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 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

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 United Kingdom 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

[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.

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[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 case examples 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

[2] Although noise is an important impact, in this paper the term environment will account only for emissions, to focus the scope.

to present the effects of pavement within the freight road transportation life cycle, which are currently 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 impacts and relate policies, sensitivity analysis and 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 United Kingdom, 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 (Gorman, 2007; Holguin-Veras and Cetin, 2009; Janic, 2008). 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, 2006), due to the 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. 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 imprecision 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 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	Laden	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 the is 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, 2003; 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).

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 can be seen presented for two freight vehicles (Sathaye et al., 2009). This estimation procedure is applied, instead of using previously assumed ESALs values, due to the wide variation in values that have previously been assumed (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.

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

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

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

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

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

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.

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

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

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

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

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, 2006). 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 a previous paper (Sathaye et al., 2009). 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. 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 is 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, 2006). The years between overlays is the ratio of the expected value of ESALs to failure, obtained by using Eq. 6, and the annual ESALs on a roadway segment. An example showing the estimation of years between overlays has been presented in a previous paper (Sathaye et al., 2009).

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, 2006). Inputs are customized to the local climate, government regulations, roadway types, average speeds, and local vehicle age and VKT profiles.

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 vehicles. Weight correction factors are not introduced for other pollutants since broadly applicable factors have not been reported in the literature. Tailpipe emission factors used for scenarios on State Route 13 (SR-13) can be seen in a previous paper (Sathaye et al., 2009).

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 further details are presented in a previous paper (Sathaye et al., 2009).

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. The estimation of these emission factors is described in a previous paper (Sathaye et al., 2009). 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
SO_2 (10^3 kg)	1.0
CO (10^3 kg)	1.7
Pb (kg)	0.11
NO_x (10^3 kg)	0.76
GWP (10^3 kg CO_2 eq.)	560
Energy (TJ)	6.6

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. Multiple operational shifts will be considered in sections 4.1 and 4.2, including consolidation of loads within each vehicle class and consolidation from small to large vehicles on SR-13. For comparison, the status quo ESALs on the design lane and years between overlays are shown for each highway section in Table 3 and Table 5. The corresponding freight vehicle emissions for vehicles on all lanes are shown in Table 4 and Table 6. The use of the design lane for tables displaying 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 3 - SR-13 Status Quo ESALs and Years Between Overlays

ESALs/yr	Years between overlays
61.5×10^3	19

Table 4 - SR-13 Status Quo Emissions

	E2007	M6.2	OL		E2007	M6.2	OL
PM_{10} (10^3 kg/yr)	0.032	0.019	0.021	$PM_{2.5}$ (10^3 kg /yr)	0.029	0.015	0.0074
NO_x (10^3 kg /yr)	0.82	0.58	0.033	CO (10^3 kg /yr)	0.53	0.42	0.089
SO_2 (10^3 kg /yr)	0.0013	0.0013	0.053	Pb (kg/yr)			0.0055
Energy (TJ/yr)	1.8	1.7	0.34	GWP (10^3 kg CO_2 eq./yr)	100	100	30

Table 5 - I-80 Status Quo ESALs and Years Between Overlays

ESALs/yr	Years between overlays
1.49×10^6	8.1

Table 6 - I-80 Status Quo Emissions

	E2007	M6.2	OL		E2007	M6.2	OL
PM_{10} (10^3 kg /yr)	0.83	0.58	0.102	$PM_{2.5}$ (10^3 kg /yr)	0.77	0.47	0.035
NO_x (10^3 kg /yr)	30	22	0.16	CO (10^3 kg /yr)	8.0	4.9	0.42
SO_2 (10^3 kg /yr)	0.033	0.034	0.25	Pb (kg/yr)			0.026
Energy (TJ/yr)	46	48	1.6	GWP (10^3 kg CO_2 eq./yr)	3400	3500	140

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). Table 7 and Table 8 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. In Table 7, the first column shows the percent change in ESALs versus the status quo and the remaining two columns show results after policy implementation. In Table 8, 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 4. 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 urban areas may be environmentally damaging.

