Title

Unintended Impacts of Increased Truck Loads on Pavement Supply-Chain Emissions

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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 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 scenarios with estimated emissions resulting from load consolidation and changes in load factors. These scenarios reveal several points having to do with the tradeoff between tailpipe versus pavement supply-chain emissions. In some cases, unintended emissions from the pavement supply-chain are found to be significant. 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, Environment

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Table of Acronyms and Symbols

Caltrans	California Department of Transportation
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2 eq.	Carbon Dioxide Equivalent
E2007	EMFAC2007
EIO-LCA	Economic Input-Output Life Cycle Assessment
ESAL	Equivalent Single Axle Load
g	Gram
GHG	Greenhouse Gases
GWP	Global Warming Potential
HDM	California Department of Transportation Highway Design Manual
HMA	Hot Mix Asphalt
hr	Hour
I-x	Interstate Highway x, where x is a number
LCA	Life-Cycle Assessment
m	Meter
MFD	Macroscopic Fundamental Diagram
M6.2	MOBILE6.2
O_3	Ozone
OL	Overlay
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
Pb	Lead
PeMS	Freeway Performance Measurement System
$PM_{2.5}$	Particulate Matter with Diameter < 2.5 micrometers
PM_{10}	Particulate Matter with Diameter < 10 micrometers
pmf	Probability Mass Function
s	Second
SR-x	State Route x, where x is a number
TJ	Terajoule
USDOT	U.S. Department of Transportation
VIUS	Economic Census: Vehicle Inventory & Use Survey

1. Introduction

The reduction of trips made by freight logistics vehicles is 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 (Browne et al., 2005). 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 locations. The U.K. has raised its regulation from 29.5×10^3 kg to 37.2×10^3 kg over the last 25 years and the European Commission has issued a directive requiring its member countries to permit vehicles weighing 36.3×10^3kg on their roadways (McKinnon, 2005). Such adaptations are becoming increasingly common, despite trends such as just-in-time business, which contribute to a reduction of 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. Supporting studies often make use of the load factor as a general indicator of the sustainability of a transportation system. The

[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.

decline of load factors, even in coarse analyses at a national level, is commonly accepted as a detriment, especially with regards to environmental[2] impacts (European Environment Agency, 2000; Stanley et al., 2009). 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 and transportation analyses has been expanding from a focus on passenger vehicles to account for freight transportation as well (Bontekoning et al., 2003; Facanha and Horvath, 2007; Forkenbrock, 2001).

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).

In this paper descriptive scenarios of operational shifts made by freight vehicles on two roadways are presented to contrast the benefits and unintended environmental impacts of various hypothetical policies. Tailpipe and pavement supply-chain emissions are estimated under various paradigms in order to highlight the effects of pavement within the freight road transportation life cycle, which are currently

[2] In this paper the term environment will account only for emissions, but not noise, in order to streamline the scope.

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 tailpipe GHG pollutant considered 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. These results are then followed by a discussion of additional impact considerations, uncertainty assessment, sensitivity analysis, and a conclusion.

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 current environmental concerns, tailpipe CO_2 emissions have received attention in the literature. A study in London assessed the emissions improvements due to both load factor and empty running policies (Browne and Allen, 1999). In Japan, the reductions of CO_2 emissions due to load factor controls and cooperative transport systems have been assessed for a test road network (Taniguchi and van der Heijden, 2000). Cooperative transport systems involve multiple companies working together to make their logistics operations more efficient. 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 U.S. and U.K. 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 U.K., the increase in maximum vehicle weight from 37.2×10^3 to 39.9×10^3 kg is estimated to have reduced annual PM_{10}, NO_x and CO_2 emissions in 2003 (McKinnon, 2005). 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 U.S., emissions are almost entirely neglected from truck weight studies, although the potential for reduced fuel consumption has been investigated (U.S. Federal Highway Administration, 2000).

Tailpipe emissions are common indicators of environmental sustainability in freight policy analyses (Forkenbrock, 1999; Gorman, 2007; Holguin-Veras and Cetin, 2009). However, the concept of environmental life-cycle assessment (LCA) has also come to the forefront in the last decade to account for indirect effects (Hackney and de Neufville, 2001; ISO 14040, 1997). A LCA of freight transportation in the U.S. 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 and Horvath, 2007), due to the exponential relationship between axle load and pavement damage (American Association of State Highway and Transportation Officials, 1993). This provides 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 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 policies. 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. These characteristics include the weights under various loading conditions and the Equivalent Single Axle Loads (ESALs) per trip.

The 2002 Economic Census: Vehicle Inventory and Use Survey (VIUS) provides distance traveled (VKT) information by truck type (U.S. Census Department of Commerce, 2004). For this paper, truck types are distinguished by gross vehicle weight (GVW) and axle configuration. Each joint GVW-axle configuration type will be referred to as a configuration class, whereas the term vehicle class will be used to describe the set of configuration classes having the same GVW and number of axles. The term axle class will refer to the set of configuration classes that all have the same number of axles. In order to simplify the methodology, only configuration classes comprising 5% or more of the VKT within their associated axle class are accounted for. These configuration classes are listed in Table 1, along with vehicle characteristics. The empty vehicle weights (EVW) are extracted directly from the VIUS data, as an average weighted by VKT. The GVW values are assumed to be the average of the endpoints of the published weight range for all vehicles, except for the heaviest weight range, for which GVW is calculated based on the maximum allowable weight in the U.S. of 36.3×10^3 kg. These averages are used due to the likely inaccuracy of reported GVW values, since cargo weight (CW) may vary greatly for each vehicle over the course of a year. In addition, for larger vehicles the VIUS GVW values would imply unreasonably high load factors. However, this should not be a significant source of error for deriving policy implications, since the averages are generally not greatly different from the VIUS GVW values. Subsequently, the laden CW can calculated by Eq. 1. A load factor for laden trips (U) of 70% is assumed, which is within the range of values found in previous research and data (Department of Transport: London, 2005; Facanha and Horvath, 2006; Quak and De Koster, 2009). The $MGVW$ values are then calculated by use of Eq. 2. In the case that the calculated $MGVW$ exceeds 36.3×10^3 kg, the $MGVW$ is set to this value, in accordance with the maximum allowed truck weight on most all highways in the U.S and Eq. 1 is substituted for CW in Eq. 2 in order to derive GVW.

$$CW = GVW - EVW \qquad \text{Eq. 1}$$

$$U = \frac{CW}{MGVW - EVW} \qquad \text{Eq. 2}$$

Table 1 - Vehicle Characteristics and Trip Profile Based on VIUS Data

Axles	Configuration	EVW	GVW	$MGVW$	ESALs per trip Empty	ESALs per trip Laden	ESALs per trip Full	% VKT within axle class
2	Straight Truck	4100	5400	6000	0.012	0.026	0.046	25%
	Straight Truck	4700	6800	7700	0.022	0.068	0.14	14%
	Straight Truck	5500	8100	9200	0.039	0.15	0.31	13%
	Straight Truck	6200	10300	12100	0.064	0.44	1.1	33%
	Straight Truck	7600	13400	15870	0.14	1.4	3.5	15%
3	Straight Truck	9900	16600	19400	0.21	0.63	1.3	7.8%
	Straight Truck	10700	20400	24600	0.28	1.5	3.6	25%
	2-Axle Tractor and Trailer	10700	20400	24600	0.12	2.1	5.0	6.4%
	Straight Truck	11800	24900	30600	0.43	3.5	9.4	31%
	2-Axle Tractor and Trailer	11800	24900	30600	0.18	5.0	13	4.8%
	Straight Truck	14500	29700	36200	1.0	7.6	20	26%
4	2-Axle Straight Truck and Trailer	3900	5400	6100	0.0017	0.0032	0.0055	8.9%
	2-Axle Straight Truck and Trailer	4600	6800	7800	0.0047	0.0080	0.015	10%
	2-Axle Tractor and Trailer	12200	20400	23900	0.12	0.63	1.3	11%
	2-Axle Tractor and Trailer	12400	24900	30300	0.17	1.5	3.6	8.4%
	Straight Truck	12400	24900	30300	0.34	1.4	3.0	14%
	2-Axle Tractor and Trailer	13200	29700	36300	0.23	3.1	7.8	22%
	Straight Truck	13200	29700	36300	0.4	2.8	6.5	25%
5	3-Axle Tractor and 2-Axle Trailer	13500	24900	29900	0.21	0.71	1.5	5.8%
	3-Axle Tractor and 2-Axle Trailer	14000	29700	36300	0.29	1.4	3.3	89%
6	3-Axle Tractor and 3+ Axle Trailer	15100	29700	36300	0.29	0.99	2.2	3.7%
	4-Axle Tractor and 2-Axle Trailer	15100	29700	36300	0.16	0.85	2.0	0.65%
	3-Axle Tractor and 3 Axles on 2 Trailers	15100	29700	36300	0.29	1.2	2.6	1.4%

