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Authors

Sathaye, Nakul
Horvath, Arpad
Madanat, Samer M

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Nakul Sathaye, Arpad Horvath and Samer Madanat
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Unintended Impacts of Increased Truck Loads on Pavement Supply-chain emissions

Nakul Sathaye[a] (corresponding author)
nsathaye@berkeley.edu, phone: 510-520-9175, fax: 510-642-1246

Arpad Horvath[a]

Samer Madanat[a]

[a]Institute of Transportation Studies, Department of Civil and Environmental Engineering, University of California, 109 McLaughlin Hall, Berkeley, CA 94720-1720

Abstract:

In recent years, the reduction of freight truck trips has been a common policy goal. To this end, policies aimed at influencing load consolidation, load factors and increasing maximum truck weight limits have been suggested and implemented, resulting in higher gross vehicle weights. The purpose of such policies has generally been to mitigate congestion and environmental impacts. However, trucks cause most of the damage incurred by highways pavements. The supply chain associated with pavement maintenance and construction releases significant air emissions, raising the question of whether increased vehicle weights may cause unintended environmental consequences. This paper presents case examples with estimated emissions resulting from shifts in load consolidation and increased maximum weight. These examples indicate that increased load factors in local and long-distance freight movement can cause significant increases in emissions of certain pollutants. Emissions associated with pavement construction are also found to increase as a result of pavement design specifications that account for heavier trucks.

Keywords: City Logistics, Life-Cycle Assessment, Green Logistics, Load Consolidation, Truck Weight

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1. Introduction

The reduction of trips made by freight logistics vehicles has been widely regarded as an indubitable improvement for transportation systems. Policy-makers have implemented a variety of programs and regulations towards this end across the world (Sathaye et al., 2006). In particular, increased vehicle capacity utilization has been an aim strived for through load factor shifts, load consolidation, and increases in maximum vehicle weight.[1]

Many governments around the world have implemented policies and programs directed at increasing loads carried by freight vehicles. Examples can be found in metropolitan areas such as Copenhagen where vehicles are required to meet specific load factor requirements (Geroliminis and Daganzo, 2005). In addition, freight centers for facilitating cargo transfer, often with the aim of consolidating the loads of smaller vehicles, have been constructed for decades in several European countries and Japan (Visser et al., 1999). Some companies have followed this trend, realizing significant savings through reduced fuel consumption (McKinnon, 2003). Maximum vehicle weight limits have also received significant attention and have periodically increased in many countries (Lumsden, 2006). The United Kingdom has raised its regulation from 32.5 to 44 tons over the last 25 years and the European Commission has issued a directive requiring its member countries to permit 40-ton vehicles on their roadways (McKinnon, 2005). Such adaptations are becoming increasingly common as much of the logistics industry has been driven by trends such as just-in-time business, causing a reduction in load factors.

Policy implementations for increasing loads have been promoted by governments, and not without reason, as economic and environmental analyses typically accord full support.

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[1] In this paper the load factor is defined as the fraction of capacity-distance utilized in terms of weight. The term load factor accounts for both empty and laden vehicles unless otherwise described as pertaining only to laden trips. Load consolidation refers to the shifting of cargo between freight vehicles to increase the laden load factor and reduce the number of trips. The maximum truck weight considered in this paper will refer to the laden gross vehicle weight.

Supporting studies often make use of the load factor as a general indicator of the sustainability of a transportation system. The decline of load factors, even in coarse analyses at a national level, is commonly accepted as a detriment, especially with regards to environmental impacts (European Environment Agency, 2000). At the local scale, an increasing load factor is typically associated with economic benefits and the reduction of environmental and traffic congestion problems (Organisation for Economic Co-Operation and Development, 2003). Furthermore, the justification for consolidating loads to larger vehicles in cities is thought to be strengthening as engine noise and vibration from trucks have been reduced, while environmental concerns have been mounting (McKinnon, 2003). Similarly, increased maximum weight limits have been substantiated due to the associated reduction in truck tailpipe emissions (McKinnon, 2005). The importance of these sorts of studies is becoming increasingly apparent as the focus of environmental analyses of transportation is expanding from a focus on passenger vehicles to incorporate freight transportation as well (Facanha and Horvath, 2007).

The aforementioned implementations and studies are representative of the status quo regarding freight logistics policies around the world. However, heavy vehicles not only affect congestion and air quality through their tailpipe emissions, but are also the primary contributors to the deterioration of roadway infrastructure (Small et al., 1989). The infrastructure component of the road freight life cycle can have significant emissions. Multiple pollutants have been found to be released during maintenance, repair and construction, at comparable or greater levels than tailpipe emissions (Facanha and Horvath, 2006).

This paper presents the first study of the effects of logistics policies on emissions in the pavement supply chain. Descriptive case examples of operational shifts made by freight vehicles on California roadways are presented to contrast the benefits and unintended environmental impacts of various policies. Tailpipe and pavement supply-chain emissions are estimated under various paradigms in order to present the effects of pavement within the freight road transportation life cycle, which are neglected in logistics and environmental policy-making. The emissions accounted for are criteria pollutants (PM_{10}, $PM_{2.5}$, SO_2, CO, Pb, NO_x) and greenhouse gases (GHGs). CO_2 is the only GHG from tailpipe emissions as it dominates releases due to fuel combustion. On the other hand, multiple global warming pollutants are significant contributors to pavement supply-chain emissions and are additionally taken into account. Energy consumption is also estimated. Emissions and energy consumption estimates are made for both initial construction and life-cycle overlays of asphalt pavements.

2. Previous Work

Most assessments of the environmental impacts associated with load factor shifts have been constrained to tailpipe emissions. Being at the forefront of environmental concerns, tailpipe CO_2 emissions have received attention in the literature. In London, researchers estimate that a 20% improvement in the load factor of laden vehicles from 0.5 to 0.6 would result in a 17% reduction in annual CO_2 releases from freight vehicles, and that a 20% reduction in empty running would cause these emissions to fall by 8% (Browne and Allen, 1999). In Japan, load factor controls and cooperative transport systems have been assessed for a test road network. Cooperative transport systems involve multiple companies working together to make their logistics operations more efficient. Results indicate that the policy of load factor controls could achieve a 52% reduction in CO_2 tailpipe emissions from freight vehicles, whereas cooperative transport would cause an 18% improvement (Taniguchi and van der Heijden, 2000). Increased load factors can undoubtedly contribute to policies aimed at reducing GHG emissions. However, other pollutants (e.g., criteria air emissions) having local and regional effects should also be considered in policy making.

Transportation agencies in the United States and United Kingdom have devoted significant attention to maximum weight restrictions. Much of this research has been directed towards the analysis of infrastructure and the effects that heavier vehicles would impose. Proposals for the increase of vehicle weight limits are often accompanied by government subsidies or regulations imposed on trucking companies to increase the axles per vehicle, thus potentially reducing infrastructure deterioration (McKinnon, 2005; U.S. Federal Highway Administration, 2000). Though sparse, the research on the environmental effects of increased vehicle weight limits indicates that significant tailpipe emissions reductions can be attained, but thus far only a handful of pollutants have been considered. In the United Kingdom, the increase in maximum vehicle weight from 41 to 44 tons is estimated to have reduced annual PM_{10} emissions by 31.5 tons, NO_x by 884 tons and CO_2 emissions by 135 700 tons in 2003 (McKinnon, 2005). This study is fairly comprehensive and accounts for several indirect effects including modal diversion, the percent of vehicles constrained by volume capacity and increased total demand for freight transport. However, the environmental implications are coarsely estimated without geographical disaggregation which leaves significant questions about the impacts of the PM_{10} and NO_x releases. In the United States emissions are almost entirely neglected from truck weight studies, although fuel consumption has been investigated. The U.S. Department of Transportation (USDOT) has analyzed a hypothetical North American trade scenario focused on facilitating international trade by allowing heavier loads which would fit containers acceding to the International Organization for Standardization limits (U.S. Federal Highway Administration, 2000). The scenario predicts an approximately 6% decrease in energy consumption.

Tailpipe emissions and energy consumption are common indicators of sustainability, however the concept of environmental life-cycle assessment (LCA) has also come to the forefront in the last decade to account for indirect effects. A LCA of freight transportation in the United States reveals that significant emissions result outside the operational phase (Facanha and Horvath, 2006). In fact the majority of emissions of PM_{10}, SO_2, CO, and Pb are found to occur outside the operational phase for road freight transportation. In particular, PM_{10} and SO_2 are found to have significant emissions associated with infrastructure, comprising approximately 75% and 20% of the life-cycle emissions, respectively. A rough estimate of life-cycle emissions, after increasing the truck capacity of large trucks, produces estimates in accordance with these results (Facanha, 2006). Such results give strong indication that there may be unintended environmental impacts when road freight movement is shifted to heavier vehicles.

3. Data and Methodology

Several transportation and environmental data sources are used in conjunction to estimate changes in emissions under various logistics policies. Data are first compiled and processed to estimate changes in freight vehicle traffic. Pavement design and deterioration models are then used to determine the effects of these policies on pavement maintenance and design strategy. Finally, the resulting tailpipe and pavement supply-chain emissions are estimated.

3.1. Estimation of Vehicle Trips and ESALs

Data about vehicle characteristics are necessary to accurately represent changes in freight traffic flows before and after policy implementations. The process used to develop this information involves multiple sources, which are used to classify vehicles and estimate their capacities. Equivalent Single Axle Loads (ESALs) per vehicle are then estimated and a validation procedure is finally applied to adjust the estimates so that they are representative of local vehicle characteristics.

