

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 pollutant 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.

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 32.5 to 41 tons over the last 25 years and the European Commission has issued a directive requiring its member countries to permit 40-ton vehicles on their roadways (McKinnon, 2005). Such adaptations are becoming increasingly common as much of the logistics industry is driven by trends such as just-in-time business, causing a reduction in load factors.

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

This paper presents the first study of the effects of logistics policies on emissions in the pavement supply chain. Descriptive case examples of operational shifts made by freight vehicles on California roadways are presented to contrast the benefits and unintended environmental impacts of various policies. Tailpipe and pavement supply-chain emissions are estimated under various paradigms in order to present the effects of pavement within the freight road transportation life cycle, which are neglected in logistics and environmental policy-making. The emissions accounted for are criteria pollutants (PM₁₀, PM_{2.5}, SO₂, CO, Pb, NO_x) and greenhouse gases (GHG). CO₂ is the only GHG from tailpipe emissions as it dominates releases due to fuel combustion. On

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.

the other hand, multiple global warming pollutants are significant contributors to pavement supply-chain emissions and are additionally taken into account. Energy consumption is also estimated. Emissions and energy consumption estimates are made for both initial construction and life-cycle overlays of asphalt pavements.

2. Previous Work

Most assessments of the environmental impacts associated with load factor shifts have been constrained to tailpipe emissions. Being at the forefront of environmental concerns, tailpipe CO₂ emissions have received attention in the literature. For examples, researchers estimate CO₂ emissions reductions in London (Browne and Allen, 1999), Japan (Taniguchi and van der Heijden, 2000). Increased load factors can undoubtedly contribute to policies aimed at reducing GHG emissions. However, other pollutants (e.g., criteria air emissions) having local and regional effects should also be considered in policy making.

Transportation agencies in the United States and United Kingdom have devoted significant attention to maximum weight restrictions. 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 (McKinnon, 2005). In the United States emissions are almost entirely neglected from truck weight studies, although fuel consumption has been investigated. The U.S. Department of Transportation (USDOT) has analyzed a hypothetical North American trade scenario focused on facilitating international trade by allowing heavier loads which would fit containers acceding to the International Organization for Standardization limits (U.S. Federal Highway Administration, 2000). The scenario predicts an approximately 6% decrease in energy consumption.

Tailpipe emissions and energy consumption are common indicators of sustainability, however the concept of environmental life-cycle assessment (LCA) has also come to the forefront in the last decade to account for indirect effects (ISO 14040, 1997). A LCA of freight transportation in the United States reveals that significant emissions result outside the operational phase (Facanha and Horvath, 2006). In fact the majority of emissions of PM₁₀, SO₂, CO, and Pb are found to occur outside the operational phase for road freight transportation. In particular, PM₁₀ and SO₂ are found to have significant emissions associated with infrastructure, comprising approximately 75% and 20% of the life-cycle emissions, respectively. A rough estimate of life-cycle emissions, after increasing the truck capacity of large trucks, produces estimates in accordance with these results (Facanha, 2006). Such results give strong indication that there may be unintended environmental impacts when road freight movement is shifted to heavier vehicles.

3. Data and Methodology

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

3.1. Estimation of Vehicle Trips and ESALs

Data about vehicle characteristics are necessary to accurately represent changes in freight traffic flows before and after policy implementations. The process used to develop this information involves multiple sources, which are used to classify vehicles and estimate their capacities. Equivalent Single Axle Loads (ESALs) per vehicle are then estimated. Both capacity and ESALs values are then verified against commonly assumed values. This process is described in detail in (Sathaye et al., 2009). The only difference in the methodology of this paper is that Caltrans ESALs defaults are assumed, so the validation is simply a comparison against these values.

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

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

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

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

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

$$EW = \frac{GVW}{U \times \left(\frac{1}{R} - 1\right) + 1} \quad \text{Eq. 4}$$

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

The next step is the estimation of empty and laden ESALs per trip for each vehicle class. This estimation is conducted based on axle configurations for freight vehicles. Reports compiled as part of the Comprehensive Truck Size and Weight Study (U.S. Federal Highway Administration, 1996a; U.S. Federal Highway Administration, 1996b) are used to determine the mileage distribution across axle configuration types for the California vehicle population. The ESALs per vehicle for each configuration are estimated based on GVW and the pavement deterioration fourth power law for each axle group (American Association of State Highway and Transportation Officials, 1993).