The information of Table 1 is then combined with average annual daily truck trip counts, provided by the California Department of Transportation (Caltrans), for various locations along California highways (California Department of Transportation, 2008). In the scenarios of section 4, 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 Caltrans trip 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 trip counts are split to represent the configuration classes based on the within-axle class VKT percentages listed in Table 1.

The trips are then further split between those which are laden and empty. For the scenarios in this paper, unless otherwise specified, 33% of trips for all configuration 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). The product of this percentage and U=70% agrees with load factors found in the literature (European Environment Agency, 2006). We note that as with VIUS GVW data, the reported empty percent of trips is susceptible to inaccuracies and omissions, and the use of a single value is not likely to be a significant source of error for deriving policy implications.

The next step is the estimation of ESALs per trip for each configuration class under empty, laden and full conditions. This estimation is conducted based on axle configurations for freight vehicles, the results of which are shown in Table 1. The ESALs per trip for each configuration class are estimated based on the pavement deterioration fourth power law for each axle group and assumptions for load distribution across axles. Eq. 3 presents the formula used for calculating ESALs per trip based on the fourth power law, which is generally accepted in the literature (American Association of State Highway and Transportation Officials, 1993). Examples of the ESALs per trip estimation based on Eq. 3 are presented for two freight vehicles in Appendix A. This estimation procedure is applied, instead of using previously assumed ESALs values, due to the wide variation in such values (Avis, 2009; Holguin-Veras et al., 2006).

In addition, the correspondence between GVW, EW and $MGVW$ to assumed ESALs values would be very inaccurate if they are taken from different sources.

$$e_{cv} = \sum_{g=1}^{G_c} A_{gc} \times \left(\frac{L_{gc}}{A_{gc} \times 8\,182}\right)^4 \qquad \text{Eq. 3}$$

$e_{cv} = ESALs\ per\ trip\ for\ configuration\ class\ c\ and\ vehicle\ class\ v$

$G_c = number\ of\ axle\ groups\ for\ configuration\ class\ c$

$L_{gc} = load\ carried\ by\ axle\ group\ g\ for\ configuration\ class\ c\ (kg)$

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

The VKT distributions in Table 1 are then applied to derive an estimate of the ESALs per trip when empty, laden and full for each vehicle class, by use of Eq. 4. These values for ESALs per trip are used to model pavement deterioration.

$$E_v = \sum_{c=1}^{C_v} f_{cv} \times e_{cv} \qquad \text{Eq. 4}$$

$E_v = ESALs\ per\ trip\ for\ vehicle\ class\ v$

$f_{cv} = percent\ of\ VKT\ made\ by\ configuration\ class\ c\ within\ vehicle\ class\ v$

$C_v = number\ of\ configuration\ classes\ within\ vehicle\ class\ v$

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 B. Once the pavement is designed, its structural number (SN) can be determined. The SN is calculated according to an equation which was provided by the American Association of Highway Officials (AASHO) as described in Eq. 5 (Small et al., 1989).

$$SN = (0.44 \times T_{HMA} + 0.14 \times T_B + 0.11 \times T_{SB}) \times \left(\frac{inch}{2.54\ cm}\right) \qquad \text{Eq. 5}$$

$SN = pavement\ structural\ number$

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

$T_B = base\ thickness\ (cm)$

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

The SN is then applied in a pavement deterioration model to determine the overlay frequency. The deterioration model applied in this research was a standard 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. 6. For this model, pavement failure is defined as unacceptable ride quality.

$$E[\rho] = exp\left(12.15 + 6.68 \times \ln(SN + 1) + 2.62 \times \ln(L_2) - 3.03 \times \ln\left(\frac{.0022kip}{kg} \times L_1 + L_2\right)\right) \qquad \text{Eq. 6}$$

$\rho = ESALs\ to\ failure$

$L_1 = standard\ axle\ load = 8\,182$ kg

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

In the scenarios of this paper we assume that maintenance policy affects only the frequency of 7.6-cm 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. 6, to the annual ESALs on a roadway segment. An example showing the estimation of years between overlays is presented in Appendix B.

3.3.Tailpipe Emissions

Tailpipe emission factors are estimated by two models, EMFAC2007 v2.3 (California Air Resources Board, 2006) and 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 VKT profiles. The emission factors used are for 2010 to provide current estimates.

The reasons for using two models are twofold. First, the vehicle classes presented in section 3.1 and the weight classes of the emission 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 (E2007) weight classes are based on GVW and the model uses an area-wide unified driving cycle, whereas heavy-duty classes in MOBILE6.2 (M6.2) 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 emission factors for vehicles with GVW heavier than the average of the minimum and maximum weights of the heaviest E2007 and M6.2 weight classes. Interpolation is used for smaller vehicle classes. Weight correction factors are not introduced for other pollutants since broadly applicable factors have not been reported in the literature. Appendix C presents some of the tailpipe emission factors used for scenarios on State Route 13 (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 emission factors (Horvath, 2008). However, several augmentations have been made to compile a more comprehensive portfolio of emissions. This section provides an overview of the emissions estimation process and Appendix D 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. E2007 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 emission factors for economic sectors in the U.S. 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 emission 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 7.6-cm, two-lane, 1.6-km HMA overlay, which is assumed to be used for SR-13. Appendix D describes the estimation of these emission 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 Two Lanes on a 1.6-km Highway Segment

PM_{10} (10^3 kg)	0.42
$PM_{2.5}$ (10^3 kg)	0.14
NO_x (10^3 kg)	0.76
CO (10^3 kg)	1.7
SO_2 (10^3 kg)	1.0
Pb (kg)	0.11
Energy (TJ)	6.6
GWP (10^3 kg CO_2 eq.)	560

4. Scenarios

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 1.6 km in length and all results are for one direction of traffic and pavement. Several operational shifts will be considered in sections 4.1 through 4.5, 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. For comparison, estimated status quo data for SR-13 are 68.6×10^3 ESALs/yr on the design lane and there are 19 years between overlays. For I-80, there are 1.58×10^6 ESALs/yr on the design lane and 7.9 years between overlays. The corresponding freight vehicle emissions for vehicles on all lanes are shown in Table 3 and Table 5. The use of the design lane for ESALs information, and all lanes for tables listing emissions will be applied throughout section 4. Also, OL is used to denote overlay in the tables of section 4. Table 4 and Table 6 display further information, for each axle class.