Average annual daily truck counts are provided by the California Department of Transportation (Caltrans) for various locations along California highways (California Department of Transportation, 2007). In this paper, we assume that each location represents traffic on a surrounding highway segment, consisting only of the single roadway. To clarify, peripheral roads such as entrances, exits and cross streets are not included in the assumed segment. The counts are classified by the number of axles, although vehicles with five or more axles are grouped into a single class. Two-axle vehicles, with rating of less than 1.5-tons, or having only two tires on the rear axle are not included in the Caltrans data. All other trucks are included in the counts. The data also provide the number of ESALs occurring per year. The Caltrans data provide a basic description of local freight traffic flows and pavement impacts, but the vehicle classification is relatively coarse. On the other hand, the 2002 Economic Census Vehicle and Use Survey (ECVUS) uses a more refined weight-based vehicle classification system (U.S. Census Department of Commerce, 2004). However, these data are geographically coarse since only state-wide mileage accrual information is available. Accordingly, the vehicle classifications of the two data sources are mapped to provide a more detailed taxonomy for heavy vehicle traffic and its impact on pavement deterioration. The mapping, shown in Table 1, assumes that each ECVUS weight class corresponds to a single Caltrans axle class, and that gross vehicle weight (GVW) increases with the number of axles per vehicle.

Table 1 - Mapping Between Weight and Axle Classes

ECVUS weight class (pounds)	Caltrans axle class
10 001-14 000	2
14 001-16 000	2
16 001-19 500	2
19 501-26 000	2
26 001-33 000	3
33 001-40 000	3
40 001-50 000	4
50 001-60 000	4
60 001-80 000	5+

However, vehicles with five or more axles are not well characterized by this mapping. A different subset of ECVUS data, classified by axles, are applied to apportion the trips of the Caltrans five or more axles class. These traffic counts are allocated between those with five and those with six axles, although vehicles with six axles are comparatively uncommon.

ECVUS data indicate that mileage accrued by five-axle vehicles in California comprises over 97% of miles traveled by vehicles with five or more axles. Six-axle trucks make up most of the remainder and thus the vehicle population with more than six axles is assumed negligible. Note that the term “vehicle class” will refer to those created after the described data mapping and refinement process for the remainder of this paper unless otherwise specified.

Information about vehicle capacities and loads is necessary to estimate the change in the number of trips under a particular policy. Trips are first divided between those that are laden and those that are empty. For the case examples of this paper, unless otherwise specified, 33% of trips for all vehicle classes are assumed to be made empty which is within the range of previous data (Holguin-Veras and Patil, 2005; Holguin-Veras and Thorson, 2003a; U.S. Federal Highway Administration, 1995). A load factor for laden trips (U) of 70% is assumed, in accordance with values found in previous research and data (Department of Transport: London, 2005; Facanha and Horvath, 2006). The product of these two percentages agrees with load factors found in the literature (European Environment Agency, 2006). Other parameters are assumed based on common characteristics for each vehicle class. These parameters are GVW and the ratio (R) of empty weight (EW) to maximum gross vehicle weight (MGVW). The EW is assumed to consist of the vehicle tare weight plus the driver and basic amenities. GVW values are initially assumed to be the average of the minimum and maximum weights for each ECVUS class, before adjustment by the data validation procedure. Values for R are assumed according to common vehicle types found along the highway segment analyzed. Assumed parameter values can be seen in the example presented in Appendix A.

Based on these assumptions, cargo weights (CW) for vehicle classes are derived and applied to determine the changes in the number of trips made under various policies. The CW values for vehicle classes having four or less axles are estimated as follows. Eq. 1 through Eq. 3 are used to derive Eq. 4. From Eq. 4, the calculated value for EW is then substituted into Eq. 2 and Eq. 3 to derive CW and MGVW.

$$U = \frac{CW}{MGVW - EW} \qquad \text{Eq. 1}$$

$$R = \frac{EW}{MGVW} \qquad \text{Eq. 2}$$

$$CW = GVW - EW \qquad \text{Eq. 3}$$

$$EW = \frac{GW}{\frac{U}{R-1} + 1} \qquad \text{Eq. 4}$$

A different procedure is applied to estimate CW for five-axle and six-axle vehicles since the MGVW of these vehicles is generally dictated by government regulations. In contrast to the methodology presented for vehicles with four or less axles, the value for U is not assumed and MGVW is set at 80 000 pounds in accordance with USDOT regulations. Eq. 2 is used to calculate EW. Eq. 1 and Eq. 3 are subsequently used to calculate U and CW, respectively. The value of U for vehicles with five and six axles is used for data validation.

The next step is the estimation of empty and laden ESALs per trip for each vehicle class. This estimation is conducted based on axle configurations for freight vehicles. Reports compiled as part of the Comprehensive Truck Size and Weight Study (U.S. Federal Highway Administration, 1996a; U.S. Federal Highway Administration, 1996b) are used to determine the mileage distribution across axle configuration types for the California vehicle population. For example, two three-axle configurations are commonly found in California. The first is a single-unit truck with tandem rear axles and the second a tractor-semitrailer in which the tractor has front and rear single axles, and the trailer has a single axle. About 59% of 3-axle truck mileage is made by the first configuration and 41% by the second in California (U.S. Federal Highway

Administration, 1996b). The ESALs per vehicle for each configuration are estimated based on GVW and the pavement deterioration fourth power law for each axle group. Eq. 6 presents the formula used for calculating ESALs per vehicle based on the fourth power law. This law is generally accepted in the literature (American Association of State Highway and Transportation Officials, 1993).

$${}_{C}e_{ct,x} = \sum_{g=1}^{G_c} A_{gc} \times \left(\frac{L_{gc,x}}{A_{gc} \times 18\,000}\right)^4 \tag*{Eq. 5}$$

${}_{C}e_{ct,x} = ESALs\ per\ vehicle\ for\ axle\ configuration\ c\ and\ vehicle\ class\ t;\ x\ denotes\ if\ empty\ or\ laden$

$G_c = number\ of\ axle\ groups\ on\ vehicle\ for\ axle\ configuration\ c$

$L_{gc,x} = load\ carried\ by\ axle\ group\ g\ for\ axle\ configuration\ c\ (pounds)$

$A_{gc} = number\ of\ axles\ in\ axle\ group\ g\ for\ axle\ configuration\ c$

Examples of the ESALs per vehicle estimation based on Eq. 5 are presented for two trucks in Appendix B. The mileage distribution for axle configurations in California is then applied to derive an estimate of the ESALs per trip when empty and laden for each vehicle class, by use of Eq. 6. These values for ESALs per trip are used to model pavement deterioration.

$${}_{T}e_{t,x} = \sum_{c=1}^{C_t} {}_{C}f_{ct} \times {}_{C}e_{ct,x} \tag*{Eq. 6}$$

${}_{T}e_{t,x} = ESALs\ per\ vehicle\ for\ vehicle\ class\ t$

${}_{C}f_{ct} = fraction\ of\ vehicle\ mileage\ made\ with\ axle\ configuration\ c\ within\ vehicle\ class\ t$

$C_t = number\ of\ axle\ configuration\ types\ for\ vehicle\ class\ t$

Finally, three validation tests are used to verify the estimates for trips and ESALs per trip. For ease of terminology we will refer to the ESALs estimation process involving Eq. 5 as that based on axle configurations, as opposed to those extracted from the Caltrans data. Eq. 7 is the formula used to compute the weighted average ESALs per trip based on axle configurations for each axle class. The ESALs per trip by axle class are used in the first two validation methods. Note that for this paper there are four axle classes, corresponding to the Caltrans classes as shown in Table 1. Accordingly, although five-axle and six-axle vehicles have different numbers of axles, they are considered to belong to the same axle class.

$$_{N}e_{n} = emp \times \sum_{t=1}^{T_n} {}_{T}f_{tn} \times {}_{T}e_{t,empty} + (1 - emp) \times \sum_{t=1}^{T_n} {}_{T}f_{tn} \times {}_{T}e_{t,laden} \qquad \text{Eq. 7}$$

$_{N}e_{n} = ESALs\ per\ trip\ for\ axle\ class\ n$

$emp = fraction\ of\ vehicles\ traveling\ empty$

${}_{T}f_{tn} = fraction\ of\ vehicles\ belonging\ to\ to\ vehicle\ class\ t\ within\ axle\ class\ n$

$T_n = number\ of\ vehicle\ classes\ within\ axle\ class\ n$

The first test involves a comparison of the estimated ESALs per trip based on axle configurations versus those derived from Caltrans traffic data, for each axle class. The ESALs per trip values derived from Caltrans data are found by solving a linear system of equations that can be created using traffic information for highway segments in the vicinity of the segment being considered. The segments included in the linear system are those which have similar traffic characteristics to the segment analyzed and subsequently are expected to have similar ESALs per trip for each axle class. Eq. 8 displays the linear formula applied for a single segment.

$$\sum_{n=2}^{{}_{A}N} \beta_n \times {}_{N}x_{mn} = {}_{M}e_m \qquad \text{Eq. 8}$$

$\beta_n = \textit{ESALs per trip estimated from Caltrans data for axle class } n$

${}_{N}x_{mn} = \textit{daily trips made by axle class } n \textit{ on highway segment } m$

${}_{M}e_m = \textit{daily ESALs for highway segment } m \textit{ extracted from Caltrans data}$