The mileage distribution for axle configurations in California is then applied to derive an estimate of the ESALs per trip when empty and laden for each vehicle class. These values for ESALs per trip are used to model pavement deterioration.

Finally, we validate the estimates of ESALs per trip for each vehicle class by confirming that they are in accordance with previous data (Sathaye et al., 2009). An additional validation method confirms the process for calculating CW for the vehicles with five or more axles. The calculated values of U , based on Eq. 1, must be near a priori expectations about the laden load factor. As aforementioned, we assumed these values to be near 70% in this research.

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 surface thicknesses for a flexible pavement. These are based on variables such as subgrade material and a design ESALs value. In the case examples of section 4, we assume that all pavements are constructed using this three-layer design. An example of pavement design by this method is presented in (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 (Small et al., 1989).

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

In the case examples we assume that maintenance policy affects only the frequency of three-inch HMA overlays. This is the minimum thickness specified by the HDM in response to unacceptable ride quality (California Department of Transportation, 2006). The years between overlays is the ratio of the expected value of ESALs to failure and the annual ESALs on a roadway segment.

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). The application of the two models provides a range for comparison against emissions from the pavement supply chain. Inputs are customized to the local climate, government regulations, roadway types, average speeds, and local vehicle age and mileage profiles.

NO_x emissions for heavy-duty vehicles have additionally been found to generally change by half the percentage increase in weight (Gajendran and Clark, 2003). This correction is incorporated when accounting for emissions factors for vehicles with *GVW* heavier than the average of the minimum and maximum weights of the heaviest E2007 and M6.2 vehicle classes.

3.4. Pavement Supply-Chain Emissions

The estimation of pavement supply-chain emissions involves the integration of multiple data sources. The most comprehensive LCA tool for pavements, the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) provides the basis for developing emissions factors (Horvath, 2008). However, several augmentations have been made to compile a more comprehensive portfolio of emissions which is representative of local conditions. One such augmentation is the inclusion of PM_{2.5} emissions estimates. A further discussion of these augmentations can be found in (Sathaye et al., 2009). Table 1 presents the emissions associated with a three-inch, two-lane, one-mile HMA overlay, which is assumed to be used for SR-13. Note that GHG emissions are represented by global warming potential (GWP) in CO₂ equivalent units as described in EIO-LCA documentation (Cicas et al., 2006).

Table 1 - HMA Overlay Emissions for One Direction on a Two-Lane Highway

PM ₁₀ (MT)	0.42
PM _{2.5} (MT)	0.14
SO ₂ (MT)	1.0
CO (MT)	1.7
Pb (kg)	0.11
NO _x (MT)	0.77
GWP (MT CO ₂ eq.)	560
Energy (TJ)	6.6

4. Case Examples

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

4.1.1. Consolidation within Vehicle Classes

Governments and international agencies have generally encouraged increases in load factors (European Environment Agency, 2006). In accordance with this sentiment, load factor requirements have been considered and implemented in some cities, but this is typically done without consideration for the sizes of vehicles involved (Geroliminis and Daganzo, 2005). Table 2 through Table 4 present the results of shifting loads on SR-13 so that 100% of vehicles are fully laden, without any transfer of cargo across vehicle classes. Most of the pollutant emissions associated with overlays are within the same order of magnitude to those of tailpipe emissions. In particular, SO₂ is found to be dominated by overlay emissions and the drop in particulate tailpipe emissions is greatly offset by those from overlays. These results indicate that blindly imposing load factor controls in urban areas can cause significant increases in pavement supply chain-emissions.

Table 5 through Table 7 present the results of the same policy applied to I-80. Again SO₂ 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 2 - SR-13 Change in Overlay Frequency after Within Class Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day
Status Quo	0%	0%	22.7	52
After Shift	100%	44%	15.7	75