Table 7 - SR-13 ESALs and Years Between Overlays after Within-Class Consolidation

%Δ ESALs	ESALs/yr	Years between overlays
67%	103×10^3	12

Table 8 - 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	0.036	$PM_{2.5}$ (10^3 kg /yr)	0.021	0.011	0.012
Difference		-0.010	-0.006	0.014		-0.009	-0.005	0.005
After Shift	NO_x (10^3 kg /yr)	0.67	0.41	0.055	CO (10^3 kg /yr)	0.37	0.30	0.15
Difference		-0.15	-0.17	0.022		-0.16	-0.13	0.06
After Shift	SO_2 (10^3 kg /yr)	0.00092	0.00092	0.088	Pb (kg/yr)			0.0092
Difference		-0.00039	-0.00039	0.036				0.0037
After Shift	Energy (TJ/yr)	1.3	1.2	0.57	GWP (10^3 kg CO_2 eq./yr)	100	100	50
Difference		-0.6	-0.5	0.23		-41	-38	20

Table 9 and Table 10 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 9 - I-80 ESALs and Years Between Overlays after Within-Class Consolidation

%Δ ESALs	ESALs/yr	Years between overlays
61%	2.40×10^6	5.1

Table 10 - 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	0.16	$PM_{2.5}$ (10^3 kg /yr)	0.54	0.33	0.056
Difference		-0.25	-0.17	0.06		-0.23	-0.14	0.021
After Shift	NO_x (10^3 kg /yr)	24	15	0.25	CO (10^3 kg /yr)	5.7	3.4	0.68
Difference		-6	-6	0.10		-2.4	-1.4	0.26
After Shift	SO_2 (10^3 kg /yr)	0.024	0.024	0.41	Pb (kg/yr)			0.042
Difference		-0.010	-0.010	0.15				0.016
After Shift	Energy (TJ/yr)	32	34	2.6	GWP (10^3 kg CO_2 eq./yr)	2400	2400	220
Difference		-14	-14	1.0		-1000	-1000	80

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 11 and Table 12 present the results of load consolidation from 2-axle to the two smaller 3-axle vehicle classes shown in Table 1, whereas Table 13 and Table 14 show the results of consolidation from 2-axle to the two larger 3-axle vehicle classes shown in Table 1. 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 particulate emissions resulting from load consolidation to 3-axle vehicles.

Table 11 - SR-13 ESALs and Years Between Overlays after 2-axle to Small 3-axle Vehicle Consolidation

%Δ ESALs	ESALs/yr	Years between overlays
31%	80.6×10^3	15

Table 12 - 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	0.028	$PM_{2.5}$ (10^3 kg /yr)	0.040	0.015	0.0096
Difference		0.012	-0.001	0.007		0.011	-0.001	0.0023
After Shift	NO_x (10^3 kg /yr)	1.01	0.55	0.043	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	0.069	Pb (kg/yr)			0.0072
Difference		-0.0001	-0.0004	0.016				0.0017
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	0.11		0	-20	10

Table 13 - SR-13 ESALs and Years Between Overlays after 2-Axle to Large 3-Axle Vehicle Consolidation

%Δ ESALs	ESALs/yr	Years between overlays
86%	114×10^3	10

Table 14 - 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	0.040	$PM_{2.5}$ (10^3 kg /yr)	0.033	0.011	0.014
Difference		0.004	-0.005	0.018		0.003	-0.004	0.006
After Shift	NO_x (10^3 kg /yr)	0.88	0.44	0.061	CO (10^3 kg /yr)	0.41	0.19	0.16
Difference		0.06	-0.14	0.028		-0.12	-0.23	0.08
After Shift	SO_2 (10^3 kg /yr)	0.00099	0.00073	0.098	Pb (kg/yr)			0.010
Difference		-0.00033	-0.00059	0.045				0.005
After Shift	Energy (TJ/yr)	1.4	1.1	0.63	GWP (10^3 kg CO_2 eq./yr)	100	100	50
Difference		-0.4	-0.6	0.29		-30	0	20