${}_{A}N = \textit{number of axles in highest axle classes}$

The linear system has as independent variables the trips for each axle class and as dependent variable the total ESALs, which are extracted from Caltrans data. The parameters estimated are the ESALs per trip for each axle class. The system is either solved exactly in the case that four highway segments in the vicinity are included since Caltrans trip data have four axle classes, or a least squares solution is obtained with the inclusion of five or more segments. In either case, Eq. 9, which is in the form of the commonly known least squares solution, is applied to solve the linear system.

$$\bar{\beta} = (\bar{x}' \cdot \bar{x})^{-1} \cdot \bar{x}' \cdot \bar{e} \qquad \text{Eq. 9}$$

$\bar{\beta} = (\ {}_{(}N - 1) \times 1 \textit{ column vector of ESALs per trip estimated from Caltrans data}$

$\qquad (\textit{contains values for } \beta_n)$

$\bar{x} = M \times (\ {}_{A}N - 1) \textit{ matrix of trips } (\textit{contains values for } {}_{N}x_{mn})$

$\bar{e} = M \times 1 \textit{ column vector of Daily ESALs } (\textit{contains values for } {}_{M}e_m)$

$M = \textit{number of highway segments included in linear system}$

The derived estimates for ESALs per trip based on the Caltrans data are then compared against the weighted average ESALs per trip based on axle configurations for each axle class. The percent difference between the ESALs based on axle configurations and those estimated from

Caltrans data for each axle class are then calculated using Eq. 10. The aim of the validation process is to ensure that the difference is minimal for each axle class.

$$\%Diff_n = 100\% \times \frac{{}_{N}e_n - \beta_n}{\beta_n} \qquad \text{Eq. 10}$$

$\%Diff_n = percent\ difference\ in\ ESALs\ per\ trip\ for\ axle\ class\ n$

The second validation test involves a comparison between the total ESALs based on axle configurations versus that specified in Caltrans data. This is conducted for highway segments in the vicinity of that under consideration. As with the first validation, the segments selected for inclusion in this validation are those that have similar traffic characteristics to the segment analyzed. This validation ensures that the difference between total ESALs based on axle configurations and that specified in Caltrans data for each included segment are minimal. Eq. 11 is for the calculation of the percent difference in total ESALs.

$$\%Diff_m = 100\% \times \frac{\left(\sum_{n=2}^{{}_{A}N} {}_{N}e_n \times {}_{N}x_{mn}\right) - {}_{M}e_m}{{}_{M}e_m} \qquad \text{Eq. 11}$$

$\%Diff_m = percent\ difference\ in\ total\ ESALs\ on\ highway\ segment\ m$

Data verified by the first validation test are likely to agree with the second validation test. However, the number of segments included in the linear system is relatively small in most cases. Therefore, the second validation is included to prevent the possibility that the ESALs per trip estimates based on Caltrans data are greatly affected by outliers, and to verify that the included segments carry traffic with similar characteristics.

The third validation test confirms the process for calculating CW for the vehicles with five or more axles. The calculated values of U, based on Eq. 1, must be near a priori expectations about the laden load factor. As aforementioned, we assumed these values to be near 70% in this research.

GVW and trip distribution within each axle class are adjusted so that the estimated data are in accordance with the three validation tests. GVW is selected as a variable for adjustment since the mapping of state-wide ECVUS data to localized Caltrans data is inexact. Thus, representative GVW values for ECVUS weight classes are likely to differ from one location to another. The mileage distribution across California is not equivalent across highway segments, making the trip distribution appropriate for adjustment. Adjustments are made until values for $\%Diff_n$, $\%Diff_m$ are considered to be reasonably low, passing the first two validations, and U for five-axle and six-axle vehicles passes the third validation test. Calculated values of GVW, MGVW, EW and CW must also conform to expectations for local traffic.

Although a variety of different assumptions could be made to obtain the traffic and ESALs estimates, the methodology used in this paper relies on verifiable information from government agencies and previous research, thus allowing for validation methods to ensure that the assumptions made are reasonable for each highway segment analyzed. Appendix A provides an example of the methodology applied to California State Route 13 (SR-13).

3.2. Pavement Design and Deterioration

The estimated ESALs per trip for each vehicle class are applied in conjunction with pavement design and deterioration models to determine the change in overlay frequency. The Caltrans Highway Design Manual (HDM) is followed for pavement design (California Department of Transportation, 2006b). The manual specifies the aggregate subbase (AS), aggregate base (AB) and hot-mix asphalt (HMA) surface thicknesses for a flexible pavement. These are based on variables such as subgrade material and a design ESALs value. In this paper, we assume that all pavements are constructed using this three-layer design. An example of pavement design by this method is presented in Appendix C. Once the pavement is designed, its structural number (SN) can be determined. The SN is calculated according to an equation provided by the American Association of Highway Officials (AASHO) as shown in Eq. 12 (Small et al., 1989).

$$SN = 0.44 \times T_{HMA} + 0.14 \times T_B + 0.11 \times T_{SB} \qquad \text{Eq. 12}$$

$SN = pavement\ structural\ number$

$T_{HMA} = HMA\ surface\ layer\ thickness\ (inches)$

$T_B = base\ thickness\ (inches)$

$T_{SB} = subbase\ thickness\ (inches)$

The SN is then applied in a pavement deterioration model to determine the overlay frequency. The deterioration model applied in this research is an AASHO equation that has undergone multiple revisions due to prior flaws in the statistical estimation process. The model, provided by Madanat and Prozzi, corrects these flaws and is used to calculate the expected number of ESALs to failure for a pavement segment (Madanat et al., 2002). This model is exhibited in Eq. 13. For this model, pavement failure is defined as unacceptable ride quality.

$$E[\rho] = exp(12.15 + 6.68 \times \ln(SN + 1) + 2.62 \times \ln(L_2) - 3.03 \times \ln(L_1 + L_2)) \qquad \text{Eq. 13}$$

$\rho = ESALs\ to\ failure$

$L_1 = standard\ axle\ load = 18\ kips$

$L_2 = dummy\ variable = \begin{cases} 1\ for\ single\ axles \\ 2\ for\ tandem\ axles \end{cases}$

In the case examples of this paper we assume that maintenance policy affects only the frequency of three-inch HMA overlays. This is the minimum thickness specified by the HDM in response to unacceptable ride quality (California Department of Transportation, 2006b). The years between overlays is the ratio of the expected value of ESALs to failure, obtained by using Eq. 13, and the annual ESALs on a roadway segment. An example showing the estimation of years between SR-13 overlays is presented in Appendix C.

3.3.Tailpipe Emissions

Tailpipe emission factors are estimated by two models. The California Air Resources Board's EMFAC2007 v2.3 (California Air Resources Board, 2006) and the U.S. Environmental Protection Agency's (EPA) MOBILE6.2 (U.S. Environmental Protection Agency, 2006c). Inputs are customized to the local climate, government regulations, roadway types, average speeds, and local vehicle age and mileage profiles.

The reasons for using two models are twofold. First, the vehicle classes based on the data estimation presented in section 3.1 and those of the emissions factors models do not represent exactly corresponding GVW values. Consequently, interpolation is used to map vehicle classes to emission factor classes. Second, the models may not utilize accurate representations of driving patterns or vehicle types for a particular segment of highway. For example, EMFAC2007 weight classes are based on GVW and the model uses an area-wide unified driving cycle, whereas heavy-duty classes in MOBILE6.2 are based on MGVW, and the model employs cycles differentiated by roadway type. The application of the two models provides a range for comparison against emissions from the pavement supply chain.

NO_x emissions for heavy-duty vehicles have additionally been found to generally change by half the percentage increase in weight (Gajendran and Clark, 2003). This correction is incorporated when accounting for emissions factors for vehicles with GVW heavier than the average of the minimum and maximum weights of the heaviest EMFAC2007 and MOBILE6.2 vehicle classes. Interpolation is used for smaller vehicles. Weight correction factors are not introduced for other pollutants since broadly applicable factors have not been reported in the literature. Appendix D presents the tailpipe emissions factors used for SR-13.

3.4. Pavement Supply-chain emissions

The estimation of pavement supply-chain emissions involves the integration of multiple data sources. The most comprehensive LCA tool for pavements, the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) provides the basis for developing emissions factors (Horvath, 2008). However, several augmentations have been made to compile a more comprehensive portfolio of emissions which is representative of local conditions. This section provides an overview of the emissions estimation process and Appendix E presents further details.

The emissions estimated in PaLATE can be divided between those associated with materials transportation, paving equipment, and the supply chain for materials. EMFAC2007 is used to estimate tailpipe emissions from trucks transporting materials. In addition, these trucks are assumed to have diesel engines, so Carnegie Mellon University’s economic input-output analysis-based life-cycle assessment (EIO-LCA) tool is used to estimate diesel supply-chain emissions (EIO-LCA, 2008). EIO-LCA provides emissions factors for economic sectors in the United States as classified in the Department of Commerce 1997 benchmark input-output data. Emissions associated with paving equipment are entirely based on factors found in PaLATE.

The materials supply-chain emissions can be divided between those from HMA plants, and aggregate and bitumen production. PaLATE uses detailed emissions factors for HMA plants and also particulate releases during aggregate storage, screening and conveyance. On the other hand, corresponding to a hybrid LCA, PaLATE relies on EIO-LCA for the rest of emissions associated with the aggregate supply chain and also for bitumen.