Table 3 - SR-13 Status Quo Emissions

	E2007	M6.2	OL		E2007	M6.2	OL
PM_{10} (10^3 kg/yr)	0.032	0.019	0.022	$PM_{2.5}$ (10^3 kg /yr)	0.029	0.015	0.0077
NO_x (10^3 kg /yr)	0.82	0.58	0.034	CO (10^3 kg /yr)	0.53	0.42	0.093
SO_2 (10^3 kg /yr)	0.0013	0.0013	0.055	Pb (kg/yr)			0.0057
Energy (TJ/yr)	1.8	1.7	0.36	GWP (10^3 kg CO_2 eq./yr)	100	100	30

Table 4- SR-13 Status Quo Results by Axle Class

Axle Class	2	3	4	5	6
Trips/yr	78000	14000	1550	6000	1.0
ESALs/yr	22000	37000	840	6200	0.79
E2007 GWP (10^3 kg CO_2 eq./yr)	89	28	2.6	13	0.81
M6.2 GWP (10^3 kg CO_2 eq./yr)	90	21	2.1	10	0.60

Table 5 - I-80 Status Quo Emissions

	E2007	M6.2	OL		E2007	M6.2	OL
PM_{10} (10^3 kg /yr)	0.83	0.58	0.10	$PM_{2.5}$ (10^3 kg /yr)	0.77	0.47	0.036
NO_x (10^3 kg /yr)	30	22	0.16	CO (10^3 kg /yr)	8.0	4.9	0.43
SO_2 (10^3 kg /yr)	0.033	0.034	0.26	Pb (kg/yr)			0.027
Energy (TJ/yr)	46	48	1.7	GWP (10^3 kg CO_2 eq./yr)	3400	3500	140

Table 6 - I-80 Status Quo Results by Axle Class

Axle Class	2	3	4	5	6
Trips/yr	860000	240000	100000	1200000	200
ESALs/yr	170000	460000	87000	830000	110
E2007 GWP (10^3 kg CO_2 eq./yr)	850	400	140	1900	120
M6.2 GWP (10^3 kg CO_2 eq./yr)	990	380	143	1900	110

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 and types of vehicles involved (Geroliminis and Daganzo, 2005). In the case that all laden trips are made with full cargo loads, without any transfer of cargo across vehicle classes, the ESALs on SR-13 increase by 70% to 117×10^3 ESALs/yr, causing a change to 11 years between overlays. Table 7 presents corresponding emissions results. In Table 7, rows labeled 'After Shift' present the emissions after the hypothetical policy is implemented and rows labeled 'Difference' display the change in emissions relative to the status quo shown in Table 3. These labeling styles will be used throughout the remainder of section 4. 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 metropolitan areas may be environmentally damaging.

Table 7 - SR-13 Emissions after Within-Class Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.022	0.013	0.038	$PM_{2.5}$ (10^3 kg /yr)	0.021	0.011	0.013
Difference		-0.010	-0.006	0.016		-0.009	-0.005	0.005
After Shift	NO_x (10^3 kg /yr)	0.67	0.41	0.058	CO (10^3 kg /yr)	0.37	0.30	0.16
Difference		-0.15	-0.17	0.024		-0.16	-0.13	0.07
After Shift	SO_2 (10^3 kg /yr)	0.00092	0.00092	0.094	Pb (kg/yr)			0.0098
Difference		-0.00039	-0.00039	0.039				0.0040
After Shift	Energy (TJ/yr)	1.3	1.2	0.61	GWP (10^3 kg CO_2 eq./yr)	100	100	50
Difference		-0.6	-0.5	0.25		-41	-38	20

In the case that the same policy is applied to I-80, ESALs increase by 63% to 2.57×10^6 ESALS/yr, and there are 4.9 years between overlays. Table 8 presents the emissions 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, indicating that there is less chance of unintended impacts resulting from consolidation of larger vehicles.

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

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.59	0.41	0.17	$PM_{2.5}$ (10^3 kg /yr)	0.54	0.33	0.059
Difference		-0.25	-0.17	0.07		-0.23	-0.14	0.023
After Shift	NO_x (10^3 kg /yr)	24	15	0.26	CO (10^3 kg /yr)	5.7	3.4	0.71
Difference		-6	-6	0.10		-2.4	-1.4	0.27
After Shift	SO_2 (10^3 kg /yr)	0.024	0.024	0.42	Pb (kg/yr)			0.044
Difference		-0.010	-0.010	0.16				0.017
After Shift	Energy (TJ/yr)	32	34	2.7	GWP (10^3 kg CO_2 eq./yr)	2400	2400	230
Difference		-14	-14	1.0		-1000	-1000	90

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. Load consolidation from all 2-axle to the two smaller 3-axle vehicle classes, shown in Table 1, results in a 28% increase in ESALs to 87.6 $\times 10^3$ ESALs/yr on SR-13 and 15 years between overlays. Table 9 presents corresponding emissions results. On the other hand, consolidation from all 2-axle to the two larger 3-axle vehicle classes, shown in Table 1, results in a 112% increase in ESALs to 146 $\times 10^3$ ESAL/yr and 9 years between overlays. Table 10 shows corresponding emissions results. In contrast to section 4.1, all vehicles maintain a laden load factor of 70% so the focus is on the effects of consolidating across vehicle classes. The increase in ESALs is far greater for consolidation to larger than smaller 3-axle vehicles, despite the greater reduction in trips. In turn, the increase in unintended pavement supply-chain emissions is also greater after consolidation to the larger 3-axle vehicles.

The fraction of VKT 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 and E2007 actually predicts an increase in these emissions resulting from load consolidation to 3-axle vehicles.

Table 9 - SR-13 Emissions after 2-axle to Small 3-axle Vehicle Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.044	0.018	0.029	$PM_{2.5}$ (10^3 kg /yr)	0.040	0.015	0.0098
Difference		0.012	-0.001	0.006		0.011	-0.001	0.0021
After Shift	NO_x (10^3 kg /yr)	1.0	0.55	0.044	CO (10^3 kg /yr)	0.51	0.27	0.12
Difference		0.19	-0.03	0.010		-0.02	-0.15	0.03
After Shift	SO_2 (10^3 kg /yr)	0.0012	0.0010	0.071	Pb (kg/yr)			0.0073
Difference		-0.0001	-0.0004	0.015				0.0016
After Shift	Energy (TJ/yr)	1.8	1.4	0.45	GWP (10^3 kg CO_2 eq./yr)	100	100	40
Difference		-0.1	-0.4	0.10		0	-20	10

Table 10 - SR-13 Emissions after 2-axle to Large 3-Axle Vehicle Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.036	0.014	0.047	$PM_{2.5}$ (10^3 kg /yr)	0.033	0.011	0.016
Difference		0.004	-0.005	0.025		0.003	-0.004	0.009
After Shift	NO_x (10^3 kg /yr)	0.88	0.44	0.073	CO (10^3 kg /yr)	0.41	0.19	0.20
Difference		0.06	-0.14	0.039		-0.12	-0.23	0.10
After Shift	SO_2 (10^3 kg /yr)	0.00099	0.00073	0.12	Pb (kg/yr)			0.012
Difference		-0.00033	-0.00059	0.06				0.006
After Shift	Energy (TJ/yr)	1.4	1.1	0.76	GWP (10^3 kg CO_2 eq./yr)	100	100	60
Difference		-0.4	-0.6	0.40		-30	0	30

Load consolidation from the two smallest 2-axle to all 5-axle vehicle classes results in a 3.9% increase to 71.3×10^3 ESALs/yr, 18 years between overlays, and the emissions shown in Table 11. Load consolidation from all 2-axle to all 5-axle vehicle classes results in a 8.4% decrease to 62.8×10^3 ESALs/yr, 20 years between overlays, and the emissions shown in Table 12. In these cases the tradeoff between trips versus ESALs results either in a small increase or a decrease in total ESALs. Consequently, unintended pavement supply-chain emissions are likely to be minimal.

