an additional 7.91 annual workers per $1 million in RTP active transportation spent. Household travel savings result in creating 481 jobs per $1 billion of AT-RTP (Active Transportation-Regional Transportation Plans) spent. Focusing on sectors that the job creation occurs in is another way to analyze this indicator (SCAG 2016).

Table 36. "Employment Benefits (Cumulative, Yearly Average, and Benefit per $1 Billion AT-RTP Spent) for 2016-2040" (SCAG 2016, pg 27)

Type	Jobs (1 year), 2016-2040 (2015$)		per $1 Billion AT-RTP
	Cumulative	Average	Spent
Labor Productivity (Healthier Workers)	106,637	4,265	7,910
Mobility (Less Congestion)	12,957	518	961
Amenities (Air Quality)	3,289	132	244
Household Travel Spending	6,478	259	481
Healthcare Expenditures	-538	-22	-40
Construction	158,667	6,347	11,770
AT-RTP Total	**287,490**	**11,500**	**21,326**
Current Infrastructure Health Effects	88,936	3,557	14,170*

*Current infrastructure per $1 billion spent assumes current levels of active transportation spending over the past 25 years or $ 6 billion (2011$). All other rows reflect the RTP analysis and are normalized by $ 12.9 billion (2011$) in expected future RTP spending on active transportation.

As can be seen, the last two reports including the Political Economy Research Institute report as well as the Southern California Association of Governments report show the average job creation of 11 jobs per $1 million spent.

Complete Street Performance Measures: Mobility/Connectivity

Connectivity Index

Description

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 represent the connectivity index (FHWA 2016).

Data Collection and Methodologies

To use this indicator for active transportation/transit projects, first, the number and directness of travel routes and available options to a user between neighborhoods and inter-neighborhoods should be measured. The evaluation contains the number of intersections density, intersections per linear mile, network density, connected node ratio, link to node ratio, and polygon density. These measures are defined by number of intersections in a given land area (e.g., a square mile or acre), number of intersections in a given land area divided by the linear network miles in the same given area, number of linear miles of street or other facility per given area (square mile), number of 3- or 4-way intersections divided by the number of 3- or 4-way intersections plus cul-de-sacs or dead ends, number of roadway links divided by the number of given nodes in the network in a given area, and number of blocks or polygons created by the network within a given area, respectively.

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 a 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.

Another consideration to identify connectivity index performance measures is connectivity between neighborhoods by active transportation/transit between a neighborhood and adjacent neighborhoods. 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 connect in adjacent neighborhoods. Historical transportation and housing planning decisions have often resulted in the current patterns of inter-neighborhood connections in many urban areas. They give rise to segregation and limited connectivity between neighborhoods that are defined by race, ethnicity, religion and/or income level.

FHWA Measurement Guidance

Connectivity indices use a variety of metrics which are shown in Table 37.

Table 37. Description of Connectivity Indices (FHWA 2016, pg 51)

Measure	Definition and Calculation	Notes	Typical Range For "Good" Connectivity
Intersection Density	Number of intersections in a given land area, such as a square mile or acre.	Can be limited to "4-leg intersections" or "intersections with pedestrian and bicycle accommodations" Easy to medium difficulty to calculate with GIS, depending on structure of available data.	100-160
Intersections per Linear Mile	Number of intersections in a given land area divided by the linear network miles in the same given area.	Can be limited to "4-leg intersections" or "intersections with pedestrian and bicycle accommodations" Easy to medium difficulty to calculate with GIS, depending on structure of available data.	
Network Density	Number of linear miles of street or other facility per given area (square mile).	Easy to calculate with GIS	18-26 miles
Connected Node Ratio (Portion of Nodes "that	Number of 3- or 4-way intersections divided by the number of 3- or 4-way intersections plus cul-de-sacs or dead ends.	Easy to medium difficulty to calculate with GIS, Depending on the structure of the existing data.	0.7 to 1

are Intersections)			
Link-to-Node* Ratio	Number of roadway links divided by the number of given nodes in the network in a given area.	Easy to medium difficulty to calculate with GIS, Depending on the structure of the existing data.	1.2 to 1.4; 2.4 is perfectly connected
Polygon Density[35]	Number of blocks or polygons created by the network within a given area.		100-160 for black girls

*Nodes include intersections, cul-de-sacs, and dead ends.

FHWA also suggests the following data sources for the connectivity index indicator:

- GIS transportation networks for each mode to be evaluated are needed to apply a connectivity index measure to an area larger than a few blocks.
- Aerial imagery or static maps can be used to manually calculate connectivity for small areas.
- Long range plans.
- STIP (Statewide Transportation Improvement Program)/TIPs (Transportation Improvement Programs).

Some Example Studies

- In the report "Using GIS to measure connectivity: an exploration of issues," Tresidder (2005) provides a method for estimating a connectivity indicator. This reference explains all connectivity measures in Table 38 and Figure 54. Table 39 includes the eight different connectivity measures analyzed (Tresidder 2005).

Table 38. Connectivity Definitions (Tresidder 2005)

Word/Phrase	Definition
Link	A roadway or pathway segment between two nodes. A street between two intersections or from a dead end to an intersection.
Node	The endpoint of a link, either a real node or a dangle node
Real node	The endpoint of a link that connects to other links. An intersection.
Dangle node	The endpoint of a link that has no other connections. A dead-end or cul-de-sac.
Circuit	A finite, closed path starting and ending at a single node.

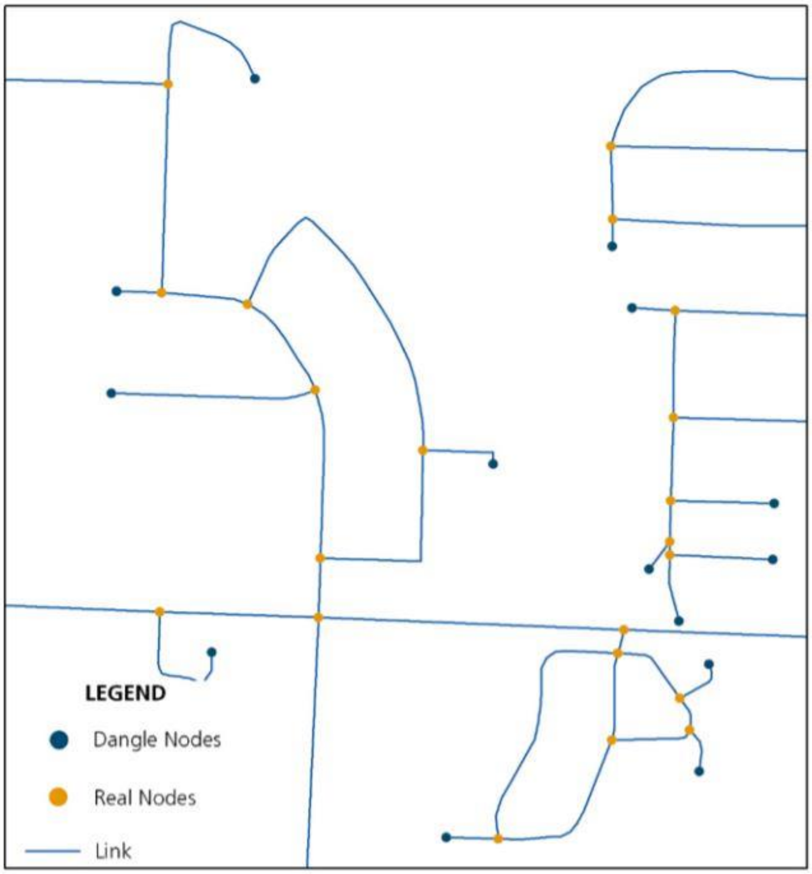


Figure 54. Connectivity definitions (Tresidder 2005, pg 5)

Table 39. Connectivity Measures (Tresidder 2005)

Measure	Definition	Calculation	Comments
Intersection Density	Number of intersections per unit of area	# Real nodes area / area	A higher number would indicate more intersections, and presumably, higher connectivity (See Figures 1 and 2).
Street Density	Number of linear Miles of street per square mile of land	Total street length per unit of area / area	A higher number would indicate more intersections, and presumably, higher connectivity.
Connected Node Ratio (CNR)	Number of street intersections divided by the number of intersections plus cul-de-sacs	# Real Nodes / # Total Nodes (real + dangle)	The maximum value is 1.0. Higher numbers indicate that there are relatively few cul-de-sacs and dead ends, and presumably, higher connectivity.
Link-Node Ratio	Number of links divided by the number of nodes within a study area	# links per unit of area (streets) / # Nodes per unit of area	A perfect grid has a ratio of 2.5. This measurement does not reflect the length of the link in any way
Average Block Length	Block lengths can be measured from the curb or from the centerline of the street intersection. The GIS measures the street length from center of intersection to center of intersection.	Sum of link length per unit of area / # of nodes per unit of area	Shorter blocks mean more intersections and therefore a greater number of routes available.
Effective walking Area (EWA)	A ratio of the number of parcels within a one quarter mile walking distance from an origin point to the total number of parcels within a one-quarter mile radius of the origin point.	Taxlots within 1/4-mile walking distance of origin point / Taxlots within 1/4-mile radius	Values range between 0 and 1, with a high value indicating that more parcels are within walking distance of the pre-defined point. The higher value reflects a more connected network.
Gamma Index	Ratio of the number of links in the network to the maximum possible number of links between nodes.	# Links per unit of area 3*(# Nodes - 2)	This measure comes from geography. Values range from 0 to 1.
Alpha Index	Ratio of the number of actual circuits to the maximum number of circuits.	(# Links - # Nodes) + 1 / 2*(# Nodes) – 5	This measure comes from geography. Values range from 0 to 1.