Table 3 - SR-13 Changes in Trips after Within Class Consolidation

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

Table 4 - SR-13 Change in Emissions after Within Class Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
Status Quo	PM ₁₀	0.025	0.019	0.018	PM _{2.5}	0.023	0.016	0.0063
After Shift	(MT/yr)	0.018	0.013	0.026	(MT/yr)	0.016	0.011	0.0092
Difference		-0.0078	-0.0058	0.0081		-0.0072	-0.0048	0.0028
Status Quo	NO _x	0.81	0.58	0.034	CO	0.60	0.76	0.076
After Shift	(MT/yr)	0.56	0.41	0.05	(MT/yr)	0.42	0.53	0.11
Difference		-0.25	-0.18	0.015		-0.18	-0.23	0.034
Status Quo	SO ₂	0.0011	0.0013	0.045	Pb			0.0047
After Shift	(MT/yr)	0.00078	0.00089	0.065	(kg/yr)			0.0068
Difference		-0.00034	-0.00038	0.020				0.0021
Status Quo	Energy	1.6	1.6	0.29	GWP	120	120	25
After Shift	(TJ/yr)	1.1	1.1	0.42	(MT CO ₂ eq./yr)	81	80	35
Difference		-0.48	-0.49	0.13		-39	-40	11

Table 5 - I-80 Change in Overlay Frequency after Within Class Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day
Status Quo	0%	0%	8.9	2663
After Shift	100%	63%	5.4	4352

Table 6 - I-80 Changes in Trips after Within Class Consolidation

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

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

		E2007	M6.2	OL		E2007	M6.2	OL
Status Quo	PM ₁₀	0.87	0.68	0.094	PM _{2.5}	0.80	0.57	0.033
After Shift	(MT/yr)	0.59	0.46	0.15	(MT/yr)	0.54	0.39	0.053
Difference		-0.28	-0.22	0.060		-0.26	-0.18	0.021
Status Quo	NO _x	36	25	0.17	CO	9.0	7.6	0.39
After Shift	(MT/yr)	24	17	0.28	(MT/yr)	6.2	5.3	0.64
Difference		-11	-8.0	0.11		-2.9	-2.4	0.25
Status Quo	SO ₂	0.031	0.034	0.23	Pb			0.024
After Shift	(MT/yr)	0.021	0.023	0.38	(kg/yr)			0.039
Difference		-0.010	-0.011	0.15				0.015
Status Quo	Energy	43	47	1.5	GWP	3200	3400	100
After Shift	(TJ/yr)	29	32	2.4	(MT CO ₂	2200	2300	200
Difference		-14	-15	0.9	eq./yr)	-1000	-1100	100

4.1.2. 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 8 and Table 9 present the results of load consolidation from two-axle to three-axle vehicles, whereas Table 10 and Table 11 present the results of load consolidation from two-axle to five-axle vehicles. The emissions associated with pavements are far greater after a shift to five-axle vehicles than to three-axes. However, tailpipe emissions are also much more significantly reduced, revealing a trade-off for policy making. Policy decisions involving vehicle size are further complicated by the increased use of diesel engines for heavier vehicle classes. The fraction of mileage traveled by diesel vehicles in Alameda County, which contains SR-13, is about 41% for the smallest two-axle vehicle class, 89% for the smallest three-axle class, and 96% for five-axle vehicles (California Air Resources Board, 2006). Subsequently, the reductions in tailpipe particulate and NO_x emissions are not nearly as great as those for other pollutants. In fact, E2007 predicts an increase in particulate emissions resulting from load consolidation to three-axle vehicles. It should be noted that in general the results for the shift to five-axle vehicles are likely to be conservative estimates since the vehicle classification used in this research does not differentiate amongst the weights for the largest vehicles for which pavement damage would be greatly affected by the fourth power law.

Table 8 - SR-13 Changes in Overlay Frequency and Trips after 2-axle to 3-axle Load Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	2-axle trips/day	3-axle trips/day
Status Quo	0%	0%	22.7	52	212.5	37
After Shift	100%	-2%	23.0	51	0	113.7

Table 9 - SR-13 Changes in Emissions after 2-axle to 3-axle Load Consolidation

	E2007	M6.2	OL	E2007	M6.2	OL		
Status Quo	PM ₁₀	0.025	0.019	0.018	PM _{2.5}	0.023	0.016	0.0063
After Shift	(MT/yr)	0.029	0.015	0.018	(MT/yr)	0.026	0.013	0.0062
Difference		0.0033	-0.0036	-0.0003		0.0031	-0.0026	-0.00010
Status Quo	NO _x	0.69	0.58	0.034	CO	0.60	0.76	0.076
After Shift	(MT/yr)	0.64	0.45	0.03	(MT/yr)	0.36	0.33	0.075
Difference		-0.048	-0.13	-0.0005		-0.25	-0.43	-0.0012
Status Quo	SO ₂	0.0011	0.0013	0.045	Pb			0.0047
After Shift	(MT/yr)	0.00084	0.00073	0.044	(kg/yr)			0.0046
Difference		-0.00027	-0.00054	-0.0007				-0.00007
Status Quo	Energy	1.6	1.6	0.29	GWP	120	120	25
After Shift	(TJ/yr)	1.2	1.0	0.29	(MT CO ₂ eq./yr)	87	73	24
Difference		-0.39	-0.61	-0.004		-33	-47	0

