Unintended environmental impacts of nighttime freight logistics activities

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Abstract:

In recent years, the reduction of freight vehicle trips during peak hours has been a common policy goal. To this end, policies have been implemented to shift logistics operations to nighttime hours. The purpose of such policies has generally been to mitigate congestion and environmental impacts. However, the atmospheric boundary layer is generally more stable during the night than the day. Consequently, shifting logistics operations to the night may increase 24-hour average concentrations of diesel exhaust pollutants in many locations. This paper presents realistic scenarios for two California cities, which provide diesel exhaust concentration and human intake estimates after temporal redistributions of daily logistics operations. Estimates are made for multiple redistribution patterns, including from 07:00-19:00 to 19:00-0:700, similar to daytime congestion charging polices, and from 03:00-18:00 to 18:00-03:00, corresponding to the PierPASS program at the ports of Los Angeles and Long Beach. Results for these two redistribution scenarios indicate that 24-hour average exhaust concentrations would increase at most locations in California, and daily human intake is likely to worsen or be unimproved at best. These results are shown to be worse for inland than coastal settings, due to differences in meteorology. Traffic congestion effects are considered, using a new graphical method, which depicts how off-peak policies can be environmentally improving or damaging, depending on traffic speeds and meteorology.

Keywords: City Logistics, Off-Peak, Nighttime Operations, Truck Traffic, Freight Policy, Atmospheric Dispersion

1. Introduction

Policies for shifting freight logistics operations away from highly impacting times and locations are receiving increased attention from policy makers and analysts (Eliasson et al., 2009; Giuliano and O'Brien, 2007; Hensher and Puckett, 2007; Holguin-Veras and Cetin, 2009; Holguin-Veras et al., 2006; Olszewski and Xie, 2005; Quak and de Koster, 2009; Sathaye et al., 2006). Of course, such policies are not new, as records indicate their implementation as early as 2000 years ago (Holguin-Veras, 2008). Despite the important drawback of increased noise near residences, presently, the policy of shifting logistics operations to the night is becoming more widely accepted and promoted. The conventional wisdom is that off-peak policies are beneficial for transportation systems and the environment[1].

Off-peak policies are being implemented to induce more efficient utilization of transportation infrastructure in many locations around the world. For instance, nighttime delivery programs have been implemented with much success in many European cities (Geroliminis and Daganzo, 2005). A delivery program in Barcelona shows that logistics operations can be conducted at night without creating a detrimental noise problem (Forkert and Eichhorn, 2008). This city has also devoted lanes of some of its main boulevards to delivery operations during off-peak hours (Dablanc, 2007). The Port Authority of New York has implemented a time of day pricing initiative to incentivize off-peak operations (Holguin-Veras et al., 2006). In addition, consideration for off-peak policies is not limited to the urban scale. The passage of state legislation in California encourages port terminals to extend service hours to nights and weekends (Giuliano and O'Brien, 2007).

These implementations are generally supported by studies which indicate that off-peak policies, and especially shifts to night, can reduce traffic congestion and emissions (Browne et al., 2006; McKinnon, 2003; OECD, 2003). However, some previous studies have found that environmental impacts may

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[1] Although noise is an important concern, the term environment will not account for noise in this paper.

increase. For example, in Southern California it has been shown that emissions can increase due to the circumvention of peak-period truck restrictions by the use of smaller vehicles (Campbell, 1995). Research on logistics in the Netherlands indicates that restrictions by time windows and vehicle type can increase emissions associated with deliveries (Quak and de Koster, 2009). Two previous studies use concepts of atmospheric science, which will be a focus of this paper, to show that exhaust concentrations can increase as a result of off-peak operations. One study provides estimates of the change in pollutant concentrations resulting from trucks, pointing out the potential problems resulting from off-peak policies (Panis and Beckx, 2007). An experimental study in Southern California shows that pollutant concentrations, resulting from aggregate traffic, can be higher during pre-sunrise than daylight hours, despite lower total traffic levels (Hu et al., 2009). Such analyses have taken steps towards investigating the environmental impacts of off-peak policies, which are becoming increasingly important as the detrimental health impacts of diesel exhaust (DE) are apparent (California Air Resources Board, 1998; Lloyd and Cackette, 2001; U.S. Environmental Protection Agency, 2002). However, current analyses of off-peak policies still generally neglect to incorporate a comprehensive assessment of environmental impacts.