These connectivity measures were calculated for the Portland metro region defined by the urban growth boundary (UGB) and used the census tract for region-wide calculations. They also used an artificial unit of analysis of a half-mile buffer around a region for analysis to compare the census tract connectivity measurement with a more localized measurement for a specific point within the tracts. However, artificial boundaries were not recommended by the researcher, because they showed difficulties without highly accurate results (Tresidder 2005).

ArcView 3.3 and ArcGIS 8, two GIS software programs, were utilized in calculating the connectivity measurements. In addition, four ArcScripts (which can be downloaded from the ESRI website) that created extensions for the mapping program provided valuable benefits in processing the data and calculating connectivity measurements (Tresidder 2005).

Acquiring suitable data was one of the most difficult parts of Tresidder's study. The database used was from Metro, the regional government including Portland, Oregon. Metro maintains the Regional Land Information System (RLIS). This study emphasized the merits and demerits of GIS, and explored some of the issues that must be addressed during connectivity measures calculation (Tresidder 2005).

Intersection density may be a valuable measure for determining accessibility to an area and related to encouraging people to leave their cars and bicycle, walk, or use public transportation. The role of GIS analysis in shaping cities and future environments is undeniable. An ESRI-focused blog describes how geoprocessing and spatial analysis in ArcGIS can facilitate understanding of spatial patterns of urban accessibility using the USA road network as a case study. Data for major highways can also be accessed from this website (Esri 2017).

Other resources include the Smart Location Database, which is a nationwide geographic data resource for measuring location efficiency. Most attributes are available for every census block group in the United States (Ramsey 2011). Other important spatial data resources are available from the United States Census Bureau, ESRI, and EPA (United States Census Bureau 2017, Esri 2017, and EPA Smart Location Database 2017).

Active Transportation to Local and Regional Transit Connectivity Index

Description

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. There are no metrics of this type in the FHWA guidance. The purpose of this index is to identify the ability to travel to and from a transit point by walking or bicycling, including consideration of the richness of within- and between-neighborhood transit points in a neighborhood.

There are two metrics of this type in the Caltrans Performance Measures Report as part of the project titled "Toward an Active California State Bicycle and Pedestrian Plan" (Caltrans 2017). While that report is primarily focused on performance measures for whole jurisdictions, the two transit to active transportation measures are scalable to individual project and neighborhood levels and can be applied prior to construction of the project.

Connectivity to transit is not necessarily sufficient to result in increased use of combined active transportation and transit trips. Safety questions, particularly with respect to crime against persons for more vulnerable populations as well as theft are also an important consideration, and providing infrastructure without also providing an acceptable level of safety will not result in the expected benefits to the neighborhood. Safety can be addressed if it is included in Level of Service (LOS) indicators for walking, bicycling and combined active transportation and transit travel, which are included in this framework. Safety issues can also be considered in this connectivity indicator. When considering connectivity, connections can be classified based on safety-related factors such as:

- Well-lit transit stations
- Transit stations with continuous on-site security personnel
- Well-lit bicycling and walking paths with no hiding places
- Bicycling and walking paths with security patrols
- Stations with graffiti maintenance
- Other factors considered in the active transportation and transit LOS indicators in this framework

These measures also provide an indication of equity with regard to the richness of connected and secure active transportation to transit nodes in a neighborhood, which is particularly important in neighborhoods that do not have income levels that support vehicle ownership.

Data Collection and Methodologies

FHWA and Other Measurement Guidance

From the Caltrans report (Caltrans 2017), the following measures for which data can be collected are:

- 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. GIS spatial analysis can be conducted 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 total bikeway within the buffer should be divided by land area within the buffer (Caltrans 2017).
- Percent of regionally significant transit or rail stations that have covered, secure bicycle parking facilities within or adjacent to the stations: This measure relies on accurate data for bike parking at transit stations. This data would need to be collected from the various operators of inter-city rail, urban rail, and BRT systems. Number of stations with secure bike parking should be divided by the total number of stations to calculate this measure. Data sources for this calculation are not necessarily available (Caltrans 2017).

- Percent of State Highway System (SHS) roadway miles with complete sidewalks or bicycle facilities on both sides. The percentage of SHS roadway miles including complete sidewalks or bicycle facilities on both sides of the road defines this measure. This measure should be calculated by dividing the roadway miles with facilities by the total SHS mileage. This measure depends on accurate sidewalk and bicycle facility data on the SHS. Bicycle and pedestrian facilities should be tracked separately. Caltrans SHS sidewalk and bicycle facility data can be two data sources for the measurement (Caltrans 2017).

Two other measures that can be extrapolated from those in the state report and which will provide more granular quantitative are:

- Number of distinct functional walking and bicycle routes with nodes at a regionally significant transit or rail station within 20 minutes 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.
- Number of regionally significant transit or rail stations that have covered, secure bicycle parking facilities within or adjacent to the stations: This measure relies on accurate data for bike parking at transit stations. This data would need to be collected from the various operators of inter-city rail, urban rail, and bus rapid transit systems.

Pedestrian and Bicycling Delay

Description

This indicator, which is usually measured in seconds, is related to biking and walking at specific locations such as a signalized intersection or across longer distances such as a corridor. Various occurrences such as signal delay, congestion-based delay, indirectness of routes, and traffic gap acceptance lead to pedestrian and bicycle delays. 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. Auto LOS, which illustrates delay that vehicles experience at intersections, has parallels to this delay indicator (FHWA 2016).

Lack of enough routes, transport facilities, connected streets and inter-neighborhood connections are some of other factors which result in travel delays in all types of transport modes. Connected streets and inter-neighborhood connections in addition to parallel routes within safe and connected networks can reduce active transportation delay to destinations and transit connections. (Smart growth America, 2018)

Signal delay, congestion-based delay, and traffic gap acceptance can happen more in advantaged neighborhoods while indirectness of routes can occur more often in disadvantaged neighborhoods with fewer active transportation routes. To evaluate the equity of a project or a project within a network using the delay for active transportation indicator, first, the number and directness of travel routes and options available to a user between neighborhood destinations and inter-neighborhood connections should be measured. Delay may be caused by a lack of destinations, resulting in long travel times to reach them. In these cases investment in more destinations should be combined with the transportation infrastructure to reach them. If destinations of opportunity are sufficiently available in the neighborhood, then investment in complete streets projects and transit will increase the number of travel routes and options available to provide active transportation connectivity and access. Signal delay, congestion-based delay, and traffic gap acceptance should be measured based on FHWA 2016 guidance written in "data collection and methodology" of this indicator seen in the following paragraphs.

Another consideration to identify indirectness of routes in delay measurements is connectivity between neighborhoods and adjacent neighborhoods by active transportation combined with transit. This type of connectivity facilitates people coming into the neighborhood with less delay, and facilitates people in the neighborhood being able to connect in adjacent neighborhoods faster. Historical transportation and housing planning decisions result in the current patterns of inter-neighborhood connections in many urban areas. Therefore, the three steps evaluating process for equity suggested in chapter 6, should be considered in the assessment.

Data Collection and Methodologies

FHWA Measurement Guidance

According to the FHWA guidebook, average delay can be calculated by the following methods (FHWA 2016):

- "Transportation agencies can measure delay for pedestrians and/or bicyclists at an intersection, assuming average walk/bike speeds, random arrivals, existing signal timing (cycle length), and desired movements.
- At unsignalized intersections, agencies can assess delay for pedestrians and bicyclists by estimating the number of available gaps in traffic providing sufficient space for crossings.
- Delay along a segment can be estimated as a sum of the delay at intersections or crossings along the segment.
- In some high-volume circumstances, pedestrians or bicyclists may be delayed by other users traveling on the same facility. The Transportation Research Board's Highway Capacity Manual 2010 and FHWA's Traffic Signal Timing Manual provides methodologies for estimating delay resulting from high volumes of pedestrians or bicyclists, both for on-street facilities as well as multiuse paths." (FHWA 2016, pg 57).

FHWA also suggests the following data sources for delay indicators (FHWA 2016):

- Data on transportation networks for pedestrians and bicycles.
- Roadway characteristic data such as number of lanes and speed.
- Multimodal traffic volumes (pedestrian, bicycle, and vehicles).

- Traffic signal timing information.
- FHWA's Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Reports.

<u>Some Example Studies</u>

- Chapter 6 of the NCHRP Report 812 (Signal Timing Manual) has considered the pedestrian intervals that consist of three intervals including walk, flashing don't walk (FDW), and steady don't walk (that follows the FDW interval) (Figure 55). FDW interval, by some agencies, is also called the pedestrian clearance interval which is defined as the time required to cross the street while FWD interval is the pedestrian clearance interval reduced by the yellow change and red clearance intervals (NCHRP Report 812, 2015).