Although most pollutants of interest for this paper are available in EIO-LCA, $PM_{2.5}$ is excluded. In recent years, the importance of estimating fine particulate emissions for assessing human health impacts has become commonly accepted. Accordingly, a procedure has been developed and applied to append $PM_{2.5}$ emissions to the EIO-LCA results. This procedure parallels that used to estimate PM_{10} emissions as described in EIO-LCA documentation (Cicas et al., 2006). The main data sources for particulate emission factors are AirDATA (U.S. Environmental Protection Agency, 2007) and the National Air Quality Emissions Trends Report (U.S. Environmental Protection Agency, 2001), from which information is extracted to obtain facility and comprehensive sectoral emissions, respectively. The procedure applies these data to calculate the ratio of $PM_{2.5}$ to PM_{10} releases for each input-output economic sector. These ratios are then multiplied by the PM_{10} emissions from EIO-LCA to obtain $PM_{2.5}$ factors.

The compiled pavement supply chain emission factors are then applied to both pavement overlays and reconstruction. Table 2 presents the emissions associated with a three-inch, two-lane, one-mile HMA overlay, which is assumed to be used for SR-13. Appendix E describes the estimation of these emissions factors. Note that GHG emissions are represented by global warming potential (GWP) in CO_2 equivalent units as described in EIO-LCA documentation (Cicas et al., 2006). Primary contributors to GWP in the pavement supply chain include CO_2, CH_4 and N_2O.

Table 2 - HMA Overlay Emissions for One Direction on a Two-Lane Highway

PM_{10} (MT)	0.42
$PM_{2.5}$ (MT)	0.14
SO_2 (MT)	1.0
CO (MT)	1.7
Pb (kg)	0.11
NO_x (MT)	0.77
GWP (MT CO_2 eq.)	560
Energy (TJ)	6.6

4. Case Examples

This section presents hypothetical operational shifts and their impacts for freight vehicles on two highway segments in Berkeley, California. The first highway segment is on SR-13 near its intersection with SR-123. It constitutes a local commercial arterial which also passes through residential neighborhoods, and services a significant proportion of smaller trucks. In contrast, the second segment lies on U.S. Interstate 80 (I-80) near its intersection with SR-13, where the majority of freight vehicles have five or more axles and are generally proceeding on long-distance trips to or from the Port of Oakland. Both of the analyzed highway segments are one mile in length and all results are for one direction of traffic and pavement. Several operational shifts will be considered including consolidation of loads within each vehicle class, consolidation from small to large vehicles on SR-13, the effects of loading under increased maximum weight on I-80 and the reduction of empty truck trips.

4.1.Consolidation within Vehicle Classes

Governments and international agencies have generally encouraged increases in load factors (European Environment Agency, 2006). In accordance with this sentiment, load factor requirements have been considered and implemented in some cities, but this is typically done without consideration for the sizes of vehicles involved (Geroliminis and Daganzo, 2005). Table 3 through Table 5 present the results of shifting loads on SR-13 so that 100% of vehicles are fully laden, without any transfer of cargo across vehicle classes. Most of the pollutant emissions associated with overlays are within the same order of magnitude to those of tailpipe emissions. In particular, SO_2 is found to be dominated by overlay emissions and the drop in particulate tailpipe emissions is greatly offset by those from overlays. These results indicate that blindly imposing load factor controls in urban areas can cause significant increases in pavement supply-chain emissions.

Table 6 through Table 8 present the results of the same policy applied to I-80. Again SO_2 tailpipe emissions are far less than those from overlays. However, in this case the tailpipe emissions for other pollutants are generally much more than those associated with overlays since a much higher fraction of five-axle trucks travel this highway.

Table 3 - SR-13 Change in Overlay Frequency after Within Class Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day
Status Quo	0%	0%	23.3	49
After Shift	100%	46%	15.9	72

Table 4 - SR-13 Changes in Trips after Within Class Consolidation

Axle class	2-axle trips/day	3-axle trips/day	4-axle trips/day	5-axle trips/day	6-axle trips/day
Status Quo	212.5	37.0	8.0	17.6	0.4
After Shift	148.8	25.9	5.6	11.8	0.3

Table 5 - SR-13 Change in Emissions after Within Class Consolidation

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM$_{10}$ (MT/yr)	0.025	0.019	0.018	PM$_{2.5}$ (MT/yr)	0.023	0.015	0.0062
After Shift		0.017	0.013	0.026		0.016	0.011	0.0091
Difference		-0.008	-0.006	0.008		-0.007	-0.005	0.0029
Status Quo	NO$_x$ (MT/yr)	0.78	0.56	0.033	CO (MT/yr)	0.61	0.83	0.074
After Shift		0.54	0.39	0.048		0.43	0.58	0.11
Difference		-0.24	-0.17	0.015		-0.19	-0.25	0.03
Status Quo	SO$_2$ (MT/yr)	0.0011	0.0013	0.044	Pb (kg/yr)			0.0046
After Shift		0.00076	0.00090	0.064				0.0067
Difference		-0.0003	-0.0004	0.020				0.0021
Status Quo	Energy (TJ/yr)	1.5	1.6	0.28	GWP (MT CO$_2$ eq./yr)	110	110	24
After Shift		1.1	1.1	0.41		79	79	35
Difference		-0.5	-0.5	0.13		-31	-31	11

Table 6 - I-80 Change in Overlay Frequency after Within Class Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day
Status Quo	0%	0%	8.8	2 688
After Shift	100%	63%	5.4	4 391

Table 7 - I-80 Changes in Trips after Within Class Consolidation

Axle class	2-axle trips/day	3-axle trips/day	4-axle trips/day	5-axle trips/day	6-axle trips/day
Status Quo	1645.0	468.3	187.3	2339.8	57.0
After Shift	1151.5	327.8	131.1	1567.7	39.8

Table 8 - I-80 Changes in Emissions after Within Class Consolidation

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM_{10} (MT/yr)	0.88	0.68	0.094	$PM_{2.5}$ (MT/yr)	0.80	0.57	0.032
After Shift		0.59	0.46	0.15		0.54	0.39	0.053
Difference		-0.28	-0.22	0.06		-0.26	-0.18	0.021
Status Quo	NO_x (MT/yr)	36	25	0.17	CO (MT/yr)	9.1	7.6	0.39
After Shift		24	17	0.28		6.2	5.2	0.64
Difference		-12	-8.0	0.11		-2.9	-2.4	0.25
Status Quo	SO_2 (MT/yr)	0.031	0.034	0.23	Pb (kg/yr)			0.024
After Shift		0.021	0.023	0.38				0.040
Difference		-0.010	-0.011	0.15				0.015
Status Quo	Energy (TJ/yr)	43	47	1.5	GWP (MT CO_2 eq./yr)	3 200	3 400	100
After Shift		29	32	2.4		2 200	2 300	200
Difference		-14	-15	0.9		-1 000	-1 100	100

4.2.Consolidation to Larger Freight Vehicles for Local Freight Movement

Urban freight centers have received significant attention from researchers, especially in conjunction with load consolidation for local carriers (Browne et al., 2005). This sort of traffic is represented by that on SR-13, which is an arterial passing through multiple commercial areas. Table 9 and Table 10 present the results of load consolidation from two-axle to three-axle vehicles, whereas Table 11 and Table 12 present the results of load consolidation from two-axle to five-axle vehicles. The emissions associated with pavements are far greater after a shift to five-axle vehicles than to three-axles. However, tailpipe emissions are also much more significantly reduced, revealing a trade-off for policy-making. Policy decisions involving vehicle size are further complicated by the increased use of diesel engines for heavier vehicle classes. The fraction of mileage traveled by diesel vehicles in Alameda County, which contains SR-13, is about 41% for the smallest two-axle vehicle class, 89% for the smallest three-axle class, and 96% for five-axle vehicles (California Air Resources Board, 2006). Subsequently, the reductions in tailpipe particulate and NO_x emissions are not nearly as great as those for other pollutants. In fact, EMFAC2007 predicts an increase in particulate emissions resulting from load consolidation to three-axle vehicles. It should be noted that in general the results for the shift to five-axle vehicles are likely to be conservative estimates since the vehicle classification used in this research does not differentiate amongst the weights for the largest vehicles for which pavement damage would be greatly affected by the fourth power law.

Table 9 - SR-13 Changes in Overlay Frequency and Trips after 2-axle to 3-axle Load Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	2-axle trips/day	3-axle trips/day
Status Quo	0%	0%	23.3	49	212.5	37
After Shift	100%	11%	20.9	55	0	104.2

Table 10 - SR-13 Changes in Emissions after 2-axle to 3-axle Load Consolidation

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM_{10} (MT/yr)	0.025	0.019	0.018	$PM_{2.5}$ (MT/yr)	0.023	0.015	0.0062
After Shift		0.029	0.015	0.020		0.026	0.013	0.0069
Difference		0.004	-0.004	0.002		0.004	-0.003	0.0007
Status Quo	NO_x (MT/yr)	0.67	0.56	0.033	CO (MT/yr)	0.61	0.83	0.074
After Shift		0.63	0.44	0.037		0.35	0.30	0.082
Difference		-0.04	-0.13	0.004		-0.26	-0.53	0.008
Status Quo	SO_2 (MT/yr)	0.0011	0.0013	0.044	Pb (kg/yr)			0.0046
After Shift		0.00080	0.00069	0.049				0.0051
Difference		-0.0003	-0.0006	0.005				0.0005
Status Quo	Energy (TJ/yr)	1.5	1.6	0.28	GWP (MT CO_2 eq./yr)	110	110	24
After Shift		1.1	0.9	0.32		84	69	27
Difference		-0.4	-0.6	0.03		-26	-41	3