A complete environmental assessment of city-logistics policies would involve the following steps:

1. Assessment of adaptations by logistics operators

2. Assessment of the effects on traffic congestion

3. Assessment of the effects on tailpipe emissions from passenger and freight logistics vehicles (and possibly life-cycle emissions)

4. Assessment of resulting pollutant concentrations through atmospheric modeling

5. Estimation of environmental impacts (e.g. human intake)

Adjustments can be made to this general framework such as iterative prediction of logistics adaptations and traffic congestion. However, the general framework is valid for almost any city logistics policy. Many studies, including those mentioned above, focus on the first two steps, with a fair number adding the tailpipe emissions component of the third (Campbell, 1995; Giuliano and O'Brien, 2007; Quak and de Koster, 2007; Quak and de Koster, 2009). We additionally note the possibility that life-cycle emissions may be sensitive to certain policies (Facanha and Horvath, 2006; Sathaye et al., 2009b). Although the fourth and fifth steps are often neglected, some studies do focus on making detailed impact assessments (Kinney et al., 2000; Wu et al., 2009). However, generalized values for monetary impact per emissions are more commonly used in policy analyses (Holguin-Veras and Cetin, 2009; Janic, 2007; Ubillos, 2008). Analysis approaches which account for only specific assessment steps or which use generalized values can be useful for deriving some insights, however results can be misleading due to the spatial and temporal variation of environmental impacts and the subtleties of transportation systems. Therefore, significant questions can remain about the usefulness and accuracy of these conclusions.

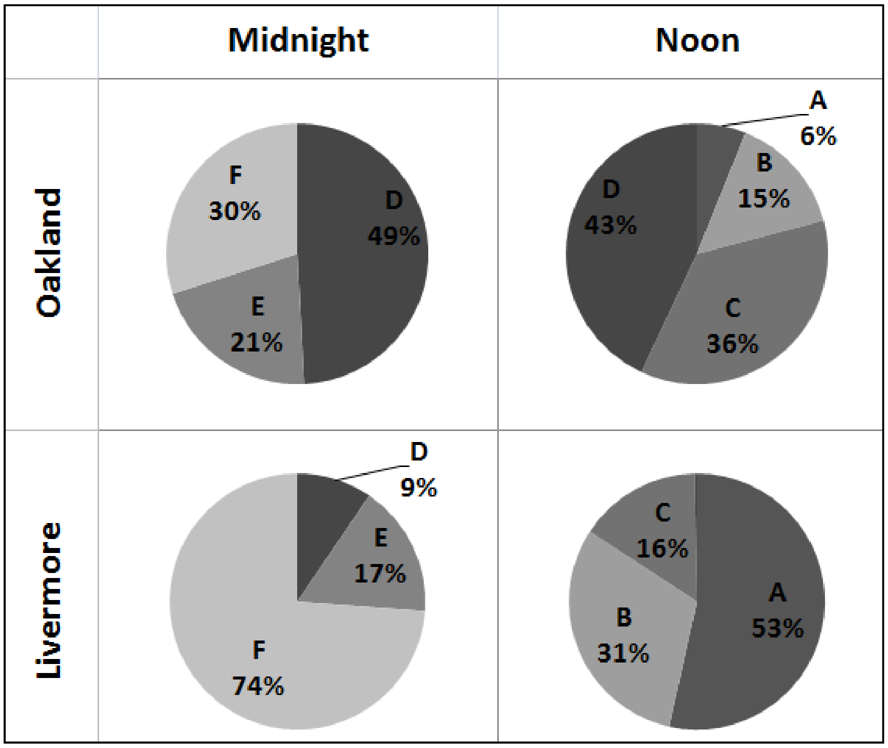
In this paper, we focus on concepts relating to the fourth and fifth steps, which have been studied in depth through the fields of atmospheric (McElroy, 2002; Seinfeld and Pandis, 1997) and environmental science (Bennett et al., 2002; Marshall et al., 2005). An important aspect of atmospheric physics for this paper is the concept of stability, which describes the degree of vertical mixing that occurs in the atmospheric boundary layer (ABL). A more unstable ABL allows for increased vertical dispersion and decreased concentration of pollutants. One of the primary contributors to the instability of the ABL is solar heating (Ahrens, 2003). Heating causes an increase in temperature and decrease in density of parcels of air at the Earth’s surface. Consequently these parcels rise through surrounding air which is more dense, causing pollutants to be dispersed to higher altitudes. Pasquill stability classes have been the most widely used scheme for categorizing stability for several decades (Pasquill, 1961). Although recently developed dispersion models have begun to use more detailed methods, the majority of models still use these classes and they provide a useful descriptive tool. An updated usage of Pasquill stability classes clearly indicates that daytime atmospheric instability increases with the level of solar radiation, and that the nighttime stability class is never less than that of daytime (Mohan and Siddiqui, 1998). Although the degree of influence of this phenomenon may vary, the ubiquitous effect of solar heating over the Earth's land masses makes it relevant for the majority of metropolitan areas.