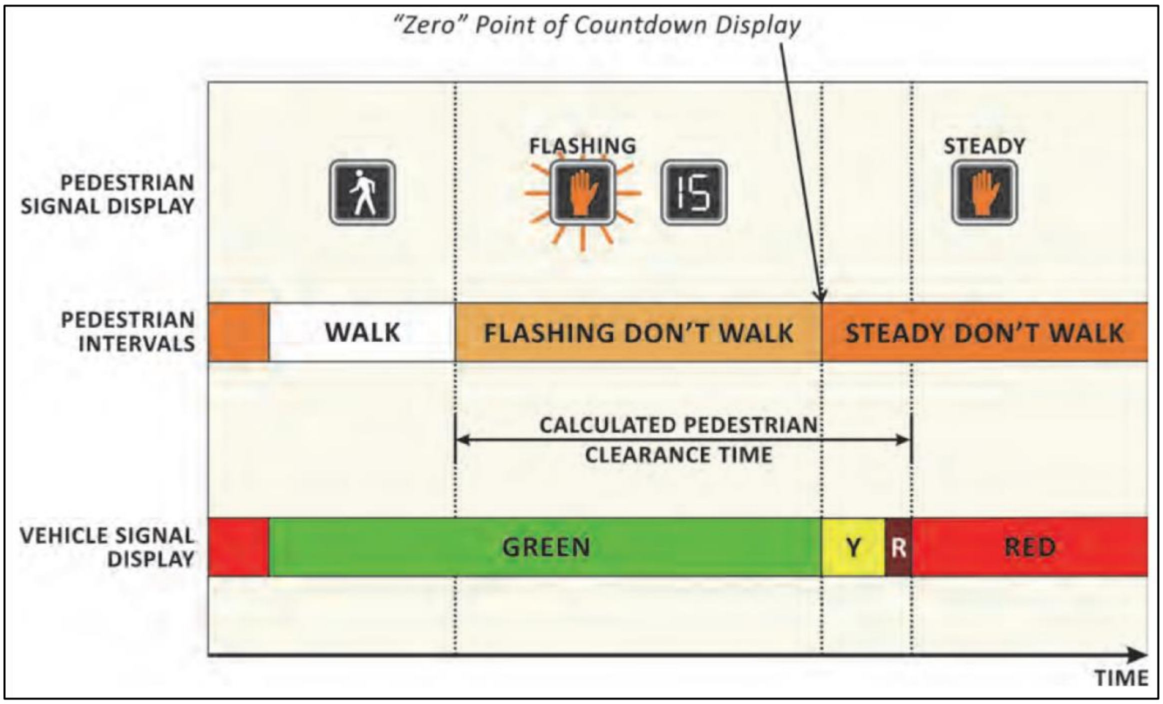


Figure 55. "Pedestrian Intervals" (NCHRP Report 812, 2015)

- Chapter 5 of the FHWA Traffic Signal Timing report (FHWA 2008) discusses the walk intervals that should provide pedestrians adequate time to perceive the walk indication. The walk interval should also leave the curb before beginning the pedestrian clearance interval. Walk times may reduce the potential for pedestrians stopping within the median while allow pedestrians to cross to a wide median before the flashing don't walk Table 40 and Table 41 important tables from the FHWA report that indicate the pedestrian timing interval and pedestrian clearance time, respectively.

Table 40. Pedestrian Walk Interval Duration from the FHWA. (FHWA 2008).

Conditions	Walk Interval Duration (PW), (s)
High pedestrian volume areas (e.g., school, central business district, sports venues, etc.)	10 to 15
Typical pedestrian volume and longer cycle length	7 to 10
Typical pedestrian volume and shorter cycle length	7
Negligible pedestrian volume	4
Conditions where older pedestrians are present	Distance to center of road divided by 3.0 feet per second

Table 41. Pedestrian clearance time. (FHWA 2008)

Pedestrian Crossing Distance, (ft)	Walking Speed, (ft/s)		
	3	3.5	4
	Pedestrian Clearance Time (PCT), (s)		
40	13	11	10
60	20	17	15
80	27	23	20
100	33	29	25

Note:
Clearance times computed as PCT - Dc/Vp
where,
Dc = pedestrian crossing distance (in feet)
Vp = pedestrian walking speed (in feet per second)

- Other agencies allow a portion of the pedestrian clearance time to occur during the change period (i.e., yellow change or yellow change plus red clearance intervals) was allowed by other agencies. The impact of pedestrian service on phase duration is minimized in this practice to be more responsive to vehicular demand. Equation 7 is used to compute the pedestrian clearance interval duration (FHWA 2008)

  $$PC = PCT - (Y+R) \qquad \text{Eq (7)}$$

  Where PC: Pedestrian clearance interval duration, s;
  PCT: pedestrian clearance time, s;
  Y: Yellow change interval, s; and
  R: Red clearance interval, s (optional)

- Chapter 4 of "Capacity Analysis of Pedestrian and Bicycle Facilities" reported by FHWA in 1998, suggest a number of models for calculating pedestrian delay at signalized crossings. The following model is one of these methods: (FHWA1998)

  Pretty (1979) uses simple models to analyze the delays to pedestrians at signalized intersections. Pretty developed the following correlation based on uniform arrival rates and equal pedestrian phases for pedestrians crossing one street at an intersection for pedestrian delay (Equation 8) (FHWA 1998).

$$d_1 = \frac{P}{2C}(C - w)^2 \qquad \textit{Eq (8)}$$

Where
d_1 = total delay to pedestrians crossing one street, ped-h/h;
P = pedestrian volume crossing one street, ped/h;
C = cycle length, s; and
w = WALK time, s.

He also offers Equation 9 for pedestrians crossing two streets at an intersection. This correlation assumes that one-half the cycle length separates the two WALK periods (FHWA 1998).

$$d_2 = P_d(0.75C - w)^2 \qquad \textit{Eq (9)}$$

Where:
d_2 = total delay to pedestrians crossing two streets successively, ped-h/h;
P_d = pedestrian volume crossing two streets, ped/h.

Complete Street Performance Measures: Safety/Public Health

Level of Service

Description

This is a quality of service indicator that measures the way users might perceive a service condition (e.g., safety, travel time, delay, comfort, speed). Various methodologies can assess pedestrian and bicycle level of service depending on context and desired outcomes. (FHWA 2016).

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. As noted in Chapter 3, the relationship between local police forces and the community can 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).

Lee (2013) found in a study that “although much has been written about local access to public transport, few studies have examined the role of the perceived environment in promoting transit by considering how the effects of these perceptions differ by neighborhood type.” In his study he analyzed self-reported frequency of transit use and measured neighborhood attributes using data from Los Angeles County, California and “…examined how the perceptions low-income people have about the walking environment affect their travel behavior.” Based on statistical analysis of his data he found that “…four perceptional attributes that affect regular transit use are physical safety, personal safety, amenities, and perceived isolation.” The results showed that “unfavorable perceptions of environmental conditions are independently associated with decreased regular transit use; however, these effects vary among different neighborhood types. Personal safety related to crime and violence is the major concern associated with decreased transit use in mixed land use neighborhoods; in low-density neighborhoods, isolation from the street environment and physical safety concerns, including dangerous crosswalks, are the significant deterrents to public transportation use. Notably, low-income travelers view the conditions of their walking environment as problematic more often than do higher-income travelers, and it appears that transit use by lower-income travelers is more likely to be affected by safety concerns than by other urban design factors of their neighborhood. Findings suggest that safety concerns precede amenity concerns; therefore, enhancing neighborhood safety is the necessary first step to increasing the utility of transit for low-income people.” (Lee, 2013, pg 1)

His findings match the neighborhood conditions that were addressed by comprehensive neighborhood programs through combined delivery of safety and infrastructure in a Los Angeles by Batteate (2013), which included use of a Pedestrian Environmental Quality Index (PEQI).

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.

Data Collection and Methodologies

FHWA Measurement Guidance

The FHWA guidebook’s focus is on pedestrians and bicyclists level of service. FHWA suggests the following level of service analysis methods for pedestrians and bicyclists that evaluate comfort, convenience, speed, and security of transportation facilities and services including (FHWA 2016):

- “Highway Capacity Manual 2010 Multimodal Level of Service (MMLOS) which is a method for evaluating how well urban streets serve the needs of all users. MMLOS uses combination of readily available data gathered by an agency to assess auto and transit level of service for evaluating auto, bus, bicycle, and pedestrian level of service on urban streets (MMLOS is included in the 2010 Highway Capacity Manual.) (NCHRP report 616, 2008)

- Danish Bicycle/Pedestrian LOS methods for quantifying pedestrian and cyclist stated satisfaction with roundabouts, signalized and unsignalized intersections, midblock crossings, and pedestrian bridges and tunnels (Jensen et al. 2007)
- Bicycle Environmental Quality Index (BEQI): a quantitative observational survey developed by the San Francisco Department of Public Health to assess the bicycle environment on roadways and evaluate what streetscape improvements could be made to promote bicycling (SFDPH 2010)
- Pedestrian Environmental Quality Index (PEQI): a quantitative observational tool developed by the San Francisco Department of Public Health to assess the quality and safety of the physical pedestrian environment and inform pedestrian planning needs (NACTO 2013)
- Level of Traffic Stress (LTS): a bicycle comfort classification system based on different bicycle skill levels (FEHR & PEERS 2017)
- Shared-Use Path Level of Service Calculator: a spreadsheet-based calculator to analyze the quality of service provided by shared-use paths of various widths that accommodate various travel mode splits.
- Capacity Analysis of Pedestrian and Bicycle Facilities: analysis procedures for calculating the operations of pedestrian and bicycle facilities based on speed, flow, and user density." (FHWA 2016, P69)

The FHWA also suggests the following data sources for LOS indicators:

- Traffic volume/speed data, including automobiles, buses, trucks, pedestrians, cyclists.
- Roadway characteristic data (e.g., travel lane width, number of travel lanes, turn lanes, driveway inventory).
- Bicycle/pedestrian facility characteristic data (e.g., sidewalk and buffer width, bicycle facility width, street trees).
- Traffic signal timing information.
- Land use and building data.

Some of aforementioned LOS analysis methods suggested by FHWA are discussed in the following example studies including the Highway Capacity Manual 2010 MMLOS, BEQI, and PEQI. Some other example Studies can also be seen in following section.

Some Example Studies:

- NCHRP Report 616 (MMLOS analysis for urban streets) provides a method to evaluate complete streets design alternatives, and smart growth from the perspective of all users of the street including auto drivers, transit passengers, bicycle riders, and pedestrians. The MMLOS method can be used to assess the effects of street designs on the perceptions of auto driver, transit passenger, bicyclist, and pedestrian of the quality of service served by the street (NCHRP report 616, 2008).