Table 11 - SR-13 Changes in Overlay Frequency and Trips after 2-axle to 5-axle Load Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	2-axle trips/day	5-axle trips/day
Status Quo	0%	0%	23.3	49	212.5	17.6
After Shift	100%	20%	19.4	59	0	44.0

Table 12 - SR-13 Changes in Emissions after 2-axle to 5-axle Load Consolidation

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM_{10} (MT/yr)	0.025	0.019	0.018	$PM_{2.5}$ (MT/yr)	0.023	0.015	0.0062
After Shift		0.024	0.011	0.021		0.022	0.009	0.0074
Difference		0.000	-0.008	0.004		0.000	-0.006	0.0012
Status Quo	NO_x (MT/yr)	0.65	0.56	0.033	CO (MT/yr)	0.61	0.83	0.074
After Shift		0.54	0.33	0.04		0.28	0.19	0.089
Difference		-0.13	-0.24	0.01		-0.33	-0.65	0.015
Status Quo	SO_2 (MT/yr)	0.0011	0.0013	0.044	Pb (kg/yr)			0.0046
After Shift		0.00060	0.00048	0.053				0.0055
Difference		-0.0005	-0.0008	0.009				0.0009
Status Quo	Energy (TJ/yr)	1.5	1.6	0.28	GWP (MT CO_2 eq./yr)	110	110	24
After Shift		0.9	0.7	0.34		63	50	29
Difference		-0.7	-0.9	0.06		-47	-60	5

4.3.Increasing Maximum Weight

Several scenarios involving increases in maximum vehicle weight regulations in the United States have been discussed. For instance, a North American trade scenario has been suggested in which weight limits are increased to enhance international trucking productivity in the United States (U.S. Federal Highway Administration, 2000). The suggested regulations would set the tridem axle weight limit to 44 000 pounds, affecting multiple truck types. In particular, the case of shifting cargo from five-axle to six-axle vehicles with an increase in maximum GVW limit to 90 000 pounds is analyzed. Table 13 and Table 14 show that pavement deterioration and associated emissions can be greatly reduced by distributing loads across multiple axles. On the other hand, Table 15 and Table 16 indicate that load consolidation for heavy vehicles hastens pavement deterioration, despite the increased axles per vehicle. Table 17 and Table 18 show that this problem is greatly exacerbated by the suggested increase in maximum GVW to 90 000 pounds. Clearly, policies for reducing pavement deterioration are in line with those for reducing pavement supply change emissions, however, increased maximum weights should be more carefully considered if increased load factors are also a goal.

Table 13 – I-80 Changes in Overlay Frequency and Trips after Shift from 5-axle to 6-axle Trucks

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	5-axle trips/day	6-axle trips/day
Status Quo	0%	0%	8.8	2 688	2 339.8	57.0
After Shift	100%	-20%	11.0	2 149	0	2 396.8

Table 14 - I-80 Changes in Emissions after Shift from 5-axle to 6-axle trucks

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM_{10} (MT/yr)	0.88	0.68	0.094	$PM_{2.5}$ (MT/yr)	0.80	0.57	0.032
After Shift		0.88	0.68	0.075		0.80	0.57	0.026
Difference		0.00	0.00	-0.019		0.00	0.00	-0.006
Status Quo	NO_x (MT/yr)	32	25	0.17	CO (MT/yr)	9.1	7.6	0.39
After Shift		32	25	0.14		9.1	7.6	0.31
Difference		0	0	-0.03		0.0	0.0	-0.08
Status Quo	SO_2 (MT/yr)	0.031	0.034	0.23	Pb (kg/yr)			0.024
After Shift		0.031	0.034	0.19				0.019
Difference		0.000	0.000	-0.05				-0.005
Status Quo	Energy (TJ/yr)	43	47	1.5	GWP (MT CO_2 eq./yr)	3 200	3 400	130
After Shift		43	47	1.2		3 200	3 400	100
Difference		0	0	-0.3		0	0	-30

Table 15 - I-80 Changes in Overlay Frequency and Trips after Shift from 5-axle to 6-axle, 80 000-lb Trucks

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	5-axle trips/day	6-axle 80 000-lb trips/day
Status Quo	0%	0%	8.8	2 688	2 339.8	0
After Shift	100%	11%	7.9	2 996	0	1 633.0

Table 16 - I-80 Changes in Emissions after Shift from 5-axle to 6-axle, 80 000-lb Trucks

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM$_{10}$ (MT/yr)	0.88	0.68	0.094	PM$_{2.5}$ (MT/yr)	0.80	0.57	0.032
After Shift		0.67	0.55	0.10		0.62	0.46	0.036
Difference		-0.21	-0.13	0.011		-0.19	-0.11	0.004
Status Quo	NO$_x$ (MT/yr)	32	25	0.17	CO (MT/yr)	9.1	7.6	0.39
After Shift		27	22	0.19		7.5	6.7	0.43
Difference		-5	-3	0.02		-1.6	-0.9	0.04
Status Quo	SO$_2$ (MT/yr)	0.031	0.034	0.23	Pb (kg/yr)			0.024
After Shift		0.025	0.028	0.26				0.027
Difference		-0.006	-0.005	0.03				0.003
Status Quo	Energy (TJ/yr)	43	47	1.5	GWP (MT CO$_2$ eq./yr)	3 200	3 400	130
After Shift		35	39	1.7		2 600	2 800	140
Difference		-8	-8	0.2		-600	-600	10

Table 17 - I-80 Changes in Overlay Frequency and Trips after Shift from 5-axle to 6-axle, 90 000-lb Trucks

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	5-axle trips/day	6-axle 90 000-lb trips/day
Status Quo	0%	0%	8.8	2 688	2 339.8	0
After Shift	100%	54%	5.7	4 151	0	1 451.6

Table 18 - I-80 Changes in Emissions after Shift from 5-axle to 6-axle, 90 000-lb Trucks

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM$_{10}$ (MT/yr)	0.88	0.68	0.094	PM$_{2.5}$ (MT/yr)	0.80	0.57	0.032
After Shift		0.62	0.52	0.15		0.57	0.43	0.050
Difference		-0.26	-0.16	0.05		-0.24	-0.14	0.018
Status Quo	NO$_x$ (MT/yr)	32	25	0.17	CO (MT/yr)	9.1	7.6	0.39
After Shift		26	21	0.26		7.1	6.5	0.60
Difference		-5	-4	0.09		-2.0	-1.1	0.21
Status Quo	SO$_2$ (MT/yr)	0.031	0.034	0.23	Pb (kg/yr)			0.024
After Shift		0.024	0.027	0.36				0.037
Difference		-0.007	-0.007	0.13				0.013
Status Quo	Energy (TJ/yr)	43	47	1.5	GWP (MT CO$_2$ eq./yr)	3 200	3 400	130
After Shift		33	37	2.3		2 400	2 600	190
Difference		-10	-10	0.8		-800	-800	60

4.4. Empty Running

Multiple studies have been conducted to investigate and model empty truck travel (Holguin-Veras and Thorson, 2003b; McKinnon and Ge, 2006). A reduction in empty running can ubiquitously reduce emissions. However, the effects on pavement supply-chain emissions are much less pronounced since the pavement damage caused by an empty vehicle is far less than when it is laden. Thus, for cases in which environmental impacts are particularly sensitive to emissions from facilities in the pavement supply chain, policy-making should be focused on vehicle weight instead of empty trips. Table 19 through Table 21 display the results of eliminating all empty trips from I-80.

Table 19 - I-80 Change in Overlay Frequency after a Reduction in Empty Running

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day
Status Quo	0%	0%	8.8	2 688
After Shift	100%	-9%	9.6	2 457

Table 20 - I-80 Changes in Trips after a Reduction in Empty Running

Axle class	2-axle trips/day	3-axle trips/day	4-axle trips/day	5-axle trips/day	6-axle trips/day
Status Quo	1 645.0	468.3	187.3	2 339.8	57.0
After Shift	1 096.7	312.2	124.8	1 559.9	38.0

Table 21 - I-80 Changes in Emissions after a Reduction in Empty Running

		EMFAC2007	MOBILE6.2	Overlay		EMFAC2007	MOBILE6.2	Overlay
Status Quo	PM_{10} (MT/yr)	0.88	0.68	0.094	$PM_{2.5}$ (MT/yr)	0.80	0.57	0.032
After Shift		0.58	0.45	0.086		0.54	0.38	0.030
Difference		-0.29	-0.23	-0.008		-0.27	-0.19	-0.003
Status Quo	NO_x (MT/yr)	32	25	0.17	CO (MT/yr)	9.1	7.6	0.39
After Shift		21	17	0.16		6.1	5.1	0.36
Difference		-11	-8	-0.01		-3.0	-2.5	-0.03
Status Quo	SO_2 (MT/yr)	0.031	0.034	0.23	Pb (kg/yr)			0.024
After Shift		0.021	0.022	0.21				0.022
Difference		-0.010	-0.011	-0.02				-0.002
Status Quo	Energy (TJ/yr)	43	47	1.5	GWP (MT CO_2 eq./yr)	3 200	3 400	130
After Shift		29	31	1.4		2 100	2 300	120
Difference		-14	-16	-0.1		-1 100	-1 100	-10

4.5. Pavement Reconstruction

Although pavement reconstruction occurs far less frequently than maintenance activities, logistics policies can also indirectly affect pavement designs. A policy that increases the weight of freight vehicles is likely to induce pavement engineers to design stronger pavements. The subsequent increase in materials usage or change in type can greatly influence environmental impacts, as natural resource consumption and associated emissions are significant for pavement construction (Horvath, 2003; Horvath and Hendrickson, 1998). Table 22 displays flexible pavement designs for I-80, following the HDM. The current design is for status quo traffic and the new design accounts for increased ESALs due to the policy of load consolidation within vehicle classes, as presented in Table 7. Table 23 contains the associated changes in emissions. Accordingly, countries with aging roadways such as the United States, and also areas which are being newly developed are likely to incur increased emissions from the pavement supply chain if freight vehicles are expected to travel with heavier loads.