Table 15 and Table 16 display the results of consolidation from the two smallest 2-axle vehicle classes to 5-axle vehicles and Table 16 and Table 17 display the results of consolidation from all 2-axle vehicle classes to 5-axle vehicles. 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 15 - SR-13 ESALs and Years Between Overlays after Small 2-axle to 5-axle Vehicle Consolidation

%Δ ESALs	ESALs/yr	Years between overlays
4.4%	64.2×10^3	19

Table 16 - 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	0.022	$PM_{2.5}$ (10^3 kg /yr)	0.029	0.013	0.0077
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	0.034	CO (10^3 kg /yr)	0.40	0.26	0.093
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	0.055	Pb (kg/yr)			0.0057
Difference		-0.0002	-0.00040	0.002				0.0002
After Shift	Energy (TJ/yr)	1.5	1.3	0.36	GWP (10^3 kg CO_2 eq./yr)	100	100	30
Difference		-0.3	-0.5	0.01		0	0	0

Table 17 - SR-13 ESALs and Years Between Overlays after All 2-axle to 5-axle Vehicle Consolidation

%Δ ESALs	ESALs/yr	Years between overlays
-9.4%	55.7×10^3	21

Table 18 - 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	0.019	$PM_{2.5}$ (10^3 kg /yr)	0.026	0.0088	0.0067
Difference		-0.004	-0.008	-0.002		-0.004	-0.0064	-0.0007
After Shift	NO_x (10^3 kg /yr)	0.69	0.35	0.030	CO (10^3 kg /yr)	0.32	0.15	0.080
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	0.048	Pb (kg/yr)			0.0050
Difference		-0.00054	-0.00074	-0.005				-0.0005
After Shift	Energy (TJ/yr)	1.1	0.85	0.31	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 11 through Table 18 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 a list of this ratio for all vehicle classes which have been used. Table 19 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 19 is a weighted average of empty and laden ESALs per trip values. 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 consolidation policies can be both beneficial and damaging, depending on the vehicles involved.

A similar ratio is estimated for emissions versus CW, as shown in Table 19. 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 12 and Table 14. Therefore, consolidation to larger vehicles involving a change from gasoline to diesel engines should be carefully considered in cases that particulate matter or NO_x tailpipe emissions are of great concern.

Table 19 – 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 NO_x (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	86	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

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, one can reasonably assume that 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 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, 2008). 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, but only one order greater for I-80. 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 targeted 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 types of roads that each of these vehicles uses, 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 services much more traffic in turn 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 atmosphere in which the releases occur. 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 impact 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 facility location. 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 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 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.

Additional policies have been analyzed in a previous paper (Sathaye et al., 2009). One such scenario involves the affects of consolidation under increased maximum vehicle weight regulations, with increased axle requirements. This scenario reveals the improvements in overlay frequency and associated emissions that result from increasing the axles per vehicle. On the other hand, subsequent consolidation still causes increased overlay emissions. In another scenario, a reduction in empty running is shown to improve tailpipe emissions, but not make a significant reduction to those associated with overlays due to relatively low ESALs per trip when vehicles are empty. In a third scenario, the reconstruction of I-80 after increased within-class consolidation is shown to increase associated pavement construction emissions by around 6%.

6. Uncertainty, Data Quality and Sensitivity

Uncertainty and data quality assessment regarding the results in section 4 is further addressed in a previous paper (Sathaye et al., 2009) and has also been discussed more generally for LCAs of transportation (Chester and Horvath, 2009; Facanha, 2006). Of note is the 40% contribution to overlay supply chain SO_2 emissions made by the EIO-LCA Power Generation and Supply sector, which represents a U.S. average. This relatively high contribution is likely to vary geographically, due to the difference is electricity sources. For instance, the total SO_x emissions per delivered electricity in California is about 75% of the national average (Deru and Torcellini, 2007).

The focus of this paper is to analyze the general implications of policies aimed at increasing freight loads. Accordingly, the sensitivity analysis 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 20 shows the results of shifting loads from 2-axle to the largest two 3-axle vehicles, similarly to Table 14. 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, as they are calculated based on the status quo under the conditions for the associated scenario. 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, potentially increasing the importance of reducing the overlay supply-chain emissions in the future.