- This MMLOS report shows the results of a 2-year investigation of the MMLOS for user perception. The data were collected from traveler intercept surveys, field laboratory Studies, and video laboratory Studies.
- The Highway Capacity Manual (HCM) look-up table can be stated in the form of an approximate linear function of facility type and speed in compare to other model forms. Table 42illustrates the auto level of service on urban street while Table 43 and Table 44 related to bicycle and pedestrian level of services. (NCHRP report 616, 2008)

Table 42. Urban Street Level of Service (NCHRP Report 616, 2008)

Urban Street Class	I	II	III	IV
Range of FFS	45-55 mph	35-45 mph	30-35 mph	25-35 mph
Typical FFS	50 mph	40 mph	35 mph	30 mph
LOS				
A	>42 mph	> 35 mph	>30 mph	>25 mph
B	>34-42	>28-35	>24-30	>19-25
C	>27-34	>22-28	>18-24	>13-19
D	>21-27	>17-22	>14-18	>9-13
E	>16-21	>13-17	>10-14	>7-9
F	≤16	≤13	≤10	≤7

FFS = mid-block free-flow speed of street. Exhibit adapted from Exhibit 15-2, *Highway Capacity Manual*

Table 43. HCM Bicycle LOS for Bicycle Lanes on Urban Streets (NCHRP Report 616, 2008)

LOS	Average Bicycle Speed (mph)
A	> 14
B	> 9-14
C	> 7-9
D	> 5-7
E	>= 4-5
F	< 4

Adapted from Exhibit 19-5 of the Highway Capacity Manual

Table 44. HCM bicycle LOS at signals (NCHRP report 616, 2008)

LOS	Average Control Delay (secs)
A	< 10
B	>= 10-20
C	> 20-30
D	> 30-40
E	> 40-60
F	> 60

Adapted from Exhibit 19-4 of the Highway Capacity Manual

Table 45 . HCM Pedestrian LOS Criteria for Sidewalks (Report 616, 2008)

LOS	Space/Pedestrian
A	> 60 S.F.
B	> 40-60
C	> 24-40
D	> 15-24
E	> 8-15
F	<= 8

S.F. = square feet. Adapted from Exhibit 18-3 of the Highway Capacity Manual

Table 46. HCM Pedestrian LOS criteria for Paths (NCHRP Report 616, 2008)

LOS	Encounters/hour
A	<= 38
B	> 38-60
C	> 60-103
D	> 103-144
E	> 144-180
F	> 180

Adapted from Exhibit 18-8 of the Highway Capacity Manual

Table 47. HCM Pedestrian LOS Criteria at Signals (NCHRP Report 616, 2008)

LOS	Average Crossing Delay (secs)
A	< 10
B	>= 10-20
C	> 20-30
D	> 30-40
E	> 40-60
F	> 60

Adapted from Exhibit 18-9 of the Highway Capacity Manual

Table 48. HCM Pedestrian LOS Criteria for Urban Streets (Report 616, 2008).

LOS	Mean Walking Speed (fps)
A	> 4.36
B	> 3.84-4.36
C	> 3.28-3.84
D	> 2.72-3.28
E	> 1.90-2.72
F	< 1.90

fps = foot per second. Adapted from Exhibit 18-14 of the Highway Capacity Manual

Table 49. FDOT Bicycle and Pedestrian LOS Score Thresholds (Report 616, 2008)

LOS	Score
A	< 1.5
B	> 1.5 & < 2.5
C	> 2.5 & < 3.5
D	> 3.5 & < 4.5
E	> 4.5 & < 5.5
F	> 5.5

The facility segment **bicycle** LOS score (BLOS) is estimated according to the following equation in the NCRP report (Equation 10 to Equation 14)

$$BLOS = 0.507 \ln (Vol15/L) + 0.199SPt(1 + 10.38HV)2 + 7.066(1/PR5)2 - 0.005(We)2 + 0.760 \qquad Eq(10)$$

Where:
BLOS = Bicycle level of service score
ln = Natural log
Vol15 = Directional motorized vehicle count in the peak 15 minute time period
L = Total number of directional through lanes
SPt = Effective speed factor = 1.1199 Ln(SPp − 20) + 0.8103

SPp = Posted speed limit (a surrogate for average running speed)
HV = Percentage of heavy vehicles
PR5 = FHWA's five points pavement surface condition rating
We = Average effective width of outside through lane

$$PLOS = -1.2276 \ln (Wol + Wl + fp \times \%OSP + fb \times Wb + fsw \times Ws) + 0.0091 (Vol15/L) + 0.0004 SPD^2 + 6.0468 \quad Eq(11)$$

Where:
PLOS = Pedestrian level of service score
Ln = Natural log
Wol = Width of outside lane
Wl = Width of shoulder or bicycle lane
fp = On-street parking effect coefficient (=0.20)
%OSP = Percent of segment with on-street parking
fb = Buffer area barrier coefficient (=5.37 for trees spaced 20 feet on center)
Wb = Buffer width (distance between edge of pavement and sidewalk, feet)
fsw = Sidewalk presence coefficient (= 6 − 0.3Ws)
Ws = Width of sidewalk
Vol15 = Count of motorized vehicles in the peak 15 minutes period
L = Total number of directional through lanes
SPD = Average running speed of motorized vehicle traffic (mi/hr)

Recommended Bicycle LOS Model (NCHRP Report 616, 2008)

Bicycle LOS Model 1:

$$Bicycle\ LOS\ \#1 = 0.160*(ABSeg) + 0.011*(\exp(ABInt)) + 0.035*(Cflt) + 2.85 \quad Eq\ (12)$$

Bicycle LOS Model 2:

$$Bicycle\ LOS\ \#2 = 0.20*(ABSeg) + 0.03*(\exp(ABInt)) + 0.05*(Cflt) + 1.40 \quad Eq\ (13)$$

Where:
ABSeg* = The length weighted average segment bicycle score
Exp = The exponential function, where e is the base of natural logarithms.
ABInt* = Average intersection bicycle score
Cflt = Number of unsignalized conflicts per mile, i.e., the sum of the number of unsignalized intersections per mile and the number of driveways per mile

***** For more information regarding calculating bicycle segment LOS and bicycle intersection LOS, chapter 7 of NCHRP report 616 can be helpful.

Recommended Pedestrian LOS Model (NCHRP Report 616, 2008):

$$Ped\ LOS = Worse\ of\ (Pedestrian\ Density\ LOS, Ped\ Other\ LOS) \quad Eq\ (14)$$

Where:
Ped LOS = The letter grade level of service for the urban street combining density and other factors.
Ped Density LOS = The letter grade level of service for sidewalks, walkways, and street corners based on density
Ped Other LOS = The letter grade level of service for the urban street based on factors other than density

* For more information regarding calculating Pedestrian Density LOS, Ped Other LOS, chapter 8 of NCHRP report 616 (NCHRP Report 616, 2008) can be useful.

- A single average level of service for each of three modal users of the urban street including bus passengers, bicycle riders, and pedestrians is reported in the proposed multimodal LOS framework for urban streets (NCTCOG-BPAC 2015).
- Figure 56 and Table 50 show integrated multimodal evaluation framework time and space resource constraints and HCM multimodal level of service thresholds, respectively (NCTCOG-BPAC 2015).

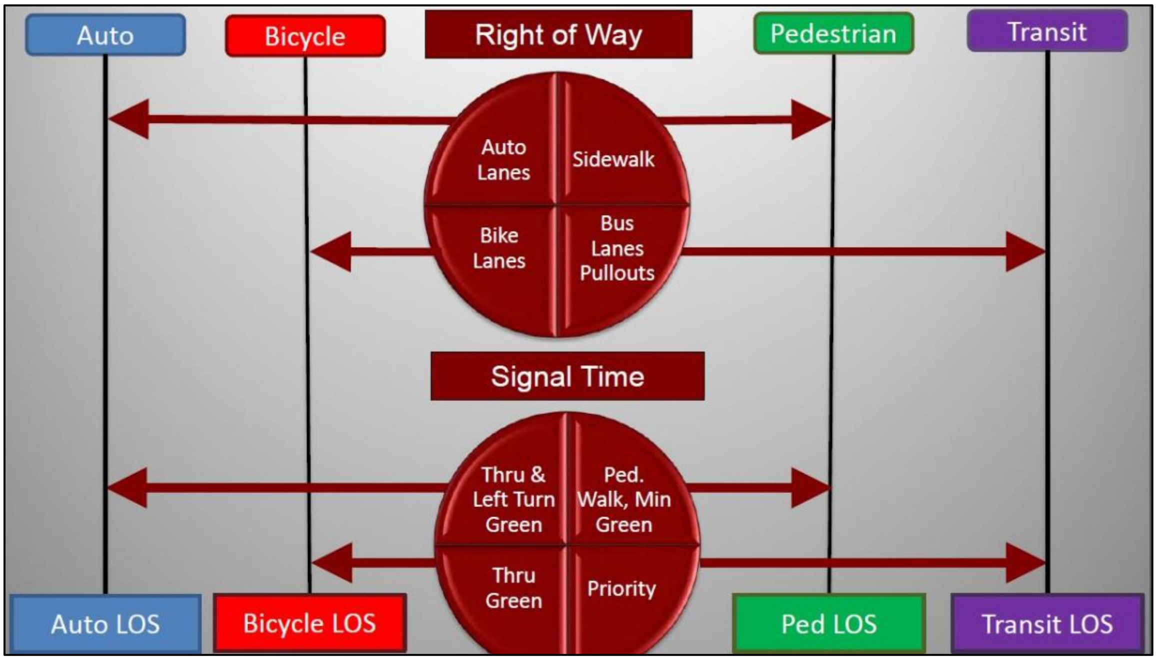


Figure 56. "Integrated multimodal evaluation framework time and space resource constraints" (NCTCOG-BPAC 2015).

Table 50. HCM multimodal level of service thresholds (NCTCOG-BPAC 2015).