Table 22 - I-80 Pavement Designs

	Current	New
HMA surface (inches)	7.9	8.5
Base (inches)	8.1	8.7
Subbase (inches)	10.1	10.9

Table 23 - I-80 Emissions Associated with Pavement Reconstruction

	PM10 (MT)	PM2.5 (MT)	SO2 (MT)	CO (MT)	Pb (kg)	NOx (MT)	GWP (MT CO_2 eq./yr)	Energy (TJ)
Current Design	3.0	1.05	4.0	0.70	6.8	6.7	3 600	46
New Design	3.2	1.12	4.2	0.75	7.2	7.2	3 800	49

5. Discussion

Policies inducing increased loads can reduce emissions in many cases. However, confounding effects also exist. Emissions of CO and NO_x are likely to be greatly reduced by any form of consolidation as the supply-chain effects are comparatively small. On the other hand, the other pollutants analyzed have comparable tailpipe and overlay emissions for roads with freight traffic comprised mainly of smaller vehicles, indicating the potential for significant unintended emissions. SO_2 emissions are the most apparent unintended effect. In the United States, increased vehicle weights are likely to greatly counteract the reduced SO_2 tailpipe emissions resulting from the introduction of ultra-low sulfur diesel. Furthermore, tailpipe emission factors for certain pollutants are expected to drop significantly in coming years as aging vehicles are replaced and emissions controls technologies are implemented. For example, EMFAC2007 predicts that average fleet emissions factors for SR-13 traffic for NO_x and CO will decrease by around 70%, and for PM_{10} and $PM_{2.5}$ by around 80% between 2008 and 2020. Accordingly, logistics policy analyses in many locations are likely to benefit greatly from a shift in focus on tailpipe emissions alone to additionally account for those of the pavement supply chain.

Regardless of the difference between tailpipe and pavement supply-chain emissions, environmental impacts may be prevalent due to proximity to sensitive areas and the local atmosphere in which the releases occur. The impacts can be quantified by the intake fraction (Bennett et al., 2002). This metric is defined as the ratio of mass taken in by people to the total mass of emissions for a particular pollutant. Therefore, the intake fraction is much higher for vehicles passing through a densely populated city versus along a rural route. Although only emissions are estimated in this paper, the inclusion of the intake fraction would provide a quantitative tool for a more complete assessment.

Nevertheless, a qualitative assessment of the potential for exposure reveals much about possible environmental impacts. Much of SR-13 lies in a residential neighborhood making tailpipe emissions particularly impacting. This is likely to be the case for many areas where urban load consolidation is suggested as a policy measure, as these are typically in commercial or residential areas having fairly dense populations. Of course, materials transportation for pavement maintenance is likely to follow a similarly impacting route, but the proximity of facilities such as HMA plants, sand and gravel mines, and petroleum refineries can differ. In the case of SR-13, the EPA’s AIRdata shows that several facilities lie in highly sensitive areas (U.S. Environmental Protection Agency, 2007). The nearest sand and gravel mine can be found not far from residences in the City of Pleasanton. Nearby refineries are stationed in the City of Richmond, which has been referred to as Contra Costa County’s “cancer belt” (Tamminen, 2006). An asphalt plant can be found within 200 meters of residences in Berkeley. This would seem to indicate with strong likelihood that trade-offs exist for load consolidation policy-making in many cases. Proximity to sensitive areas can similarly affect the implications of load factor increases for long-distance transport. For example, much of the I-80 route in Solano County, lying to the north of Berkeley, is in a sparsely populated area potentially rendering the local impacts of tailpipe emissions negligible for policy-making. Thus, although highways servicing traffic flows with a significant proportion of large vehicles may have comparatively low pavement supply-chain emissions, the impacts may be severe depending on the intake fraction near associated facilities.

Emissions may greatly differ depending on the type of maintenance and reconstruction strategy a local transportation authority employs. Although 3-inch HMA overlays have been assumed in this research, pavement engineers use a variety of repair methods. Additionally, several different types of materials can be included for pavement maintenance and construction, with each having different supply-chain emissions characteristics. For instance, the use of steel as reinforcement is likely to cause significantly higher GHG and Pb releases, as evinced by the high corresponding emissions factors in EIO-LCA (EIO-LCA, 2008).

Broadening the scope of emissions and sources considered in freight logistics, policy development may present new trade-offs, but the case examples indicate that some policies are very unlikely to cause unintended impacts. For instance, Table 21 shows that a reduction in empty trips is found to reduce emissions associated with tailpipe and the pavement supply chain. This is in contrast to some past studies which found that load consolidation for laden vehicles is more effective for mitigation of environmental impacts than reductions in empty trips (Browne and Allen, 1999). Empty running policies are likely to be more useful for heavier vehicles making longer trips since time constraints are less restrictive and both origins and destinations are more likely to supply cargo for transport. Another change that reduces overlay emissions is the increased number of axles per vehicle. As has been known for decades by pavement engineers, increasing the number of axles on heavy vehicles greatly slows pavement deterioration due to the reduction in ESALs. In turn, associated environmental impacts are also lessened.

The nuances of particular policy implementations and policies, other than those analyzed in this paper, may also contribute to changing the load factors and sizes of vehicles used by freight logistics operators. As highlighted by the results of load consolidation on SR-13, the selection of freight vehicle size to which consolidation occurs can greatly influence emissions. In this case it may be deemed more beneficial to consolidate loads into three-axle than five-axle vehicles in order to curb the unintended effects incurred by those in the vicinity of facilities of the pavement supply chain. These effects are also likely to alter assessments of logistics supply chains and geographical retail consolidation. Such consolidation has been shown to be environmentally damaging due to increased tailpipe emissions occurring during passenger automobile trips between stores and homes (McKinnon and Woodburn, 1994). However, the effect of lightweight vehicles on pavement deterioration and associated emissions is nearly negligible, so the reduction in heavy vehicle travel may be more beneficial. Other policies may also have indirect effects on vehicle weights. For example, timing restrictions may induce freight carriers to consolidate loads into larger vehicles in order to fulfill cargo requirements within designated time constraints, resulting in hastened pavement deterioration. On the other hand, restrictions on heavy vehicles may cause companies to utilize smaller vehicles to circumvent regulations, resulting in reversed trade-offs for policy making (Campbell, 1995; Castro et al., 2003). The impacts of such operational shifts on pavement construction and maintenance should be considered in logistics policy making.

The specification of the LCA system boundaries can greatly influence results. This paper has employed a comprehensive methodology by incorporating pavement supply-chain emissions in addition to tailpipe, however there may be additional unintended impacts. For example, emissions of SO_2, CO and Pb associated with truck manufacturing, maintenance, and end of life have been found to comprise a significant fraction of life-cycle trucking emissions (Facanha, 2006). Accordingly, these results additionally raise the question of how increased vehicle weights would impact emissions in these phases of the life cycle.

Freight logistics policy-making with account of environmental impacts is a multi-faceted process. The analysis of this paper is presented to add another piece and to contribute to the development of a methodology which can be applied to provide more comprehensive environmental assessments of policies that influence the weight of freight logistics vehicles. These considerations should be incorporated on a case-by-case basis as policy needs arise.

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Appendix A. Traffic and ESALs Data Estimation

Table A.1 presents the results of the methodology presented in section 3.1, for the status-quo case on SR-13. Each column represents a different vehicle class, which can be distinguished by the assumed values of GVW in the first row. For this highway segment, many of the GVW values have been adjusted downward from initially being the average of the minimum and maximum values for their corresponding ECVUS weight classes. The adjustments for the GVW values are done in increments of 250 pounds until the validation tests are passed. Each GVW still falls within and represents a weight range displayed in Table 1. The second row of Table A.1 displays the corresponding axle class and the third row contains assumed values for R.

The next four rows are produced according to Eq. 1 through Eq. 4, although as stated, U is only calculated for the heaviest vehicles. These values of U for the five-axle and six-axle vehicles classes fit within a priori expectations, thus passing the third validation test. The 8th row shows the daily one-way trips classified by axles, which were extracted from Caltrans data, whereas the 9th row exhibits the daily trip distribution within each axle class, after data validation and adjustment has been conducted. In this case, the proportion of trips traveled by the heaviest two-axle and four-axle classes have been reduced, because the initial ESALs estimates for the two-axle and four-axle classes did not pass the second validation test. The 10th and 11th rows are computed using Eq. 5 and Eq. 6. The final row, used for the first and second validation tests, is the weighted average ESALs for each axle class. These values are computed by applying the data of the 10th and 11th rows to Eq. 7.