Table 11 - SR-13 Emissions after Small 2-axle to 5-axle Vehicle Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.032	0.016	0.023	$PM_{2.5}$ (10^3 kg /yr)	0.029	0.013	0.0080
Difference		0.000	-0.003	0.001		0.000	-0.002	0.0003
After Shift	NO_x (10^3 kg /yr)	0.77	0.48	0.036	CO (10^3 kg /yr)	0.40	0.26	0.096
Difference		-0.05	-0.10	0.001		-0.13	-0.16	0.004
After Shift	SO_2 (10^3 kg /yr)	0.0011	0.00092	0.057	Pb (kg/yr)			0.0060
Difference		-0.0002	-0.00040	0.002				0.0002
After Shift	Energy (TJ/yr)	1.5	1.3	0.37	GWP (10^3 kg CO_2 eq./yr)	100	100	30
Difference		-0.3	-0.5	0.01		0	0	0

Table 12 - SR-13 Emissions after All 2-axle to 5-axle Vehicle Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.028	0.011	0.020	$PM_{2.5}$ (10^3 kg /yr)	0.026	0.0088	0.0070
Difference		-0.004	-0.008	-0.002		-0.004	-0.0064	-0.0006
After Shift	NO_x (10^3 kg /yr)	0.69	0.35	0.031	CO (10^3 kg /yr)	0.32	0.15	0.085
Difference		-0.12	-0.23	-0.003		-0.21	-0.27	-0.008
After Shift	SO_2 (10^3 kg /yr)	0.00077	0.00057	0.051	Pb (kg/yr)			0.0053
Difference		-0.00054	-0.00074	-0.005				-0.0005
After Shift	Energy (TJ/yr)	1.1	0.85	0.33	GWP (10^3 kg CO_2 eq./yr)	100	100	30
Difference		-0.7	-0.88	-0.03		-100	-100	0

The results of Table 9 through Table 12 reveal the importance of knowing the ratio of ESALs to CW per trip, which has also received some attention in the literature on toll policies (Holguin-Veras et al., 2006). We will not explore the tolling implications in this paper, but will similarly provide values of this ratio for all vehicle classes which have been used. Table 13 lists the ratio for various vehicle classes, showing that consolidation to the larger 2-axle or 3-axle vehicles is likely to result in the most severe unintended impacts, whereas consolidation to 5-axle vehicles would cause relatively less pavement damage, while reducing tailpipe emissions. The third column of Table 13 is a weighted average of empty and laden ESALs per trip values, based on the assumed 33% of trips made empty. As mentioned in previous research (Holguin-Veras et al., 2006), developing accurate values for the ratio of ESALs to CW is constrained by data availability, however, the results do provide a general idea of how across-vehicle class consolidation policies can be both beneficial and damaging, depending on the vehicles involved.

A similar ratio can be estimated for emissions versus CW, as shown in Table 13. Of note is the relatively high value of this ratio for $PM_{2.5}$ and NO_x for 3-axle compared to 2-axle vehicles. This is in accordance with the emissions results shown in Table 9 and Table 10. Therefore, consolidation to larger vehicles involving a change from gasoline to diesel engines should be carefully considered as increases of particulate matter and NO_x emissions may increase health impacts and O_3 formation potential.

Table 13 – Impact Comparison per CW by Vehicle Class (CW is in units of 10^6 kg)

Axles	GVW (kg)	$\frac{avg\ ESALs}{CW}$	E2007 SO_2 (g/km)/CW	M6.2 SO_2 (g/km)/ CW	E2007 $PM_{2.5}$ (g/km)/ CW	M6.2 $PM_{2.5}$ (g/km)/ CW	E2007 NOx (g/km)/CW	M6.2 NO_x (g/km)/CW
2	5400	16	3.2	5.7	17	34	1200	1400
	6800	25	2.6	3.3	30	22	1100	1100
	8100	43	2.5	2.8	38	29	1200	1100
	10300	76	2.0	2.0	40	26	1000	880
	13400	170	1.7	1.5	41	21	1000	750
3	16600	74	1.6	1.4	47	20	1100	740
	20400	120	1.3	0.94	41	15	1000	540
	24900	199	0.95	0.69	32	11	860	430
	29700	360	0.82	0.60	27	9.3	740	370
4	5400	1.7	2.8	4.8	14	30	1000	1300
	6800	3.1	2.5	3.1	28	21	1100	1100
	20400	56	1.5	1.1	49	17	1200	640
	24900	82	0.99	0.73	33	11	890	440
	29700	130	0.75	0.55	25	8.6	680	340
5	24900	47	1.1	0.79	36	12	950	480
	29700	66	0.79	0.58	26	9.0	740	360
6	29700	53	0.85	0.62	28	9.7	790	380

4.3.Increasing Maximum Weight

Several scenarios involving increases in maximum vehicle weight regulations in the U.S. have been discussed in previous research. For instance, a North American trade scenario has been suggested in which weight limits are increased to enhance international trucking productivity in the U.S. (U.S. Federal Highway Administration, 2000). The suggested regulations would set the tridem axle weight limit to 19 960 kg, 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 40.8×10^3 kg is analyzed. Table 14 shows that emissions can be greatly reduced by distributing loads across multiple axles. In this case, there is a 10% reduction to 1.43×10^6 ESALs/yr, and an increase to 8.8 years between overlays. On the other hand, load consolidation for heavy vehicles still hastens pavement deterioration, causing an 11% increase in ESALs to 1.76×10^6 ESALs/yr, and 7.1 years between overlays. Emissions are shown in Table 15. Table

16 shows that this problem is greatly exacerbated by the suggested increase in maximum GVW to 40.8×10^3 kg, for which there is a 35% increase to 2.14×10^6 ESALs/yr, and 5.9 years between overlays. 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 14 - I-80 Emissions after Shift from 5-axle to 6-axle Trucks

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg/yr)	0.87	0.60	0.094	$PM_{2.5}$ (10^3 kg/yr)	0.80	0.49	0.032
Difference		0.03	0.02	-0.010		0.03	0.01	-0.004
After Shift	NO_x (10^3 kg/yr)	31	22	0.14	CO (10^3 kg/yr)	8.3	5.0	0.39
Difference		1.1	0.7	-0.02		0.3	0.1	-0.04
After Shift	SO_2 (10^3 kg/yr)	0.035	0.035	0.23	Pb (kg/yr)			0.024
Difference		0.001	0.001	-0.03				-0.003
After Shift	Energy (TJ/yr)	47	50	1.5	GWP (10^3 kg CO_2 eq./yr)	3500	3600	130
Difference		1	1	-0.2		110	100	-10

Table 15 - I-80 Emissions after Shift from 5-axle to 6-axle, 36.3×10^3-kg Trucks

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg/yr)	0.68	0.49	0.12	$PM_{2.5}$ (10^3 kg/yr)	0.63	0.40	0.040
Difference		-0.15	-0.09	0.01		-0.14	-0.07	0.004
After Shift	NO_x (10^3 kg/yr)	25	18	0.18	CO (10^3 kg/yr)	6.8	4.3	0.48
Difference		-5.1	-3.5	0.02		-1.2	-0.6	0.05
After Shift	SO_2 (10^3 kg/yr)	0.028	0.029	0.29	Pb (kg/yr)			0.030
Difference		-0.005	-0.005	0.03				0.003
After Shift	Energy (TJ/yr)	39	41	1.9	GWP (10^3 kg CO_2 eq./yr)	2900	3000	160
Difference		-7	-7	0.2		-520	-500	20

Table 16 - I-80 Emissions after Shift from 5-axle to 6-axle, 40.8×10^3-kg Trucks

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg/yr)	0.61	0.45	0.14	$PM_{2.5}$ (10^3 kg/yr)	0.56	0.36	0.049
Difference		-0.22	-0.13	0.04		-0.21	-0.11	0.013
After Shift	NO_x (10^3 kg/yr)	22	17	0.22	CO (10^3 kg/yr)	6.2	4.0	0.59
Difference		-7.5	-5.1	0.06		-1.8	-0.9	0.15
After Shift	SO_2 (10^3 kg/yr)	0.026	0.027	0.35	Pb (kg/yr)			0.036
Difference		-0.008	-0.007	0.09				0.009
After Shift	Energy (TJ/yr)	36	38	2.3	GWP (10^3 kg CO_2 eq./yr)	2700	2700	190
Difference		-10	-10	0.6		-800	-700	50

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 reduce tailpipe and supply-chain 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 17 displays the emissions results of eliminating all empty trips from I-80 for which there is an 8% reduction to 1.46×10^6 ESALs/yr, and 8.6 years between overlays.