LOS Segment Score: Auto Mode		LOS Score: Bicycle, Transit, and Pedestrian*	
Travel Speed as a % of Base Free-Flow Speed	LOS Critical Volume to Capacity Ratio ≤1.00	LOS	LOS Score
> 85	A	A	≤2.00
> 67-85	B	B	> 2.00-2.75
> 50-67	C	C	> 2.75-3.5
> 40-50	D	D	> 3.5-4.25
> 30-40	E	E	> 4.25-5.00
≤ 30	F	F	> 5.00
LOS F if Critical Volume to Capacity Ratio > 1.00		* No Sidewalk	

- Another resource for LOS estimation is the Quality/level of service (Q/LOS) application from the Florida Department of Transportation that implements the 2010 Highway Capacity Manual methodologies for the bicycle, pedestrian, and transit modes to compute Q/LOS for planning and preliminary engineering. Q/LOS is a free downloadable software available at www.dot.state.fl.us/planning/systems/sm/los/default.shtm (FDOT 2013).
- The Pedestrian Environmental Quality Index (PEQI) application is a quantitative observational tool to evaluate the quality and safety of the physical pedestrian environment. In addition, PEQI determines what pedestrian planning needs that help build social capital and political visibility for neighborhoods and communities. The PEQI form on every street segment and intersection should be completed to get an aggregate score. The following figure shows the data used to compute a PEQI score (Figure 57) (PEQI 2.0 2017)

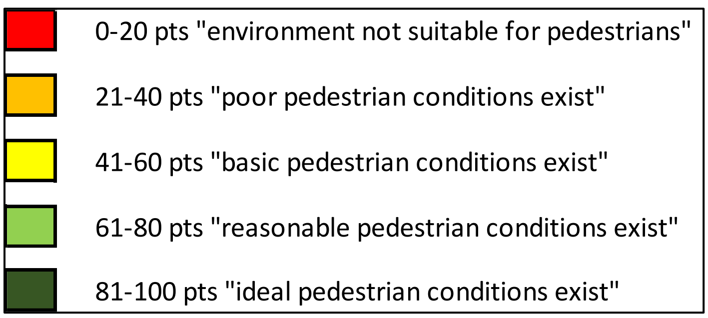


Figure 57. Used data for PEQI calculation (Figure recreated from PEQI 2.0. 2017)

- To measure the impacts of built environment factors on bicycle environmental quality, bicycle activity and bicycle safety, the BEQI was developed by the San Francisco Department of Public Health (SFDPH). This index measures 22 indicators to assess the service quality of the bicycle at the intersection-level that considers only safety features to protect cyclists from vehicle traffic and at the street segment-level. In other words, it focuses on traffic and design features, land use, and safety measures that consider visibility for cyclists (SFDPH 2010).
- The BEQI Data Manual guide from SFDPH has a complete explanation about evaluating the factors of this index. To create a map of existing bicycling conditions, the database calculates scores for both street segments and intersections to be imported into ESRI’s ArcMap GIS program. Table 51 shows BEQI indicators by domain, from SFDPH BEQI Factsheet, 2010. Figure 58 illustrates the map of BEQI analysis results on Treasure Island, San Francisco.

Table 51. BEQI indicators by domain (SFDPH 2010)

Intersection	Street Segment			
Intersection Safety	Traffic	Street Design	Land Use	Safety/Other
- Left turn bicycle lane - Dashed intersection bicycle lane*	- Number of vehicle lanes - Vehicle speed	- Presence of a marked area for bicycle traffic	- Line of sight - Bicycle parking - Retail use	- Bicycle/pedestrian scale lighting - Presence of
- No turn on red signs	- Traffic calming features	- Bicycle lane markings - Bike lane width		bicycle lane signs
	- Parallel parking adjacent to bicycle lane/route	- Trees - Street slope		
		- Connectivity of bike lanes		
**relevant only at complex intersections with high traffic volumes and/or speeds*	- Traffic volume	- Pavement type/condition		
	- Percentage of heavy vehicles	- Driveway cuts		

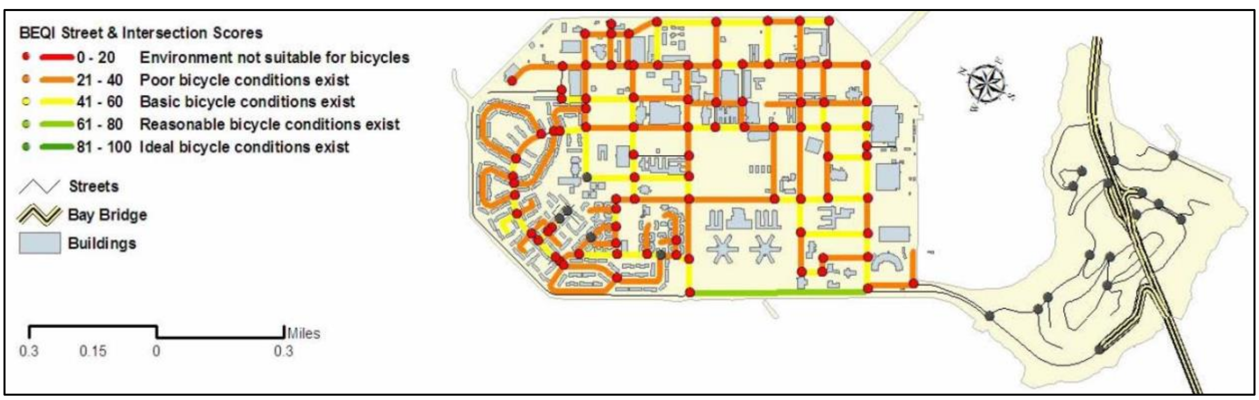


Figure 58. "BEQI street & intersection scores" (left), "Map of BEQI analysis results on Treasure Island, San Francisco" (right), (SFDPH 2010)

Crashes

Description

This indicator is calculated by the measured number of crashes or rate of crashes (crashes per volume of users) over a selected period. Crashes can be typically separated into severity (i.e., injuries, fatalities, property damage only) and modes (autos, pedestrians, and bicyclists) (FHWA 2016).

In disadvantaged neighborhoods, lack of enough neighborhood routes and inter-neighborhood connection points defined by physical barriers to connection with more advantaged neighborhoods can result in delay and/or crashes, especially during peak hours. Cottrill et al. (2010) evaluated the occurrence of pedestrian–vehicle crashes in census tracts with high low-income and minority populations (referred to as Environmental Justice or EJ tracts) compared to pedestrian–vehicle crashes in non-EJ tracts in the Chicago metropolitan area. As can be seen in table 27, environmental and behavioral indicators such as transit availability index, pedestrian accessibility index, crime rate, median household income, population density, percentage of people with no car, etc. are defined to assess this performance measure. Cotrill and colleagues found that accident rates were higher where there was more pedestrian activity and transit availability crash rates were higher because of higher exposure to potential pedestrian-vehicle crashes, although there was the possibility of under-reporting in some areas for various reasons. Their overall conclusion was that “results suggest that it may be necessary to better incorporate a safety perspective or measures of safety improvements in pedestrian and transit improvements and expansion programs within EJ areas.”

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 a low density of destinations of opportunity or lack of connectivity between different neighborhoods.

Data Collection and Methodologies

<u>FHWA Measurement Guidance</u>

To determine the number and severity of crashes, crash data are required for location, the conditions and time of the day, and people who are involved in crashes. Volume data and facility type data are usually used to determine crash hotspots and identify crash rates (FHWA 2016).

The measures shown below, based on crash history, can be used to assess the safety of the transportation system for bicycle and walking travel (FHWA 2016):

- Number of bicycle-involved and/or pedestrian-involved crashes over 5 years.
- Number of fatal or serious injuries of bicyclists and/or pedestrians over 5 years.
- Crashes per volume of bicyclists and/or pedestrians over 5 years (crash rates).

The FHWA also suggests the following data sources for crash data (FHWA 2016):

- Local or State crash report database.
- State reported data.
- Fatality Analysis Reporting System (FARS).
- Potentially: emergency room visit data.
- Pedestrian and bicycle counts (volumes).
- Demographic information.
- Facility inventories.
- Highway Safety Improvement Program Online Reporting Tool.
- Highway Performance Monitoring System (HPMS).
- State Highway Safety Plan (HSP) and the State Strategic Highway Safety Plan (SHSP).

Some Example Studies

- State DOTs, MPOs, and other agencies use data for non-motorized fatalities and serious injuries (collected by State DOTs) including the number of non-motorized serious injuries, the number of non-motorized fatalities by FARS (Fatality Analysis Reporting System) which is a nationwide census prepared for NHTS, Congress and the American public yearly about fatal injuries suffered in motor vehicle traffic crashes), and FARS Annual Report file. (NHTS 2017)
- A Highway Safety Improvement Program (HSIP) report provides the complete data regarding crashes and sorts them by State (HSIP 2017)
- "Evaluating pedestrian crashes in areas with high low-income or minority populations" by C. D. Cottrill et al. (2010) is a valuable study that evaluates the occurrence of pedestrian–vehicle crashes in census tracts with high low-income and minority populations (referred to as Environmental Justice: EJ tracts) compared to pedestrian–vehicle crashes in non-EJ tracts in the Chicago metropolitan area. Evaluating the incidence to environmental characteristics and behavioral factors in EJ versus non-EJ areas is one goal of Cottrill et al.'s study (Cottrill et al. 2010)
- Spatial Decision Support System (SDSS) analyses that integrate a Multi-Criteria Decision-Making (MCDM) environment are conducted to explain pedestrian–vehicle crashes. Pedestrian crash incidents in EJ areas are related to general population demographics (such as income and presence of children), variables of exposure, crime rates, and transit availability. Improving the relationship between a safety perspective (or measures of safety improvements in pedestrian), transit improvements, and expansion programs within EJ areas are suggestions of this paper. Table 52 provides a brief explanation of each environmental and behavioral indicator of Cottrill et al.'s study selected mostly based on several published research reports and local knowledge

derived from professionals who work in the area of transportation, safety and public health in the Chicago metro area (Cottrill et al. 2010).