Table 10 - SR-13 Changes in Overlay Frequency and Trips after 2-axle to 5-axle Load Consolidation

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	2-axle trips/day	5-axle trips/day
Status Quo	0%	0%	22.7	52	212.5	17.6
After Shift	100%	13%	20.0	59	0	46.1

Table 11 - SR-13 Changes in Emissions after 2-axle to 5-axle Load Consolidation

		E2007	M6.2	OL		E2007	M6.2	OL
Status Quo	PM ₁₀	0.025	0.019	0.018	PM _{2.5}	0.023	0.016	0.0063
After Shift	(MT/yr)	0.024	0.011	0.021	(MT/yr)	0.022	0.009	0.0072
Difference		-0.00095	-0.0080	0.0024		-0.00085	-0.0065	0.0008
Status Quo	NO _x	0.69	0.58	0.034	CO	0.60	0.76	0.076
After Shift	(MT/yr)	0.54	0.33	0.04	(MT/yr)	0.28	0.19	0.086
Difference		-0.14	-0.25	0.0045		-0.32	-0.57	0.010
Status Quo	SO ₂	0.0011	0.0013	0.045	Pb			0.0047
After Shift	(MT/yr)	0.00061	0.00049	0.051	(kg/yr)			0.0053
Difference		-0.00051	-0.00079	0.0060				0.00062
Status Quo	Energy	1.6	1.6	0.29	GWP	120	120	25
After Shift	(TJ/yr)	0.9	0.7	0.33	(MT CO ₂	64	50	28
Difference		-0.70	-0.91	0.038	eq./yr)	-56	-70	3

4.1.3. Increasing Maximum Weight

Several scenarios involving increases in maximum vehicle weight regulations in the United States have been discussed. For instance, a North American trade scenario has been suggested in which weight limits are increased to enhance international trucking productivity in the United States (U.S. Federal Highway Administration, 2000). The suggested regulations would set the tridem axle weight limit to 44 000 pounds, affecting multiple truck types. In particular, the case of shifting cargo from five-axle to six-axle vehicles with an increase in maximum GVW limit to 90 000 pounds is analyzed. Table 12 and Table 13 show that pavement deterioration and associated emissions can be greatly reduced by distributing loads across multiple axles. On the other hand, Table 14 and Table 15 indicate that load consolidation for heavy vehicles hastens pavement deterioration, despite the increased axles per vehicle. Table 16 and Table 17 show that this problem is greatly exacerbated by the suggested increase in maximum GVW to 90 000 pounds. Clearly, policies for reducing pavement deterioration are in line with those for reducing pavement supply change emissions, however, increased maximum weights should be more carefully considered if increased load factors are also a goal.

Table 12 – I-80 Changes in Overlay Frequency and Trips after Shift from 5-axle to 6-axle Trucks

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	5-axle trips/day	6-axle trips/day
Status Quo	0%	0%	8.9	2663	2339.8	57.0
After Shift	100%	-20%	11.1	2124	0	2396.8

Table 13 - I-80 Changes in Emissions after Shift from 5-axle to 6-axle trucks

		E2007	M6.2	OL		E2007	M6.2	OL
Status Quo	PM ₁₀	0.87	0.68	0.094	PM _{2.5}	0.80	0.57	0.033
After Shift	(MT/yr)	0.87	0.68	0.075	(MT/yr)	0.80	0.57	0.026
Difference		0.00	0.00	-0.019		0.00	0.00	-0.0066
Status Quo	NO _x	31	25	0.17	CO	9.0	7.6	0.39
After Shift	(MT/yr)	32	25	0.14	(MT/yr)	9.0	7.6	0.31
Difference		0.39	0.26	-0.035		0.00	0.00	-0.079
Status Quo	SO ₂	0.031	0.034	0.23	Pb			0.024
After Shift	(MT/yr)	0.031	0.034	0.18	(kg/yr)			0.019
Difference		0.00	0.00	-0.047				-0.0049
Status Quo	Energy	43	47	1.5	GWP	3200	3400	130
After Shift	(TJ/yr)	43	47	1.2	(MT CO ₂	3200	3400	100
Difference		0.00	0.00	-0.302	eq./yr)	0.00	0.00	-30