Table A.1 - Status Quo Traffic Data for SR-13

Laden GVW (lbs)	11 000	14 000	16 000	21 100	29 000	35 500	42 500	52 500	63 500	65 500
Axles	2	2	2	2	3	3	4	4	5	6
R	0.70	0.65	0.60	0.55	0.50	0.48	0.45	0.43	0.38	0.40
MGVW (lbs)	12 000	16 000	18 000	24 000	34 000	42 000	51 000	63 000	80 000	80 000
TW (lbs)	8 500	10 200	10 900	13 400	17 100	20 000	22 900	27 000	30 000	32 000
CW (lbs)	2 500	3 800	5 100	7 700	11 900	15 500	19 600	25 500	33 500	33 500
U	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.67	0.70
${}_{N}x_{mn}$	212.5				37		8		18	
${}_{T}f_{\text{tn}}$	0.430	0.251	0.128	0.190	0.588	0.412	0.630	0.370	0.976	0.024
${}_{T}e_{t,laden}$	0.02	0.05	0.10	0.33	0.26	0.65	0.52	1.27	1.31	1.04
${}_{T}e_{t,empty}$	0.009	0.020	0.026	0.060	0.106	0.190	0.247	0.384	0.215	0.214
${}_{N}e_{n}$	0.0717				0.328		0.631		0.944	

As an example of how a policy of load consolidation would be assessed, the data in Table A.1 indicate that about 33 500/2 500 = 13.4 trip loads of the smallest class of two-axle vehicles could be consolidated into a single five-axle vehicle trip. This is based on the ratio of CW values for these two vehicle classes.

Table A.2 displays the results of the first two validation tests applied for SR-13. The second to last row provides the ESALs per trip for each axle class, computed by using Eq. 9. The last row of Table A.2 displays the percent difference in the ESALs values for each axle class, calculated by using Eq. 10 for the first validation test. The rightmost column of Table A.2 shows the percent difference in total ESALs for each highway segment, calculated in accordance with Eq. 11. The low percent differences confirm the accuracy of the estimation method for SR-13.

Table A.2 - Trips and ESALs used in validation for SR-13

Axles:	2	3	4	5	$_{M}e_{m}$	% $Diff_{m}$
Daily Trips by axle class ($_{N}x_{mn}$):	453	130	9	65	141	0.71%
	78	13.5	2.5	1	12	1.68%
	212.5	37	8	18	49	0.16%
	172	40.5	8.5	28.5	58	0.57%
	440.5	93.5	26	173	240	0.90%
β_{n}	0.0720	0.325	0.646	0.930		
% $Diff_{n}$	-0.46%	0.90%	-2.31%	1.50%		

Appendix B. ESALS per vehicle Example Calculations

This appendix presents two examples of the ESALs calculation process based on axle configuration. The general formula used to compute ESALs per trip can be seen in Eq. 5. The following is the ESALs per trip calculation for a three-axle single unit vehicle having a GVW of 35 500 pounds. The first term represents the front single axle and the second represents the rear tandem axles. The distribution of GVW is similar to those listed for commercial trucks, but with slightly higher weighting towards the front, since ratings are typically listed for MGVW (GMC, 2008).

$$1 \times \left(\frac{GVW \times 0.325}{1 \times 18\,000}\right)^4 + 2 \times \left(\frac{GVW \times 0.675}{2 \times 18\,000}\right)^4 = 0.25$$

The following is the ESALs per trip calculation for a five-axle vehicle consisting of a three-axle tractor and a semi-trailer having a tandem axle group. The assumed GVW is 63500 pounds. The first term represents the steering axle and is assigned 12000 pounds. The remainder of the GVW is split between the two tandem axle groups. This weight distribution has been assumed in the literature (U.S. Federal Highway Administration, 2000).

$$1 \times \left(\frac{12\,000}{1 \times 18\,000}\right)^4 + 2 \times \left(\frac{0.5 \times (GVW - 12\,000)}{2 \times 18\,000}\right)^4 + 2 \times \left(\frac{0.5 \times (GVW - 12\,000)}{2 \times 18\,000}\right)^4 = 1.24$$

Appendix C. Pavement Design and Deterioration Example

This appendix provides an example of pavement design and deterioration modeling for SR-13. The methodology for pavement design follows Caltrans documentation (California Department of Transportation, 2006a). A corrected AASHO equation is used to determine the pavement lifespan (Madanat et al., 2002).

Chapter 630 of the HDM describes the flexible pavement design process. The first step involves the calculation of the traffic index (TI) according to Eq. C.1, which is extracted from Chapter 610 of the HDM. The $ESALs_{Tot}$ variable represents total traffic over the pavement design life. The lane distribution factor (LDF), indicates the fraction of heavy-duty vehicles in the design lane and is obtained from Table 613.3B of the HDM.

$$TI = 9 \times \left(\frac{ESALs_{Tot} \times LDF}{10^6}\right)^{0.119} \qquad \text{Eq. C.1}$$

Caltrans traffic data indicates that about 49 ESALs occur one-way daily over the segment of SR-13 being analyzed. We assume a 20-year pavement design life in accordance with the minimum presented in Table 612.2 of the HDM. The HDM provides 1 for the value of LDF, since SR-13 is a two-lane highway.

$$TI\ for\ SR\text{-}13 = 9 \times \left(\frac{(49 \times 365 \times 20) \times 1}{10^6}\right)^{0.119} = 7.96$$

Table C.1 presents pavement design results for SR-13. The results are based on Eq. C.2 through Eq. C.6 along with interpolation of data in Table 633.1 of the HDM, which converts values for gravel equivalents (GE) to pavement layer thicknesses. A safety factor of 0.2 feet is assumed. The subgrade soil along the route of SR-13 is primarily clay, but is nearby to areas with silty sand, according to the Uniform Soil Classification System (Holzer et al., 2006). Thus, following Table 623.1A of the HDM, the California R-value for the subgrade ($CR_{Subgrade}$) is assumed to be 35. CR_{AB} is 78 and CR_{AS} is 60, which correspond to AB-Class 2 and AS-Class 1 respectively, in Table 663.1B of the HDM.

$$GE_{HMA} = 0.0032 \times TI \times (100 - CR_{AB}) + SafetyFactor \qquad \text{Eq. C.2}$$

$$GE_{HMA+AB} = 0.0032 \times TI \times (100 - CR_{AS}) + SafetyFactor \qquad \text{Eq. C.3}$$

$$GE_{AB} = GE_{HMA+AB} - GE_{HMA} \qquad \text{Eq. C.4}$$

$$GE_{total} = 0.0032 \times TI \times \left(100 - CR_{Subgrade}\right) \qquad \text{Eq. C.5}$$

$$GE_{AS} = GE_{total} - GE_{HMA+AB} \qquad \text{Eq. C.6}$$

Table C.1 – Pavement Design for SR-13

	GE (feet)	Thickness (feet)
HMA	0.76	0.38
AB	0.46	0.42
AS	0.44	0.44
HMA+AB	1.22	
Total	1.66	

After design of a pavement is completed, a deterioration model is applied to estimate the ESALs to failure. Eq. 12, provided by AASHTO, is used to estimate the pavement SN (Small and Winston, 1988).

$$SN = 0.44 \times 4.6 + 0.14 \times 5.0 + 0.11 \times 5.2 = 3.28$$

The SN is subsequently incorporated into Eq. 13, provided by Madanat and Prozzi, to estimate the ESALs to failure (Madanat et al., 2002).

$$E[ESALs\ to\ failure\ for\ SR\text{-}13]$$

$$= exp(12.15 + 6.68 \times \ln(3.27 + 1) + 2.62 \times \ln(1) - 3.03 \times \ln(18 + 1))$$

$$= 419\ 380\ ESALs$$

Finally, the expected time between overlays for SR-13 is estimated for the status quo case.

$$\frac{419\ 380 ESALs}{(49 \times 365\ ESALs/year)} \approx 23\ years$$

Appendix D. Tailpipe Emissions and Energy Consumption Factors

Table D.1 presents the emissions and energy consumption factors produced by EMFAC2007 and MOBILE6.2 for SR-13. These factors are averages of winter and summer values and have also been weighted by percent of vehicle population consuming diesel and gasoline for each class. Typical climatic conditions are extracted from weather station data for Oakland, California (Western Regional Climate Center, 2008). The vehicles on SR-13 are assumed to have traveled at an average of 20 mph, in accordance with the 25 mph speed limit.

Table D.1 - Emissions and Energy Consumption Factors for SR-13

GVW (lbs)	11 000	14 000	16 000	21 100	29 000	35 500	42 500	52 500	63 500	65 500
Axles	2	2	2	2	3	3	4	4	5	6
EMFAC PM10 (g/mi)	0.044	0.10	0.15	0.28	0.47	0.63	0.80	0.90	0.90	0.90
MOBILE6.2 PM10 (g/mi)	0.11	0.12	0.13	0.25	0.29	0.33	0.36	0.35	0.35	0.35
EMFAC PM2.5 (g/mi)	0.040	0.087	0.13	0.26	0.44	0.58	0.74	0.83	0.83	0.83
MOBILE6.2 PM2.5 (g/mi)	0.09	0.10	0.10	0.22	0.24	0.28	0.30	0.30	0.30	0.30
EMFAC SO2 (g/mi)	0.0070	0.0083	0.010	0.013	0.016	0.017	0.019	0.020	0.020	0.020
MOBILE6.2 SO2 (g/mi)	0.014	0.011	0.011	0.013	0.014	0.015	0.015	0.015	0.015	0.015
EMFAC CO (g/mi)	5.7	5.6	5.4	5.1	6.2	7.6	9.1	10	10	10
MOBILE6.2 CO (g/mi)	12.4	7.5	5.1	5.6	6.7	6.6	6.2	5.3	4.8	4.8
EMFAC NOx (g/mi)	3.0	3.9	4.8	7.2	11	14	17	18	20	21
MOBILE6.2 NOx (g/mi)	3.4	4.4	4.6	6.5	8.3	9.5	10	11	11	11
EMFAC CO2 (g/mi)	740	860	980	1 300	1 600	1 800	2 000	2 100	2 100	2 100
MOBILE6.2 CO2 (g/mi)	930	1 000	1 100	1 200	1 400	1 500	1 600	1 600	1 600	1 600
EMFAC Energy (MJ/mi)	11	11	12	17	22	24	27	29	29	29
MOBILE6.2 Energy (MJ/mi)	13	14	15	16	19	20	21	22	22	22

Appendix E. Pavement Supply-chain emissions

This appendix gives an example of the emissions estimation process used for the pavement supply chain. The example is for an HMA overlay which is one-mile long, 24-ft wide and has a thickness of three inches. HMA is composed of bitumen and aggregate, for which Table E.1 displays the quantities of these materials used. Accordingly there exist three primary sources of emissions associated with the pavement supply chain. Those are HMA plants, and aggregate and bitumen production. End transportation of materials and paving equipment emissions are also accounted for.