Table 52. Environmental and Behavioral Indicators. (Cottrill et al. 2010).

Environmental Indicators at Census Tract-Level	Description
Transit availability index *(TAI)*	Composite index giving the extent to which residents have access to transit (bus and rail); based on three input measures - frequency (person-minutes served), hours of service (number of hours) and service coverage (percentage of census tract area covered). See Minocha et al. (2008) for more details
Pedestrian accessibility index *(PED)*	Composite index ranking tract suitability for pedestrian travel; based on input values of population, income, number of households, amount of commercial and residential land uses as a percentage of census tracts, weighted trip origins and destinations, and Pedestrian Environment Factor (PEF) values, where PEF's are the average number of blocks for the quarter section within each census tract and the eight adjacent quarter sections. See Cottrill and Thakuriah (2008) for more details
Sum of annual average daily traffic *(SUM.AADT)*	Total annual average daily traffic on links of all highway functional classes within census tract; output from regional traffic assignment model and GIS
Total miles of roads *(SUM_LENGTH)*	Total miles of roads of all functional classifications within census tract; output from GIS Count of all schools within census tract
Total number of schools (NO_SCHOOLS)	Count of all schools within census tract
Crime rate (CRIME)	Total violent and non-violent crimes in census tracts
Behavioral indicators at census tract-level	
Median household income (MEDINC)	Median household income; based on census 2000
Population density (POP_SQMILE)	Population per square mile in census tract (census 2000 population)
Percent with no cars (PERNOCAR)	Percentage of population without access to a vehicle (census 2000 data)
Percent commercial *(PER_COMM)*	Percentage of census tract used for commercial purposes (based on CATS land use 1990 file)
Percent children *(PER_CHILDREN)*	Percentage of population under the age of 16 (census 2000 data)
Percent who speak limited or no English *(PER_LOWENGLISH)*	Percentage of persons who speak no English or limited English (Census 2000 data)

Physical Activity and Health

Description

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 (FHWA 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" (FHWA 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 (FHWA 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.

Data Collection and Methodologies

FHWA Measurement Guidance

To measure physical activity levels, finding their relationship with transportation and health can be helpful. Based on the FHWA guidebook, physical activity levels can be measured in the following ways (FHWA 2016).

- "Average minutes of physical activity per day per capita. (For more detailed evaluation of minutes spent walking or bicycling, emerging sources of data collection, such as GPS or app-based fitness-tracking systems that allow for empirical data collection in real time can be useful.)
- Average minutes of physical activity attributable to active transportation per day.
- Portion of people regularly using active transportation modes.
- Number of walking or biking trips.
- Portion of population that is inactive or active." (FHWA 2016, pg 81).

The FHWA also suggests the following data sources for this performance measure:

- "Surveys tracking physical activity or other health indicators.
- Estimates of physical activity from transportation based on travel demand model outputs.
- Emerging sources of physical activity data like Strava, Inc. or other fitness tracking applications (https://www.strava.com/)
- Estimates of impacts on health outcomes from integrated models, such as the Integrated Transport and Health Impact Model.
- County-level health indicators measures are available at County Health Rankings & Roadmaps." (FHWA 2016, pg 81).

Some Example Studies

- Rissel et al. reviewed 27 papers regarding the influence of active transportation on physical activity and public health. Using bootstrapping analysis, the authors showed that if public transport use by inactive adults increases, there would be a significant rise in the level of sufficiently active adults in New South Wales, Australia. Several papers in the literature review recognized a range of 8–33 minutes of additional physical activity associated with public transport use, which generally involves some walking to bus stops or train stations. Large variation of measures of a physical activity and energy expenditure is a limitation of this study (Rissel et al, 2012).
- The "Active Living Research" website offers several tools to collect data on streets, schools, parks, or other community settings to realize how well they support physical activity. These data illustrate the need to make changes in each community and help leaders determine the most effective way to do. The Active Living Research also helps policy makers, practitioners, and advocates to make more activity-friendly environments

with its tools and resources. Observational tools to assess the environment, observational tools to assess physical activity, and surveys to assess perceptions of the environment are three types of tool that are provided by Active Living Research (Active living research 2017).

- The Integrated Transport and Health Impact Modelling Tool (ITHIM) represents “a range of related models and tools developed at the Center for Diet and Activity Research (CEDAR) to perform integrated assessment of the health effects of transport scenarios and policies at the urban and national level. The health effects of transport policies are modelled through the changes in physical activity, road traffic injury risk, and exposure to fine particulate matter (PM2.5) air pollution. Some versions of ITHIM also predict changes in CO_2 emissions. ITHIM is being used in research and by health and transport professionals to estimate the health impacts of scenarios, compare the impact of travel patterns in different places, and model the impact of interventions. ITHIM works either as a stand-alone model, or it can be linked with other models (e.g., transport, health, economic). The health effects of ITHIM are presented as disability-adjusted life-years (DALY) and number of attributable deaths.” (CEDAR 2017, pg 1)
- Comparing distributions of weekly physical activity under different scenarios can be connected to ITHIM models to physical activity. Cardiovascular diseases, colon cancer, depression, diabetes, breast cancer, and dementia are examples of outcomes influenced by physical activity such as the level of walking and cycling. Figure 59 illustrates the general overview of the ITHIM model. Arrows display the flow of data inside the mode (CEDAR 2017).

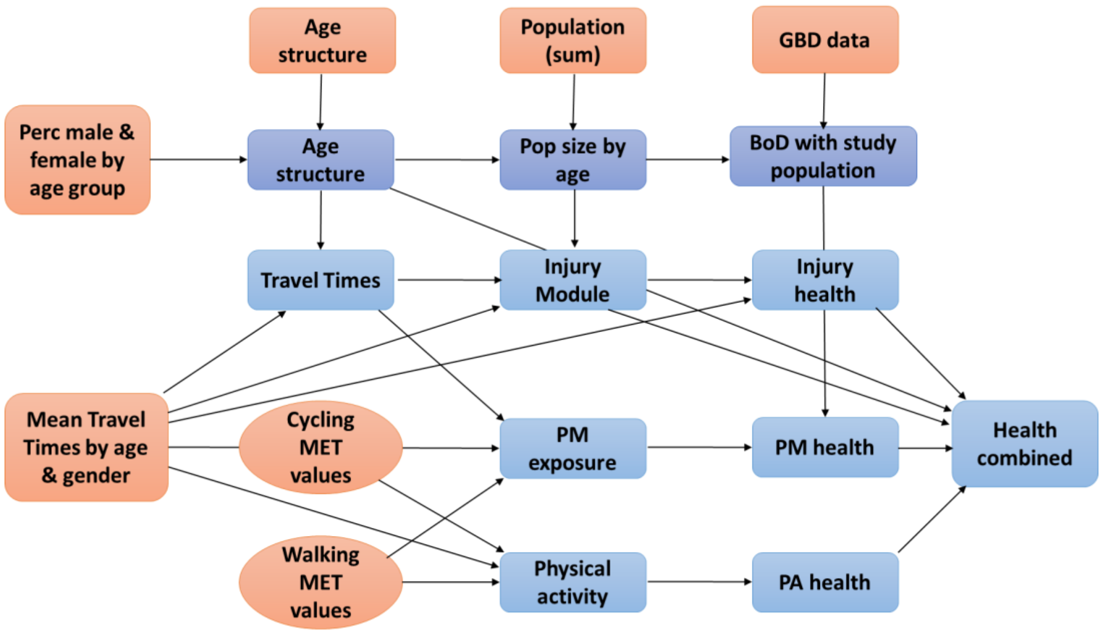


Figure 59. The general overview of the ITHIM model (CEDAR 2017)
**Arrows show the flow of data inside the mode. (PM = fine particulate matter air pollution, GBD = Global Burden of Disease study, PA= Physical Activity, MET= Metabolic Equivalent of Task).*

- "Increasing Walking, Cycling, and Transit: Improving Californians' health, saving costs, and reducing greenhouse gases" reported by N. Maizlish uses data from California travel and health surveys, vital statistics, collision databases, and regional and statewide travel models as well as the ITHIM that estimated health (the number of deaths and years of life lost, disability), economic, and environment (greenhouse gas emission). Since California legislation and policy has promoted strategies to lower transportation-related greenhouse gas (GHG) emissions by reducing VMT, this study depicts that walking and bicycling, as a component of VMT reduction, increase physical activity, which improves population health by reducing risks of heart disease, stroke, diabetes, dementia, depression (Maizlish, 2017).

  The scenarios which are considered in Maizlish's study include CSMP2020 (CA Department of Transportation Strategic Management Plan), AT2030 (Active Transportation), and USSG1.0 (U.S. Surgeon General). The First Scenario foresees a doubling of 2010 baseline levels of walking and transit and a tripling of bicycling by 2020. In second scenario, walking and transit quadruple from 2010 baseline levels and bicycling increases nine-fold by 2030. Levels of physical activity (from active transport) attained by half the California population encountering the recommended level of physical activity of 150 minutes per week of moderate physical activity of the U.S.S.G in scenario three.

- The results of this report indicate decreasing annual number of deaths with increasing level of active transportation (-2,095 for CSMP2020 and -8,057 for USSG1.0.), remarkable increase in annual monetized value of health outcomes through chronic disease reduction (ranging from 1.0 to 59.6 billion dollars), and decreasing GHG emissions (carbon reductions of 3% to 14%) (Maizlish, 2017).