Table 17 - I-80 Emissions after Eliminating Empty Trips

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg/yr)	0.56	0.39	0.096	$PM_{2.5}$ (10^3 kg/yr)	0.51	0.31	0.033
Difference		-0.28	-0.19	-0.008		-0.26	-0.16	-0.003
After Shift	NO_x (10^3 kg/yr)	20	14	0.15	CO (10^3 kg/yr)	5.4	3.2	0.40
Difference		-10	-7	-0.01		-2.7	-1.6	-0.03
After Shift	SO_2 (10^3 kg/yr)	0.022	0.023	0.24	Pb (kg/yr)			0.025
Difference		-0.011	-0.011	-0.02				-0.002
After Shift	Energy (TJ/yr)	31	32	1.5	GWP (10^3 kg CO_2 eq./yr)	2300	2300	130
Difference		-15	-16	-0.1		-1100	-1200	-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 18 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 section 4.1. Table 19 contains the associated changes in emissions. Accordingly, countries with aging roadways such as the U.S., 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 18 - I-80 Pavement Designs

	Current	New
HMA surface (cm)	21	23
Base (cm)	22	23
Subbase (cm)	28	30

Table 19 - I-80 Emissions Associated with Pavement Reconstruction

	PM_{10} (10^3 kg)	$PM_{2.5}$ (10^3 kg)	NO_x (10^3 kg)	CO (10^3 kg)	SO_2 (10^3 kg)	Pb (kg)	Energy (TJ)	GWP (10^3 kg CO_2 eq./yr)
Current Design	3.1	1.1	6.8	12	7.2	0.75	49	3800
New Design	3.3	1.2	7.3	13	7.7	0.79	52	4100

5. Discussion of Impacts and Related Policies

Although a quantitative estimation of impacts is beyond the scope of this paper, a discussion reveals much about the implications of the results of section 4. In addition, there exist additional types of policies which could have effects on pavement supply-chain emissions.

The hypothetical policy scenarios indicate that changes in pavement supply-chain emissions in many cases are unlikely to be a significant problem, however, there still exist situations in which considerable environmental damage may occur. In order to understand in which situations these may occur, the magnitudes of tailpipe and overlay supply-chain emissions can be compared. In the cases that the magnitude of supply-chain emissions are comparable to tailpipe, the unintended emissions are a potential cause for concern, since freight tailpipe emissions are presently a significant source of environmental problems. The only exceptions are Pb and SO_2, for which tailpipe emissions are already minimal. Of course, Pb has been banned from gasoline and diesel for many years. For SO_2, a reasonable assumption would be that the overlay supply-chain emissions are a cause of concern if they are about two orders of magnitude greater than tailpipe, since SO_2 emissions from on-road vehicles are not a large contributor to the total (U.S. Environmental Protection Agency, 2008b). Supply-chain SO_2 emissions are revealed to be two orders of magnitude larger for freight transportation on SR-13, which is primarily made up of smaller vehicles making local trips, and only one order greater for I-80, which serves larger vehicles on line-haul routes. The other pollutants and energy consumption, except for NO_x, are shown to be of similar order of magnitude for the case of freight traffic made up primarily of smaller vehicles, whereas tailpipe emissions on roads servicing large trucks tend to be significantly greater than those of the overlay supply chain. These results indicate that policies for increasing loads can be aimed at larger vehicles, without strong likelihood that unintended emissions will occur. On the other hand, increasing loads on smaller vehicles, which are often making local trips, is more likely to result in significant unintended impacts. This is a result of the difference in the types of vehicles and roads involved, as the tradeoff between overlay frequency and trip reduction differs. This tradeoff is represented by the contrast between SR-13 and I-80, since the latter highway serves much more traffic and in turn has higher tailpipe emissions, while the overlay frequency for both induces supply-chain emissions that are of a similar order of magnitude.

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 atmospheric conditions 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.

However, 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 AirData (U.S. Environmental Protection Agency, 2007) shows that several facilities lie in highly sensitive areas. 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 tradeoffs 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. In addition, the regional proximity can also influence the impact of emissions. For instance, acid rain in the northeastern part of the U.S. has been a significant health concern which results from SO_2 emissions across the region (Nazaroff and Alvarez-Cohen, 2001).

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. The consolidation of the retail industry 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, peak-period 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.

6. Data Uncertainty, Quality and Sensitivity

This section makes several points regarding the broader policy implications of the results in section 4, through an evaluation of the models and data used. The methodology of this section is similar to that employed in previous life-cycle assessments of transportation systems (Chester and Horvath, 2009; Facanha, 2006).

6.1.Model and Choice Uncertainty

This following provides a discussion of several sources of model and choice uncertainty. These sources are pavement design and deterioration models, system boundary selection, geographic variation of parameters and component methodology.

There is some uncertainty and potential variation in the pavement design and deterioration models used for this paper. Aspects of have been revised or called into question previously (Madanat et al., 2002). and damage can vary based on a multiple factors such as contact forces, instead of axle loads alone (Prozzi and Luo, 2005). However, the pavement design and deterioration models used for this paper are standards in California and the U.S. respectively. These models have been used in many studies and previous research does indicate that they are generally representative. For instance, it has been shown that although the fourth power law may not be exact, the deviations are not likely to be large enough to affect the policy conclusions of this paper (Prozzi and Madanat, 2003). In addition, the status quo results for ESALs and years between overlays in section 4 are reasonable.

The system boundary used in this study limits the analysis to a comparison of tailpipe and specific pavement maintenance and reconstruction activities. This provides basic policy implications, which are unlikely to differ greatly as a result of other types of maintenance activities, as asphalt overlays and pavements are prevalent on roadways. However, the analysis could be extended to account for additional materials such as cement and other types of routine maintenance such as chip seals. System boundaries could also be extended to include other phases of the life cycle. This paper has employed a more comprehensive methodology by incorporating pavement supply-chain emissions in addition to tailpipe, however, there may be additional unintended impacts in other life-cycle phases. 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.

The selection of appropriate LCA methodology follows closely that used in previous research for the infrastructure life-cycle phase (Chester and Horvath, 2009; Facanha, 2006; Facanha and Horvath, 2007). Through PaLATE, a hybrid methodology has been employed, in which process-based LCA is used for HMA plants, on-site equipment and a portion of particulate emissions at aggregate mines. EIO-LCA is used for the remainder of supply-chain emissions, which should be relatively representative of U.S.

averages for petroleum refineries and aggregate mines. The reader may refer to previous research (Chester, 2008) for a critique input-output models.

Results can differ by region as a result such variations such as transportation agency maintenance policies and supply-chain electricity sources. Table 1 shows the contributions to the total emissions of four pollutants made by industry sectors. As can be seen the dominant contributors are petroleum refineries, oil and gas extraction, HMA plants, and power generation and supply. Emissions from the former three sectors are not likely to have significant regional variation, however, the mix of electricity sources and subsequent emissions do vary geographically. For instance, the total SO_x emissions per delivered electricity in California is about 75% of the national average (Deru and Torcellini, 2007). Therefore, a more detailed analysis of load increase policies for California might reveal somewhat less SO_2 emissions than the results of section 4. Such uncertainties should not be ignored in future policy assessments, but are not expected to change general policy implications.