Table E.1 - Composition of HMA Overlay

Ingredient	Mass Ratio	Density (tons/yd3)	Volume (yd3)
Aggregate	0.9	2.23	863
Bitumen	0.1	0.84	255

Assumptions are made regarding the characteristics of the HMA industry. These are in accordance with the EPA AP 42 study of HMA plants (U.S. Environmental Protection Agency, 2004). Table E.2 presents the assumed proportions of the industry split by plant type, fuel type and PM emissions control.

Table E.2 - Industry Characteristics for HMA Plants

Plant Type:	Batch 48%	Drum 52%
Fuel Type:	Oil 20%	Natural Gas 80%
PM control type:	Uncontrolled 5%	Fabric Filter 95%

Emissions factors are then extracted from Table 11.1-2 and Table 11.1-4 of AP 42 for each of these types of plants. These factors are presented with converted units in Table E.3. The last row shows the industry weighted average, based on the characteristics shown in Table E.2. Note that the NO_x and SO_2 emissions factors of Table E.3 are weighted averages based on fuel type. The other emissions factors do not differ by fuel type. Table E.4 presents the NO_x and SO_2 factors by fuel type after unit conversion from AP 42 data.

Table E.3 - Emissions and Energy Consumption Factors for HMA Plants

Plant Type	PM_{10} (g/ton)	$PM_{2.5}$ (g/ton)	SO_2 (g/ton)	CO (g/ton)	NO_X (g/ton)	CO_2 (g/ton)	Energy (MJ/ton)
Uncontrolled Batch-mix	20 40	122	9.65	181	20.0	16 800	241
Fabric Filter-Controlled Batch-mix	4.45	3.76	9.65	181	20.0	16 800	241
Uncontrolled Drum-mix	29 00	680	2.23	59.0	14.4	15 000	215
Fabric Filter-controlled Drum-mix	1.91	1.32	2.23	59.0	14.4	15 000	215
Industry	127	23.0	5.79	118	17.1	15 800	228

Table E.4 - Emissions Factors for HMA Plants That Differ by Fuel Type

Plant Type	Fuel Type	NO_X (g/ton)	SO_2 (g/ton)
Batch	(Natural Gas)	11.3	2.09
	(Oil)	54.4	39.9
Drum	(Natural Gas)	11.8	1.54
	(Oil)	24.9	4.99

The industry weighted emissions factors are then multiplied by the mass of HMA being used for the overlay to derive an estimate of the emissions associated with the HMA plant. Table E.5 presents the resulting HMA plant emissions based on a total overlay volume of 1 173 yd^3, having a density of 1.82 $tons/yd^3$.

Table E.5 - Emissions Associated with the HMA Plant

PM_{10} (MT)	$PM_{2.5}$ (MT)	SO_2 (MT)	CO (MT)	Pb (kg)	NO_X (MT)	CO_2 (MT)	Energy (TJ)
0.27	0.049	0.012	0.25	0.00	0.037	34	0.49

The emissions factors associated with aggregate production are composed of two sources. The first being the supply-chain emissions, provided by EIO-LCA for the sand, gravel, clay and refractory mining sector, with the aforementioned appending procedure for fine particulates. Table E.6 displays these emissions factors after conversion using a market price of $10/ton, which is provided by PaLATE.

Table E.6 - Emissions Factors for Aggregate Mining

PM_{10} (g/ton)	$PM_{2.5}$ (g/ton)	SO_2 (g/ton)	CO (g/ton)	Pb (g/ton)	NO_X (g/ton)	GWP (g CO_2 equiv./ton)	Energy (MJ/ton)
2.93	1.87	28.9	36.9	0.00282	19.4	12 000	186

The second source of pollution for aggregates found in PaLATE is particulate emissions associated with screening, storage and conveyance. The emission factors, along with their corresponding Source Classification Code (SCC) in the EPA's Factor Information REtrieval Software are presented in Table E.7. These factors are developed, assuming an 85% reduction in particulate emissions due to continuous chemical treating of aggregate piles, and watering or treatment of roadways. This is in accordance with the AP 42 study that indicates a maximum of 90% control associated with handling and storage piles (U.S. Environmental Protection Agency, 2006a). The ratio of $PM_{2.5}$ to PM_{10} for screening is extracted from AP 42 Table 11.19.2-2. The ratio for the other emissions sources in Table E.7 is assumed to be 0.3, in accordance with the last figure of an AP 42 background document and the relatively low assumed fugitive dust emissions (U.S. Environmental Protection Agency, 2006b).

Table E.7 - Emissions Factors for Aggregate Storage, Conveying and Screening

Source	SCC	PM_{10} (g/ton)	$PM_{2.5}$ (g/ton)
Aggregate storage - construction sand and gravel	30502502	8.16	2.45
material transfer and conveying – construction sand and gravel	30502503	0.435	0.131
pile forming stacker - construction sand and gravel	30502505	4.08	1.22
bulk loading - construction sand and gravel	30502506	0.163	0.049
Screening - construction sand and gravel	30502511	4.63	0.313

Table E.8 displays the total emissions resulting from the 1 924 tons of aggregate used in the pavement overlay. This tonnage is in accordance with Table E.1.

Table E.8 - Emissions Associated With Aggregate

PM_{10} (MT)	$PM_{2.5}$ (MT)	SO_2 (MT)	CO (MT)	Pb (kg)	NO_X (MT)	GWP (MT CO_2 equiv)	Energy (TJ)
0.039	0.012	0.056	0.071	0.0054	0.037	25	0.36

Emissions factors associated with bitumen production are based entirely on the EIO-LCA petroleum refineries sector. The results of the EIO-LCA information combined with the PaLATE listed bitumen price of $1 016/ton produce the emission factors as shown in Table E.9. The total emissions resulting from 214 tons of bitumen are shown in Table E.10.

Table E.9 - Emission Factors for Bitumen Production

PM_{10} (g/ton)	$PM_{2.5}$ (g/ton)	SO_2 (g/ton)	CO (g/ton)	Pb (g/ton)	NO_X (g/ton)	GWP (g CO_2 equiv./ton)	Energy (MJ/ton)
447	353	4 330	6 180	0.459	2 520	1 480 000	25 300

Table E.10 – Emissions Associated With Bitumen Production

PM_{10} (MT)	$PM_{2.5}$ (MT)	SO_2 (MT)	CO (MT)	Pb (kg)	NO_X (MT)	GWP (MT CO_2 equiv.)	Energy (TJ)
0.096	0.075	0.93	1.3	0.098	0.54	480	5.4

Emissions factors for dump and tanker trucks are extracted from EMFAC2007. These factors are developed assuming a 20-ton truck traveling at an average of 40mph under typical local climate conditions. The trucks are assumed to make a 50-mile round trip to deliver aggregate and bitumen to the HMA plant, and a 25-mile round trip to bring HMA to the highway site. In addition, PaLATE incorporates the emissions for the extraction and production of diesel based on the EIO-LCA petroleum refineries sector. Table E.11 presents the combined emissions from tailpipe and the diesel fuel supply chain.

Table E.11 - Emissions Associated With Transportation and Diesel Fuels

PM_{10} (MT)	$PM_{2.5}$ (MT)	SO_2 (MT)	CO (MT)	Pb (kg)	NO_X (MT)	CO_2 (MT)	Energy (TJ)
0.0074	0.0064	0.029	0.072	0.0031	0.14	15	0.33

Combined emissions factors for paving equipment are presented in Table E.12 in units of grams per ton of HMA. These constitute the emissions for a paver, pneumatic roller and tandem roller. These factors are derived from AP 42 Table 3.3-1, which are adapted by using PaLATE conversion factors for fuel efficiency and equipment productivity. Table E.13 displays the emissions associated with paving equipment.

Table E.12 - Emissions Factors for Paving Equipment

PM_{10} (g/ton)	$PM_{2.5}$ (g/ton)	SO_2 (g/ton)	CO (g/ton)	Pb (g/ton)	NO_X (g/ton)	CO_2 (g/ton)	Energy (MJ/ton)
0.662	0.595	0.617	2.01	0.000	9.32	346	6.18

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Table E.13 - Emissions Associated With Paving Equipment

PM_{10} (MT)	$PM_{2.5}$ (MT)	SO_2 (MT)	CO (MT)	Pb (kg)	NO_X (MT)	GWP (MT CO_2 equiv.)	Energy (TJ)
0.0014	0.0013	0.0013	0.0043	0.00	0.020	0.74	0.013

The sum of emissions shown in Table E.5, Table E.8, Table E.10, Table E.11, and Table E.13 produce the total overlay supply-chain emissions resulting in Table 2.

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