Vehicle Miles Traveled (VMT) Impacts

Description

This indicator is the measurement of miles traveled by vehicles in a specific location for a particular period. VMT has impacts on public health due to the effect on emissions levels and air quality (FHWA 2016) VMT is also a powerful indicator for assessing transportation impacts that concentrates on additional vehicle trips on the network. VMT reduction reduces greenhouse gases and pollutants which will result in fewer harmful effects on environmental and public health.

VMT reduction may be an indicator that merits deeper consideration with regard to moving towards greater equity when comparing projects in neighborhoods that have high access to cars and therefore higher initial VMT with projects in neighborhoods that do not have access to cars and already have low VMT. If VMT reduction is considered as an only indicator of the benefits of a project, then it would favor high-traffic areas, since reductions would be greater than low-traffic neighborhoods, and high traffic neighborhoods are more likely to be wealthier. Therefore, VMT reduction should not be considered alone, and should be included with other indicators included in this framework that consider measurement of density of destinations of opportunity and connectivity between neighborhoods.

According to Ewing et al.'s (2010) study, VMT is related to access to destinations and street network design variables while walking is related to land use diversity, intersection density, and the number of destinations within walking distance. (Ewing et. al, 2010)

Data Collection and Methodologies

<u>FHWA Measurement Guidance</u>

Regarding the FHWA guidebook, VMT can be calculated per capita, on an average daily basis, in total, and/or on an annual basis. The following approaches including geographical boundary and trip generation are used to calculate VMT (FHWA 2016).

- "Geographic boundary: Use traffic counts to estimate the amount of vehicle travel that occurs within a given geographic boundary. This is the method used to develop the FHWA VMT data.
- Trip generation: Use a travel demand model to estimate the vehicle travel of residents living within a given geographic area. An alternative data source is household surveys. Travel model data can include trips produced by and/or attracted to an area, for all trip purposes (e.g., work, school, shopping, etc.)." (FHWA 2016, pg 95).

The FHWA also suggests using the following data sources for the vehicle miles of travel indicator:

- Roadway characteristics (e.g., segment length).
- Daily traffic volumes (through counts or from local jurisdiction).
- To estimate VMT for projects and land use scenarios, access sketch models or regional or State travel demand Models.
- State DOT, MPO, and the FHWA Office of Highway Policy Information may have relevant data.

Some Example Studies

- Two helpful references for calculating VMT is "Quantifying Project-Level Vehicle Miles Traveled" and "Evaluation of Sketch-Level Vehicle Miles Traveled Quantification Tools" published by the National Center for Sustainable Transportation (NCST) in May 2017 and August 2017, respectively. Regarding the first study, a key step in the analysis of traditional traffic impact assessment is trip generation which is part of calculating VMT. These studies show that the vehicle trips generation using Institute of Transportation Engineer (ITE) method, estimated 2.3 times greater than actual vehicle trips in the AM peak hour in average at 30 smart growth sites in California. This number is almost the same as PM peak hour (2.4). (NCST 2017)

  Equation 15 shows VMT calculation while equation 16 estimates VMT for smart growth/ infill/ tod projects (recreated from NCST 2017).

  Number of vehicle trips (ITE trip generation rates) * Average miles per trip (Trip lengths from regional model) =Vehicle miles traveled *Eq (15)*

  Number of vehicle trips (Adjust trip rates) * Average miles per trip (Adjust trip length) =Vehicle miles traveled (Adjust VMT estimates) *Eq (16)*

- Table 53 summarizes six VMT quantification tools for analysis and their applicability for particular types of projects and context areas.

Table 53. VMT Quantification Tools, Methodology and Applicability. (NCST 2017)

VMT Quantification Tools Selected	Methodology	Applicability
CalEEMod 2013 & 2016	Adjustment to VMT based on elasticities	• Commercial (subset), educational, industrial, recreational, residential, retail (subset). • Any context area
California Smart Growth Trip Generation Adjustment Tool	Statistically-based reduction in trips	• Mid- to high-density residential, office, restaurant, coffee shop, retail. • ''Smart growth'' project location
GreenTrip Connect	Statistically-based reduction in VMT	• Residential. • Any context area
MXD	Statistically-based reduction in trips	• Residential, retail, office, industrial (subset), commercial (subset), educational, other. • Any context area
Sketch 7	Statistically-based reduction in VMT	• Mixed use, residential, office, industrial, public, civic, medical, educational, military, airport. • Any context area

Pedestrian Miles Traveled (PMT)/ Bicycle Miles Traveled (BMT)

Description

These parallel indicators are the measurements of miles traveled in a specific location for a particular period of time by person and bicycle. These two performance measures are also appropriate for crash estimation (bicyclist and pedestrian crashes per unit of bicyclist/ pedestrian miles traveled) (Caltrans 2017).

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 to make active transportation more viable in disadvantaged neighborhoods which can result in a huge improvement in PMT and BMT performance measures, if density of destinations of opportunity, transit connections and safety issues are addressed (as discussed in physical activity indicator). According to Ewing et al.'s study, VMT is related to access to destination and street network design variables while walking is related to land use diversity, intersection density, and the number of destinations within walking distance (Ewing et al. 2010)

The PMT and BMT 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.

Data Collection and Methodologies

Caltrans and FHWA Measurement Guidance

According to a Caltrans white paper, PMT and BMT can be calculated from the percent of trips accomplished by walking/ bicycling, and the average length of walking/bicycling trips (Caltrans 2017).

- PMT and BMT can be calculated per capita, on an average daily basis, in percentage, in total, and/or on an annual basis (FHWA 2016, Caltrans 2017).
- Average length of walk/ bike trips is important for calculating the pedestrian and bicycle miles traveled measures. PMT/BMT can be calculated by multiplying the total walk/bike trips by the average trip length by trip purpose. Before this calculation, the total number of bicycle trips should be estimated from the total trips using the purpose of walk/bike mode share estimates (Caltrans 2017).
- Regarding Caltrans recommendation, better real-time data collection through local and regional efforts can improve this estimation methodology.

The Caltrans also suggests using the following data sources for the pedestrian and bicycle miles of travel indicator:

- Third party data sources (from wearable devices (e.g., fitness devices), GPS traces, mobile phone apps, etc.) can help estimate PMT/BMT, trip length and total walk/bicycle trips at a state, regional, or local level (Caltrans 2017).
- State DOT, MPO, and the FHWA Office of Highway Policy Information might have relevant data (FHWA 2016).
- Manual counts of video recordings of the selected sites can be useful (Caltrans 2017).

Some Example Studies

The following sources are helpful for measuring PMT and BMT:

- The most comprehensive research regarding PMT and BMT has been conducted by the National Institute for Transportation Communities (NITC) in 2017. According to this study, walking and bicycling metrics are completely different in comparison with VMT (NITC 2017).
- Three approaches are discussed in this report. The first one is travel survey data which is more appropriate for a statewide measure while the second one is sample-based using pedestrian and bicycling count data and more useful for bicyclist than pedestrian in facility-level. The third one is an aggregate demand model using demographic data combined with count data and this approach is more suitable for pedestrian due to the more dispersed nature of pedestrian travel (NITC 2017).
- Since Nordback (2017) focuses on appropriate methods at the state-level, the following studies from NITC’s literature review that concentrated on facility-level methods of

calculating BMT and PMT can also be useful or even more suitable for complete streets Studies:

- “Guide to urban traffic volume counting (GUTVC)” by FHWA is another study for BMT measurement. Manual counts of video recordings of the selected sites are used for data collection. This research has modified the sample-based method used in VMT determination to calculate BMT estimation (Nordback 2017).
- University of Vermont researchers produced eight estimates of annual PMT and BMT for Chittenden County. In this research, two different sets of adjustment factors were used to calculate PMT and BMT which were determined using infrared-sensitive lens counters that produced full-year continuous data. Moreover, four types of classification systems for links in the bicycle pedestrian network are used to calculate the different estimate (Nordback 2017).

Complete Street Performance Measures: Livability

Green Space Changes

Description

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 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). (FHWA 2016).

Regarding the three steps for reviewing the equity of indicators discussed in chapter 6, this indicator passes all three steps because it is not affected by the density of destinations of opportunity.

Data Collection and Methodologies

FHWA Measurement Guidance

According to the FHWA guidebook, the percentage of land consumed in comparison with the amount of land conserved can be calculated by a transportation agency by a development scenario. An agency also can compare land consumption to growth in population with subtracting population of base year from population of current year to check the growth occurrence through infill of previously developed areas. Infill development decreases natural resource impacts that lead to dense development which can result in biking and walking (FHWA 2016).

The FHWA also suggests the following data sources for this performance measure:

- GIS data on land use, zoning, and density.
- Development site plans.
- Population data (U.S. Census Bureau, regional or State estimates).
- GIS data on land cover

Some Example Studies

- "Greenfields" and "greyfields" are two terms defined by ASCE (ISI 2018). Greenfields stands for undeveloped lands conservation by locating project on previously developed lands or greyfields. According to this definition, projects located on greyfields, which are usually underutilized or abandoned sites, have fewer impacts on wildlife compared to greenfields. Greenfields consist of natural or managed vegetation, by minimizing the likelihood of new habitat fragmentation. It should be mentioned, vegetated areas of public parks are considered undeveloped land while paved areas are considered developed land. (ISI 2018).

  This definition gives more credit to projects that use greyfields and conserve greenfields instead. These projects lead to reduced pressure on undeveloped land and conservation of resources by promoting urban development to urban areas. In addition, they result in safety improvement, creation of short-term and long-term local jobs, and the creation or preservation of parks and other recreational property by promoting socioeconomic urban and neighborhood revitalization. (ISI 2018). Improved conversion (the percentage of project development located on previously developed areas), restorative (a net positive return of previously developed area back into natural or vegetated areas), and applicability (the extent to which the project is located on greenfield or greyfield) are performance improvements for assessment. (ISI 2018).