Table 20 – Percentage Contributions to Overlay Supply-Chain Emissions by Industry Sector

Source Sector	SIC Code	GWP	SO_2	PM_{10}	$PM_{2.5}$
Sand, Gravel, Clay and Refractory Mining	212320	2.0%	0.28%	2.7%	1.8%
Power Generation and Supply	221100	14%	40%	3.5%	5.9%
Stone Mining and Quarrying	212310	0.012%	0.26%	0.66%	0.38%
Waste Management and Remediation Services	562000	1.8%	0.13%	4.8%	12%
Warehousing and Storage	493000	0.18%	0.0019%	1.2%	0.95%
Iron and Steel Mills	331111	0.72%	0.44%	1.1%	2.1%
Petroleum Refineries	324110	30%	27%	6.9%	17%
Oil and Gas Extraction	211000	28%	16%	1.4%	3.7%
Support Activities for Oil and Gas Operations	213112	0.061%	6.4%	2.4%	4.2%
Cement Manufacturing	327310	0.74%	1.4%	0.59%	0.78%
Pipeline Transportation	486000	6.4%	0.043%	0.00%	0.00%
Truck Transportation	484000	0.84%	0.097%	0.20%	0.40%
State and local government electric utilities	S00202	0.57%	0.072%	0.00%	0.00%
Other (from bitumen and aggregate production supply chains)		7.4%	3.9%	7.1%	12%
HMA Plant		6.1%	1.2%	65%	34%
End Materials Transportation		2.7%	2.8%	1.8%	4.5%
On-Site Equipment		0.13%	0.13%	0.34%	0.88%

The pavement deterioration process varies significantly across locations, due to the influence of environmental effects. Pavements in areas with significant rain and freeze-thaw cycles, or extreme heat are known to have different types of deterioration processes. However, in most cases, pavements can be expected to be designed with account for these issues, which would reduce the nonuniformity of overlay frequency. Nevertheless, if design or maintenance strategies differ greatly, as is the case for the generally thicker European pavements versus those of the U.S., the implications of section 4 may not extend to such areas. These issues highlight the need for the use of context-specific pavement deterioration models in future assessments.

6.2. Parameter Uncertainty and Data Quality

In this section a data quality assessment (DQA) is presented, based on a pedigree matrix used in previous research (Chester and Horvath, 2009). The DQA is shown in Table 21. Generally, those parameters which have lower rankings have received higher quality assessments and have less uncertainty. The results of the DQA contribute to guiding the sensitivity analysis in section 6.3 and indicate which parameters may require closer examination in future policy analyses.

Table 21 - Data Quality Scoring Assessment Matrix

Parameter	Average	Impact on Final Result	Acquisition Method	Independence	Representation	Temporal Correlation	Geographical Correlation	Technological Correlation	Range of Variation
U	3.1	2	3	3	5	2	3	1	5
GVW	2.9	3	3	3	5	3	2	1	3
EVW	2.6	2	3	3	3	3	2	1	3
%empty trips	2.7	3	3	3	4	3	3	1	2
weight distributions (for each configuration class)	2.6	3	3	4	4	2	2	1	2
trips (for each vehicle class)	2.1	3	2	3	1	3	2	1	3
pavement thickness	1.7	3	2	3	1	2	1	1	2
4th power law	1.4	2	1	1	1	1	2	1	3
tailpipe emission factors	1.4	2	2	1	1	1	1	1	3
overlay supply-chain emission factors	2.3	2	2	1	1	4	2	1	5

6.3. Sensitivity Analysis

The focus of this paper is to analyze the general implications of policies aimed at increasing freight loads. Accordingly, this section is geared towards varying parameters of interest, which are likely to influence such implications. In particular, results are presented that account for future emission factors, asphalt recycling and varying load factors.

In recent years there have been significant reductions in criteria pollutant emission factors from heavy-duty vehicles. For examples, NO_x and particulate emission factors have dropped significantly (Ban-Weiss et al., 2007). Such reductions can be expected to continue as governments push for the implementation of control technologies and fleet modernization (California Air Resources Board, 2009). Table 22 shows the results of shifting loads from 2-axle to the largest two 3-axle vehicles, similarly to Table 10. However, in this case, the tailpipe emission factors used are 2020 projected values. In the 2020 scenario, particulate and NO_x emission factors from diesel vehicles are much less, reducing the likelihood of an unintended increase in tailpipe emissions. In general, the decrease in tailpipe emissions is far less than those in the analogous 2010 scenario of section 4, potentially increasing the importance of reducing the overlay supply-chain emissions in the future. Note that the rows labeled 'Difference' display the change versus the status quo with 2020 emission factors, not versus the status quo shown in section 4. This will be the case for all 'Difference' rows in tables in section 6.3, as they are calculated based on the status quo under the conditions for the associated scenario.

Table 22 - SR-13 2020 Tailpipe Emissions after 2-axle to Large 3-Axle Vehicle Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10} (10^3 kg /yr)	0.0087	0.0043	0.047	$PM_{2.5}$ (10^3 kg /yr)	0.0080	0.0025	0.016
Difference		-0.0040	-0.0020	0.025		-0.0036	-0.0015	0.009
After Shift	NO_x (10^3 kg /yr)	0.30	0.11	0.073	CO (10^3 kg /yr)	0.14	0.050	0.20
Difference		0.02	-0.05	0.039		-0.06	-0.184	0.10
After Shift	SO_2 (10^3 kg /yr)	0.0010	0.00072	0.12	Pb (kg/yr)			0.012
Difference		-0.0003	-0.00058	0.06				0.006
After Shift	Energy (TJ/yr)	1.4	1.1	0.76	GWP (10^3 kg CO_2 eq./yr)	100	100	60
Difference		-0.4	-0.6	0.40		-30	0	30

Asphalt is a heavily recycled product, with estimates indicating that up to 85% may be recycled in the U.S., although the majority of this is used in road bases rather than for new overlays (Horvath, 2003). The most common recycling method involves combining recycled and virgin material at an HMA plant (Santucci, 2007). PaLATE can be used to estimate recycled overlay supply-chain emissions by this method. In this case, the emissions associated with the aggregate and bitumen supply chains can be reduced depending on the fraction of recycled material assumed, whereas HMA emissions remain the same. The resulting emissions are shown in Table 23, which show that recycling can induce a significant reduction in overlay supply-chain emissions. However, Table 24 also indicates that the general policy conclusions are not likely to be greatly affected unless the fraction of recycled material in overlays is very high, since significant particulate emissions occur at the HMA plant and SO_2 emissions from the overlay supply-chain remain relatively large.

Table 23 – HMA Recycled Overlay Emissions for One Direction on a Two-Lane Highway

% of overlay from recycled asphalt	80%	50%	20%	0%
PM_{10} (10^3 kg)	0.31	0.35	0.39	0.42
$PM_{2.5}$ (10^3 kg)	0.073	0.010	0.13	0.14
SO_2 (10^3 kg)	0.24	0.54	0.83	1.0
CO (10^3 kg)	0.61	1.0	1.4	1.7
Pb (kg)	0.024	0.055	0.086	0.11
NO_x (10^3 kg)	0.29	0.47	0.64	0.76
GWP (10^3 kg CO_2 eq.)	150	300	460	560
Energy (TJ)	2.0	3.7	5.5	6.6

Table 24 - SR-13 Emissions after Within-Class Consolidation with Asphalt Recycling