Table 14 - I-80 Changes in Overlay Frequency and Trips after Shift from 5-axle to 6-axle, 80 000-lb Trucks

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	5-axle trips/day	6-axle 80 000-lb trips/day
Status Quo	0%	0%	8.9	2663	2339.8	0
After Shift	100%	12%	7.9	2971	0	1633.0

Table 15 - I-80 Changes in Emissions after Shift from 5-axle to 6-axle, 80 000-lb Trucks

		E2007	M6.2	OL		E2007	M6.2	OL
Status Quo	PM ₁₀	0.87	0.68	0.094	PM _{2.5}	0.80	0.57	0.033
After Shift	(MT/yr)	0.66	0.55	0.10	(MT/yr)	0.61	0.46	0.036
Difference		-0.21	-0.13	0.011		-0.19	-0.11	0.0038
Status Quo	NO _x	31	25	0.17	CO	9.0	7.6	0.39
After Shift	(MT/yr)	27	21	0.19	(MT/yr)	7.4	6.8	0.43
Difference		-4.5	-3.5	0.020		-1.6	-0.86	0.045
Status Quo	SO ₂	0.031	0.034	0.23	Pb			0.024
After Shift	(MT/yr)	0.025	0.028	0.26	(kg/yr)			0.027
Difference		-0.01	-0.01	0.027				0.0028
Status Quo	Energy	43	47	1.5	GWP	3200	3400	130
After Shift	(TJ/yr)	35	39	1.7	(MT CO ₂	2600	2800	140
Difference		-8.1	-8.0	0.17	eq./yr)	-600	-600	10

Table 16 - I-80 Changes in Overlay Frequency and Trips after Shift from 5-axle to 6-axle, 90 000-lb Trucks

	% Trips Shifted	%Δ ESALs	Years between overlays	ESALs/day	5-axle trips/day	6-axle 90 000-lb trips/day
Status Quo	0%	0%	8.9	2663	2339.8	0
After Shift	100%	55%	5.7	4126	0	1451.6

Table 17 - I-80 Changes in Emissions after Shift from 5-axle to 6-axle, 90 000-lb Trucks

		E2007	M6.2	OL		E2007	M6.2	OL
Status Quo	PM ₁₀	0.87	0.68	0.094	PM _{2.5}	0.80	0.57	0.033
After Shift	(MT/yr)	0.61	0.51	0.15	(MT/yr)	0.56	0.43	0.050
Difference		-0.26	-0.16	0.052		-0.24	-0.14	0.018
Status Quo	NO _x	31	25	0.17	CO	9.0	7.6	0.39
After Shift	(MT/yr)	26	21	0.27	(MT/yr)	7.0	6.6	0.60
Difference		-5.3	-4.1	0.096		-2.0	-1.08	0.21
Status Quo	SO ₂	0.031	0.034	0.23	Pb			0.024
After Shift	(MT/yr)	0.024	0.027	0.36	(kg/yr)			0.037
Difference		-0.0074	-0.0068	0.13				0.013
Status Quo	Energy	43	47	1.5	GWP	3200	3400	130
After Shift	(TJ/yr)	33	36	2.3	(MT CO ₂ eq./yr)	2400	2600	190
Difference		-10	-10	0.82		-800	-800	60

5. Conclusion

The increase of loads on road freight transportation vehicles has the potential to significantly reduce tailpipe emissions. However there can exist confounding life-cycle effects. In particular, this paper shows that although the net emissions of multiple pollutants including GHG emissions can be reduced, SO₂ and particulate emissions can be increased. This unintended result appears to cause significant offsets, especially in the case of local freight transportation. This additionally highlights the importance generally assessing impacts, which are likely to be strongly correlated with proximity of roadways and supply-chain facilities to human populations. These conclusions indicate that future policy analyses should make some consideration for life-cycle environmental impacts of metropolitan freight logistics policies, especially associate with the pavement supply chain.

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