- LEED has a similar definition for greenfields and previously disturbed areas. According to LEED description, land that has not been graded, compacted, cleared, or disturbed and that supports (or could support) open space, habitat, or natural hydrology, are defined as "greenfield". On the other hand, areas that have been graded, compacted, cleared, previously developed, or disturbed in any way are defined as “previously disturbed”. (USGBC, 2018)

- “The measure of land consumption caused by urban planning” by Gerundo et al. is a relevant research project which introduces several metrics and methodologies for measuring municipal urban land consumption. This reference might be adjustable for the green land creation and consumption. The methodologies include:
    - Definition of the urbanized area.
    - Selection of metrics for measuring land consumption caused by urban planning.
    - Indexes definition and identification of thresholds for interpreting results (Gerundo et al. 2011).

  This paper uses the aggregation of zoning categories since zoning is one of the most important tools that urban planners conduct to control physical characteristics of developing landscapes. Zoning categories are aggregated to two levels:

    - Aggregation of consolidated zones (ACZ) is the first level including zoning categories which recognize the existing built-up area;
    - Aggregation of expansion zones (AEZ) is defined as the second level including the existing built-up area and urban expansion zones (Gerundo et al. 2011). Table 54 illustrates the selected metrics for measuring urban land consumption.
- “Defining greenspace: Multiple uses across multiple discipline” by Taylor et al. (2017) is another study with a good insight to understand greenspace. This research uses six different definition types of greenspace from physical and social sciences that investigate the interactions with or within greenspace. Additionally, constructing the definition of greenspace for the context of the study which leads to utilize both qualitative and quantitative aspects is this paper’s recommendation (Gerundo et al. 2011, Taylor et al., 2017).Table 55 indicates several terms used interchangeably with greenspace across all disciplines. Table 56 depicts six types of definitions used to describe “greenspace”. Several examples that show how the two different interpretations of greenspace are used are shown in Table 57 (Taylor et al., 2017).

Table 54. Selected Measures for Calculating Urban Land Consumption (Gerundo et al. 2011)

Metrics	Formula	Description
Increase of urbanized area	$\Delta S_u = \frac{S_{AEZ} - S_{ACZ}}{S_{ACZ}}$	The increase of the urbanized area indicates, as a percentage, the variation caused by new expansions.
Weight of AEZ	$P_{AEZ} = \frac{S_{AEZ}}{S_m}$	The weight of the AEZ results from the proportion between the total surface of the AEZ and the total surface of municipal territory (S_m).
Variation of the weighted average of coefficient of perimetric shape caused by the expansion zones	$\Delta Cf = \Delta\left(\frac{\sum_k Cf_k A_k}{\sum_k A_k}\right)$	The perimetric shape coefficient, Cf_k, connected to k-th patch of surface A_k, derives from the proportion between the perimeter of an ideal circle which has the same surface of a single patch and the perimeter of the patch itself. This coefficient can change from 0 to 1. Value is equal to 1 when the patch has a circular shape and to 0 when there is the maximum indentation of margins.
Variation of *edge density* caused by the expansion zones	$\Delta ED = \Delta\left(\frac{\sum_k e_k}{Sup_{comunale}}\right)$	ED is expression of the shape and complexity of a patch of a particular class of use or permitted use. It derives from the proportion between the sum of the length of all ek perimeters of patches and the surface of municipal land. It can assume values more than or equal to zero. In particular it assumes rising values, surface being equal, when changing from patches with a compact shape to more indented patches.

Table 55. Number of Terms Were Used Interchangeably with Greenspace Across All Disciplines (Taylor et al., 2017)

Discipline of Journal	Papers	Key term	Other Terms Used
Biological, Earth, and Environmental Sciences	25	Greenspace; green space; public greenspace; urban greenspace; urban green space	Greenspace; green space; public greenspace; urban greenspace; urban green space; garden; ecological garden; urban forest; urban parks; urban habitat; urban green areas; greenery; green belt
Architecture, Urban Environment and Building	21	Greenspace; green space; urban greenspace; productive urban greenspace	Greenspace; green space; productive urban greenspace; urban greenspace; forest; green area; green environments; green network; green infrastructure; greening project; productive greenspace; working greenspace
Medical and Health Sciences	15	Greenspace; green space	Greenspace; green space; green area; greenery; natural environment; parkland; walkable area
Social sciences (including history, education, economics, policy and political science, sociology, and behavioral sciences)	15	Greenspace; green space; urban greenspace	Greenspace; green space; green area; urban greenspace; natural environment; nature; blue space; green environments
Multidisciplinary	49	Greenspace; green space; green-space; public greenspace; urban greenspace; urban green space; green areas	Greenspace; green space; public greenspace; urban greenspace; urban green space; blue space; garden; greenery; green environment; nature surroundings; green areas; green patches; green infrastructure; multifunctional greenspace; green elements; green roof; urban green; greenness exposure; greenness; open green space; greenbelt; informal urban green-space; nature; public greenspace; riparian greenspace; sky garden; urban forest; trees; urban garden; urban farm; urban greenspace ecosystem; tree cover; urban ecosystem; landscape; urban trees; vegetated area; water bodies; woodland

Table 56. Examples Show How the Two Different Interpretations of Greenspace Are Used. (Taylor et al., 2017)

Greenspace as Nature	Greenspace as Urban Vegetated Space
"[Greenspaces] broadly encompass publicly accessible areas with natural vegetation, such as grass, plants or trees [and may include] built environment features, such as urban parks, as well as less managed areas, including woodland and nature reserves." (Lachowycz & Jones, 2013)	"Greenspace is defined as any vegetated land adjoining an urban area …and includes bushland, nature reserves, national parks, outdoor sports fields, school playgrounds and rural or semi-rural areas immediately adjoining an urban area." (Chong et al., 2013)
"The conceptualization of greenspace in this review includes both urban and Nonurban green, from natural and semi-natural landscapes to the countryside and urban parks." (Kloek, Buijs, Boersema, & Schouten, 2013)	"urban green spaces - that is forests, trees, parks, allotments or cemeteries - provide a whole range of ecosystem services for the residents of a city" (Bastian et al., 2012)
"…daily lives involve and take place in parks, allotment gardens, cemeteries, at lakes and beaches and in other green and blue areas..." (Petersen, 2013)	"…we defined a garden as the private spaces adjacent to or surrounding dwellings. (Lindemann-Matthies & Marty, 2013)
"…'natural' green space environments such as woodlands, parks and gardens..." (White et al., 2013)	"…vegetated areas located within built-up areas, including natural and planted trees, grass, shrubs and flowers. (Lo & Jim, 2012)
Our main focus is on land cover (including green and blue space types)." (MacKerron & Mourato, 2013)	"[The] sum of all woody and associated vegetation in and around dense human settlements" (Strohbach & Haase, 2012)

Table 57. Six Types of Definitions That Were Used to Describe "Greenspace" (Taylor et al., 2017)

Definition type	Description	Example
Acknowledged range (n = 5)	A definition that acknowledged the range of what can be considered 'greenspace'	"greenness describes level of vegetation, ranging from sparsely-landscaped streets to tree-lined walk-ways to playfields and forested parks (Almanza et al., 2012)
Definition by examples (n = 17)	Examples were provided to illustrate what is meant by greenspace	"combined areas of open land, cropland, urban open land, pasture, forest, and woody perennial" (Tavernia & Reed, 2009)
Ecosystem services (n = 3)	Examples that embody ecosystem services, such as urban agriculture, and/or a reference to serving human needs	"a type of land use which has notable contributions to urban environments in terms of ecology, aesthetics or public health, but which basically serves human needs and uses" (Aydin & Culkur, 2012)
Green areas (n = 4)	A reference to 'green' and/or 'natural' areas without further Explanation	"the area investigated included substantial green elements"(Gentin, 2011)
Land uses (n = 6)	Generic land uses described as greenspace	"recreational or undeveloped land" (Boone-Heinonen, Casanova, Richardson, & Gordon-Larsen, 2010)
Vegetated areas (n = 21)	Areas that feature vegetation	"green in the sense of being predominantly covered with vegetation" (Heckert, 2013)

Street Trees

Description

This indicator can be defined as the number of trees on a street or any other area that measured as number of trees, percent pf street tree canopy coverage, number of tree per mile, and tree spacing. Street trees improve livability and safety by narrowing the roadway, contributing to traffic calming. In addition, wastewater diversion, CO_2 sequestration, air quality improvement, and habitat for wildlife are some of environmental benefits provided by street trees (FHWA 2016). Appropriate street shade trees have a large canopy that provide a physical and psychological barrier between vehicles and pedestrians. Shade trees also causes pedestrian comfort and physical well-being, especially in warm climates, in addition to giving sidewalks a sense of security and adding beauty (Change Lab Solution, 2017).

Regarding the three steps for evaluating equity bias discussed in Chapter 6, the Street Trees indicator passes all three steps.

Data Collection and Methodologies

FHWA Measurement Guidance

Based on the FHWA guidebook, transportation agencies depending on the application of the information suggests a variety of ways:

- "Tree canopy coverage for the jurisdiction or a given area using aerial imagery or LIDAR data.
- Total number of street trees in a site plan, small area, or jurisdiction.
- Spacing of street trees (can be applied as a standard).
- Number of street trees per roadway mile." (FHWA 2016, pg 89)

The FHWA also suggests the following data sources for this performance measure:

- GIS-based inventory of trees.
- Aerial imagery.
- On-site inventory.

Some Example Studies:

- The "City of San Jose Tree Policy Manual and Recommended Best Practices" and "Mapping Urban Forest Structure and Function Using Hyperspectral Imagery and Lidar Data" are two appropriate reference for measuring street trees (Abeyta et al., 2013, Alonzo et al. 2016).