		E2007	M6.2	OL (80%Rec)	OL (50%Rec)	OL (20%Rec)
After Shift	PM_{10} (10^3 kg /yr)	0.022	0.013	0.028	0.032	0.036
Difference		-0.010	-0.006	0.012	0.013	0.015
After Shift	$PM_{2.5}$ (10^3 kg /yr)	0.021	0.011	0.0067	0.0091	0.011
Difference		-0.009	-0.005	0.0028	0.0038	0.005
After Shift	SO_2 (10^3 kg /yr)	0.00092	0.00092	0.022	0.049	0.076
Difference		-0.00039	-0.00039	0.009	0.020	0.031
After Shift	CO (10^3 kg /yr)	0.37	0.30	0.056	0.094	0.13
Difference		-0.16	-0.13	0.023	0.039	0.05
After Shift	Pb (kg/yr)			0.0022	0.0050	0.0079
Difference				0.0009	0.0021	0.0033
After Shift	NO_x (10^3 kg /yr)	0.57	0.41	0.014	0.030	0.047
Difference		-0.38	-0.17	0.006	0.013	0.019
After Shift	GWP (10^3 kg CO_2 eq./yr)	100	90	14	28	42
Difference		-40	0	6	11	17
After Shift	Energy (TJ/yr)	1.3	1.2	0.18	0.34	0.50
Difference		-0.6	-0.5	0.08	0.14	0.21

In accordance with the DQA shown in Table 21, the value of U is a potential source of uncertainty. This is also clear from the significant variation in U across vehicle classes which can be found in data (Department of Transport: London, 2005). Table 25 displays the variable U values which are used to develop the emissions results shown in Table 26. These results are developed using the same methodology as that used to produce Table 7, however, variable values for U have been used. Consequently a within-class consolidation results in a greater percent change in ESALs and overlay emissions, since there is a greater increase in the value of the laden load factor. Nevertheless, the general policy implications appear to be unchanged.

Table 25 - Variable U Values for each Vehicle Class

GVW	5400	6800	8100	10300	13400	16600	20400	24900	29700
U	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70

Table 26 - SR-13 Emissions after Within-Class Consolidation with Variable U

		E2007	M6.2	OL		E2007	M6.2	OL
After Shift	PM_{10}	0.019	0.011	0.042	$PM_{2.5}$	0.018	0.0094	0.015
Difference	(10^3 kg /yr)	-0.013	-0.009	0.020	(10^3 kg /yr)	-0.012	-0.0073	0.007
After Shift	NO_x	0.62	0.36	0.065	CO	0.30	0.22	0.18
Difference	(10^3 kg /yr)	-0.19	-0.28	0.031	(10^3 kg /yr)	-0.23	-0.18	0.08
After Shift	SO_2	0.00075	0.00072	0.10	Pb (kg/yr)			0.011
Difference	(10^3 kg /yr)	-0.00057	-0.00060	0.05				0.005
After Shift	Energy	1.0	1.0	0.68	GWP (10^3 kg	100	100	60
Difference	(TJ/yr)	-0.8	-0.8	0.32	CO_2 eq./yr)	-100	-100	30

7. Conclusion

This paper provides an analysis methodology and assessment of the changes in pavement supply-chain emissions that may result from policies directed at increasing freight vehicle loads. The methodology integrates pavement design and deterioration models from the field of infrastructure management, and concepts of LCA, providing a framework which may be used for future policy assessments. These methods are then used to assess changes in tailpipe and pavement supply-chain emissions under various hypothetical policies to reveal whether or not unintended environmental impacts are likely to be a significant concern.

The scenarios analyzed reveal nuanced aspects of the potential for unintended emissions to occur. The within-class consolidation results indicate that overlay frequency can increase significantly as a result of a poorly designed policy. Consequently, the increase in overlay supply-chain emissions for SR-13 greatly offset those from the tailpipe for all pollutants, with the exception of NO_x. We may assume that these strong offsets are a likely source of environmental concern, since they are of similar order of magnitude to freight vehicle tailpipe emissions which are in general a significant concern presently. On the other hand, SO_2 is the only pollutant which causes a considerable offset for the within-class consolidation scenario on I-80. However, it should be noted that this is unlikely to be a significant cause of environmental damage, since tailpipe SO_2 emissions are already extremely low and the overlay supply-chain emissions are only one order of magnitude greater. As a result, load increase policies aimed at larger vehicles are unlikely to cause damaging unintended emissions.

Across-vehicle class consolidation shows the importance of understanding the types of vehicles involved in consolidation across vehicle classes. Future policy assessments should utilize the ratio of ESALs and emissions to CW to gain foresight regarding policy impacts. Unintended increases in particulate and NO_x tailpipe emissions could result from a consolidation from smaller gasoline to larger diesel-powered vehicles, as the ratio of these emissions to CW is relatively high for larger vehicles. Also, consolidation to 5-axle vehicles is shown either to cause a small increase or a reduction in total ESALs, whereas consolidation to 3-axle vehicles has the opposite effect, in accordance with the higher ratio of ESALs to CW for 3-axle vehicles.

Freight logistics policy-making with account of environmental impacts is a multi-faceted process. The analysis of this paper is presented to guide future policy making and 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.

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Appendix A. ESALS per trip 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. 3. The following is the ESALs per trip calculation for a three-axle single unit vehicle having a GVW of 16 600 kg. 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).

$$1 \times \left(\frac{GVW \times 0.325}{1 \times 8\,182}\right)^4 + 2 \times \left(\frac{GVW \times 0.675}{2 \times 8\,182}\right)^4 = 0.62$$

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 29 700 kg. The first term represents the steering axle and is assigned 5 900 kg. 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).

$$1 \times \left(\frac{5\,900}{1 \times 8\,182}\right)^4 + 2 \times \left(\frac{0.5 \times (GVW - 5\,900)}{2 \times 8\,182}\right)^4 + 2 \times \left(\frac{0.5 \times (GVW - 5\,900)}{2 \times 8\,182}\right)^4 = 1.4$$

Appendix B. 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.

$$TI\ for\ SR\text{-}13 = 9 \times \left(\frac{(170 \times 365 \times 20) \times 1}{10^6} \right)^{0.119} = 9.3$$

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 0.5 cm 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.

$$GE_{HMA} = (2.54\frac{cm}{inch}) \times 0.0032 \times TI \times (100 - CR_{AB}) + SafetyFactor \quad \text{Eq. C.2}$$

$$GE_{HMA+AB} = (2.54\frac{cm}{inch}) \times 0.0032 \times TI \times (100 - CR_{AS}) + SafetyFactor \quad \text{Eq. C.3}$$

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

$$GE_{total} = (2.54\frac{cm}{inch}) \times 0.0032 \times TI \times \left(100 - CR_{Subgrade}\right) \quad \text{Eq. C.5}$$

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

Table C.1 – Pavement Design for SR-13

	$GE\ (cm)$	$Thickness\ (cm)$
HMA	26	15
AB	16	15
AS	17	17
HMA+AB	43	
Total	59	

After design of a pavement is completed, a deterioration model is applied to estimate the ESALs to failure. Eq. 5, provided by AASHTO, is used to estimate the pavement SN (Small and Winston, 1988).

$$SN = \left(\frac{inch}{2.54\ cm}\right) \times (0.44 \times 15 + 0.14 \times 15 + 0.11 \times 17) = 4.1$$

The SN is subsequently incorporated into Eq. 6, provided by Madanat and Prozzi, to estimate the ESALs to failure (Madanat et al., 2002).

$$E[ESALs\ to\ failure\ for\ SR\text{-}13] = exp(12.15 + 6.68 \times \ln(4.1 + 1) + 2.62 \times \ln(1) - 3.03 \times \ln(18 + 1))$$
$$= 1300000\ ESALs$$

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

$$\frac{1300000 ESALs}{(190 \times 365\ ESALs/year)} \approx 19\ years$$

Appendix C. Tailpipe Emissions and Energy Consumption Factors

This appendix presents the emissions and energy consumption factors produced by E2007 and M6.2 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 32 km/hr, in accordance with the 40 km/hr speed limit.