Table 20 - 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	0.040	$PM_{2.5}$ (10^3 kg /yr)	0.0080	0.0025	0.014
Difference		-0.0040	-0.0020	0.018		-0.0036	-0.0015	0.006
After Shift	NO_x (10^3 kg /yr)	0.30	0.11	0.061	CO (10^3 kg /yr)	0.14	0.050	0.16
Difference		0.02	-0.05	0.028		-0.06	-0.184	0.08
After Shift	SO_2 (10^3 kg /yr)	0.0010	0.00072	0.098	Pb (kg/yr)			0.010
Difference		-0.0003	-0.00058	0.045				0.005
After Shift	Energy (TJ/yr)	1.4	1.1	0.63	GWP (10^3 kg CO_2 eq./yr)	100	100	50
Difference		-0.4	-0.6	0.29		-30	0	20

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 instead of 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. In this case, the emissions associated with the aggregate and bitumen supply chains can be reduced depending on the fraction of recycled material assumed. The resulting emissions are shown in Table 21, which show that recycling can induce a significant reduction in overlay supply-chain emissions. However, Table 22 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 21 – 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 22 - 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	0.026	0.030	0.033
Difference		-0.010	-0.006	0.011	0.012	0.013
After Shift	$PM_{2.5}$ (10^3 kg /yr)	0.021	0.011	0.0063	0.0086	0.011
Difference		-0.009	-0.005	0.0025	0.0035	0.004
After Shift	SO_2 (10^3 kg /yr)	0.00092	0.00092	0.021	0.046	0.072
Difference		-0.00039	-0.00039	0.008	0.019	0.029
After Shift	CO (10^3 kg /yr)	0.37	0.30	0.053	0.089	0.12
Difference		-0.16	-0.13	0.021	0.036	0.05
After Shift	Pb (kg/yr)			0.0021	0.0047	0.0074
Difference				0.0008	0.0019	0.0030
After Shift	NO_x (10^3 kg /yr)	0.57	0.41	0.013	0.029	0.044
Difference		-0.38	-0.17	0.005	0.012	0.018
After Shift	GWP (10^3 kg CO_2 eq./yr)	100	90	13	26	39
Difference		-41	-38	5	11	16
After Shift	Energy (TJ/yr)	1.3	1.2	0.17	0.32	0.47
Difference		-0.6	-0.5	0.07	0.13	0.19

The value of U is a potential source of uncertainty (Sathaye et al., 2009), and therefore some analysis will be presented with a change in the value of the variable. Smaller vehicles can generally be expected to have lower load factors, since they are more likely to make multiple deliveries on a single tour. Accordingly, Table 23 displays the varying U values which are used to develop the emissions results shown in Table 24. These results are developed using the same methodology as that used to produce Table 8, however varying 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 23 - 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 24 - 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	0.041	$PM_{2.5}$	0.018	0.0094	0.014
Difference	(10^3 kg /yr)	-0.013	-0.009	0.019	(10^3 kg /yr)	-0.012	-0.0073	0.007
After Shift	NO_x	0.62	0.36	0.062	CO	0.30	0.22	0.17
Difference	(10^3 kg /yr)	-0.19	-0.28	0.029	(10^3 kg /yr)	-0.23	-0.18	0.08
After Shift	SO_2	0.00075	0.00072	0.10	Pb (kg/yr)			0.010
Difference	(10^3 kg /yr)	-0.00057	-0.00060	0.05				0.005
After Shift	Energy	1.0	1.0	0.65	GWP (10^3 kg	100	100	50
Difference	(TJ/yr)	-0.8	-0.8	0.31	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 conducting 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 policies assessed in section 4 reveal nuanced aspects of the potential for unintended emissions to occur. The within-class consolidation results in section 4.1 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, as discussed in section 5, 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.

Section 4.2 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.

In section 6 scenarios are presented with future emissions factors and with the assumption that a percentage of overlay materials is recycled. In addition, a scenario with varied values for U is presented, in accordance with the uncertainty for this parameter. Nevertheless, the sensitivity analysis indicates that the general conclusions should be consistent, regardless of uncertainty in the data and models.

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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