Table 2 – SR-13 Emissions and Energy Consumption Factors

Axles	2	2	3	3	4	4	5	5	6
GVW (kg)	5400	13400	16600	29700	5400	29700	24900	29700	29700
E2007 PM_{10} (g/km)	0.025	0.26	0.34	0.45	0.025	0.45	0.45	0.45	0.45
M6.2 PM_{10} (g/km)	0.061	0.14	0.17	0.17	0.06	0.17	0.17	0.17	0.17
E2007 $PM_{2.5}$ (g/km)	0.022	0.24	0.31	0.42	0.022	0.42	0.42	0.42	0.42
M6.2 $PM_{2.5}$ (g/km)	0.046	0.12	0.14	0.14	0.047	0.14	0.14	0.14	0.14
E2007 NO_x (g/km)	1.6	5.9	7.6	11	1.6	11	11	12	12
M6.2 NO_x (g/km)	1.9	4.4	4.9	5.6	2.0	5.6	5.5	5.6	5.6
E2007 SO_2 (g/km)	0.0043	0.010	0.011	0.012	0.0043	0.012	0.012	0.012	0.012
M6.2 SO_2 (g/km)	0.0076	0.0088	0.0091	0.0091	0.0075	0.0091	0.0091	0.0091	0.0091
E2007 CO (g/km)	2.7	3.3	4.1	5.2	2.7	5.2	5.2	5.2	5.2
M6.2 CO (g/km)	3.4	2.7	2.8	2.4	3.3	2.4	2.4	2.4	2.4
M6.2 Energy (MJ/km)	8.4	12	13	14	8.4	14	13	14	14
E2007 Energy (MJ/km)	6.6	13	15	18	6.6	18	18	18	18
E2007 CO_2 (g/km)	500	1000	1100	1300	500	1300	1300	1300	1300
M6.2 CO_2 (g/km)	600	900	900	1000	600	1000	1000	1000	1000

Appendix D. 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 1.6-km long, 7.3-m wide and has a thickness of 7.6 cm. 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 (kg/m^3)	Volume (m^3)
Aggregate	0.90	2600	650
Bitumen	0.10	1000	190

Assumptions are made regarding the characteristics of the HMA industry. These are in accordance with the 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 particulate emissions control.

Table E.2 - Industry Characteristics for HMA Plants

Plant Type:	Batch	Drum
	48%	52%
Fuel Type:	Oil	Natural Gas
	20%	80%
Particulate control type:	Uncontrolled	Fabric Filter
	5.0%	95%

Emission 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

emission factors of Table E.3 are weighted averages based on fuel type. The other emission 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/10^3 kg)	$PM_{2.5}$ (g/10^3 kg)	SO_2 (g/10^3 kg)	CO (g/10^3 kg)	NO_x (g/10^3 kg)	CO_2 (g/10^6 kg)	Energy (MJ/10^3 kg)
Uncontrolled Batch-mix	2 200	130	11	200	22	19	260
Fabric Filter-Controlled Batch-mix	4.9	4.1	11	200	22	19	260
Uncontrolled Drum-mix	3 200	750	2.5	65	16	17	240
Fabric Filter-controlled Drum-mix	2.1	1.4	2.5	65	16	17	240
Industry	140	25	6.4	130	19	18	250

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

Plant Type	Fuel Type	NO_x (g/10^3 kg)	SO_2 (g/10^3 kg)
Batch	(Natural Gas)	12	2.3
	(Oil)	60	44
Drum	(Natural Gas)	13	1.7
	(Oil)	27	5.5

The industry weighted emission 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 890 m^3, having a density of 220 (10^3 kg)/m^3.

Table E.5 - Emissions Associated with the HMA Plant

PM_{10} (10^3 kg)	$PM_{2.5}$ (10^3 kg)	SO_2 (10^3 kg)	CO (10^3 kg)	Pb (kg)	NO_X (10^3 kg)	CO_2 (10^3 kg)	Energy (TJ)
0.27	0.049	0.012	0.25	0.00	0.037	34	0.49

The emission 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 emission factors after conversion using a market price of \$11/(10^3 kg), which is provided by PaLATE.

Table E.6 - Emission Factors for Aggregate Mining

PM_{10} (g/10^3 kg)	$PM_{2.5}$ (g/10^3 kg)	SO_2 (g/10^3 kg)	CO (g/10^3 kg)	Pb (g/10^3 kg)	NO_X (g/10^3 kg)	GWP (g CO_2 equiv./10^6 kg)	Energy (MJ/10^3 kg)
3.2	2.1	32	41	0.00	21	13	210

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 Factor Information REtrieval Software (U.S. Environmental Protection Agency, 2008a) 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 - Emission Factors for Aggregate Storage, Conveying and Screening

Source	SCC	PM_{10} (g/10^3 kg)	$PM_{2.5}$ (g/10^3 kg)
aggregate storage - construction sand and gravel	30502502	9.0	2.7
material transfer and conveying – construction sand and gravel	30502503	0.48	0.14
pile forming stacker - construction sand and gravel	30502505	4.5	1.3
bulk loading - construction sand and gravel	30502506	0.18	0.054
Screening - construction sand and gravel	30502511	5.1	0.34

Table E.8 displays the total emissions resulting from the 1.75×10^6 kg of aggregate used in the pavement overlay. This mass is in accordance with Table E.1.

Table E.8 - Emissions Associated With Aggregate

PM_{10} (10^3 kg)	$PM_{2.5}$ (10^3 kg)	SO_2 (10^3 kg)	CO (10^3 kg)	Pb (kg)	NO_X (10^3 kg)	GWP (10^3 kg CO_2 equiv)	Energy (TJ)
0.039	0.012	0.056	0.071	0.0054	0.037	25	0.36

Emission 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 $1.12/kg produce the emission factors as shown in Table E.9. The total emissions resulting from 190×10^3 kg of bitumen are shown in Table E.10.

Table E.9 - Emission Factors for Bitumen Production

PM_{10} (g/10^3 kg)	$PM_{2.5}$ (g/10^3 kg)	SO_2 (g/10^3 kg)	CO (g/10^3 kg)	Pb (g/10^3 kg)	NO_X (g/10^3 kg)	GWP (g CO_2 equiv./10^6 kg)	Energy (MJ/10^3 kg)
490	390	4 800	6 800	0.51	2 800	1 600	28 000

Table E.10 – Emissions Associated With Bitumen Production

PM_{10} (10^3 kg)	$PM_{2.5}$ (10^3 kg)	SO_2 (10^3 kg)	CO (10^3 kg)	Pb (kg)	NO_X (10^3 kg)	GWP (10^3 kg CO_2 equiv.)	Energy (TJ)
0.096	0.075	0.93	1.3	0.098	0.54	480	5.4

Emission factors for dump and tanker trucks are extracted from E2007. These factors are developed assuming a 22 000-kg truck traveling at an average of 40mph under typical local climate conditions. The trucks are assumed to make a 80-km round trip to deliver aggregate and bitumen to the HMA plant, and a 40-km 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} (10^3 kg)	$PM_{2.5}$ (10^3 kg)	SO_2 (10^3 kg)	CO (10^3 kg)	Pb (kg)	NO_X (10^3 kg)	CO_2 (10^3 kg)	Energy (TJ)
0.0074	0.0064	0.029	0.072	0.0031	0.14	15	0.33

Combined emission factors for paving equipment are presented in Table E.12 in units of grams per 10^3 kg 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 - Emission Factors for Paving Equipment

PM_{10} (g/10^3 kg)	$PM_{2.5}$ (g/10^3 kg)	SO_2 (g/10^3 kg)	CO (g/10^3 kg)	Pb (g/10^3 kg)	NO_X (g/10^3 kg)	GWP (g CO_2 equiv./10^3 kg)	Energy (MJ/10^3 kg)
0.73	0.66	0.68	2.2	0.00	10	380	6.8

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Table E.13 - Emissions Associated With Paving Equipment

PM_{10} (10^3 kg)	$PM_{2.5}$ (10^3 kg)	SO_2 (10^3 kg)	CO (10^3 kg)	Pb (kg)	NO_X (10^3 kg)	GWP (10^3 kg 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.