We investigate this phenomenon and its influence on DE concentrations and human intake associated with nighttime metropolitan logistics policies. In Section 2, scenarios are presented for two locations in California, contrasting the extent to which estimated DE concentrations and human intake are affected by local meteorology. In Section 3, a new graphical tool is presented, which can describe environmental impacts, while accounting for various possible traffic states and associated emission factors. Section 5 concludes the paper.

2. Influence of local meteorology on diesel exhaust concentrations

Diesel particulate matter (DPM) concentrations resulting from truck DE are quantified at two locations under hypothetical scenarios in which truck trips are shifted out of peak hours. The locations are in California in the vicinity of Interstate 880 (I-880) in Oakland and Interstate 580 (I-580) in Livermore. The meteorology of these two locations contrast, in that Oakland's is representative of coastal settings and Livermore's of inland settings. Inland weather patterns are not moderated by the ocean, which changes temperature more slowly than land, and as a result diurnal temperature variations are typically larger at inland locations. This phenomenon is made apparent by the probability distributions of hourly stability class for each location, as shown in Figure 1. The letters represent stability classes ranging from A, the most unstable, to F, the most stable.

Figure 1. Stability class probability distributions during the Summer
Source: (Bay Area Air Quality Management District, 2008)



These locations are also representative of roadways that are heavily used by freight vehicles, since they service traffic associated with the Port of Oakland, which is one of the busiest ports in the United States (Port of Oakland, 2008) and recently conducted a trial program to explore the potential of night operations for mitigating congestion and air quality problems in the Bay Area and Central Valley (Port of Oakland, 2005). Recognizing the environmental impacts associated with ports, the California Air Resources Board (CARB) has recently conducted a comprehensive study of port-related DPM impacts on the health of Oakland residents (California Air Resources Board, 2008). Similar to CARB's study, the scenarios of section 2.2 provide estimates of DPM concentrations.

More specifically, this paper will focus on $DPM_{2.5}$. This indicator of environmental impacts is used for four main reasons. The first is that tailpipe criteria pollutant emissions from gasoline-powered vehicles have been greatly reduced in recent decades, diverting the policy focus towards diesel engines (Harley et al., 2005). The second is that DE has been distinguished as a cause of severe human health impacts, including lung cancer, asthma, and various respiratory symptoms (California Air Resources Board, 1998; Lloyd and Cackette, 2001; U.S. Environmental Protection Agency, 2002). Third, DPM concentrations are often used as a surrogate to represent the many toxic constituents of DE, since there is considerable variation in its composition due to changes in running conditions (Shah et al., 2004), and toxicological studies are inconclusive about the exact differences in health impacts of various DE compositions (Arey, 2004). Lastly, we use a particle diameter of 2.5 µm, since this can be expected to account for nearly the entire DPM size distribution (Lloyd and Cackette, 2001).

To give further context regarding the importance of the impacts of DPM from trucks, the CARB study (California Air Resources Board, 2008) estimates that the West Oakland community is exposed to DPM concentrations that are almost three times the average background DPM ambient concentrations for the San Francisco Bay Area. The study also estimates that DE from all sources causes a significant increase in lifetime potential cancer risk of 1200 excess cancers per million for the exposed population, to which DPM from on-road trucks contributes at least 65%. Although the implications of atmospheric stability are relevant for all DE sources, the study findings highlight the importance of trucks, which are the focus of this paper, versus other DE sources such as port equipment.

2.1. Data and methodology

Multiple data sources and models are applied to estimate $DPM_{2.5}$ concentrations near I-880 and I-580. These data and models relate to traffic and dispersion modeling.

Traffic information is extracted from California Department of Transportation data (Caltrans, 2008), which provides both average annual daily aggregate and truck traffic. This daily information is converted to an hourly format by assuming a weekday hourly trip distribution. This distribution is derived from weigh-in-motion data for Monday through Thursday on San Francisco Bay Area highways and has been used in previous research (Dreher and Harley, 1998). Composite $PM_{2.5}$ emission factors, accounting for both trucks and other vehicles, are estimated using EMFAC2007 (California Air Resources Board, 2006) and the distribution of truck flows by axle class as specified in the Caltrans data. The formula for the estimation of composite $DPM_{2.5}$ emission factors for a specific location and hour of the day is shown in Eq. A.1. We note that all $PM_{2.5}$ emitted from trucks is assumed to come from diesel engines, since gasoline-powered trucks make a negligible contribution. This is justified, since gasoline-powered trucks are relatively uncommon and have much lower $PM_{2.5}$ emission factors. The emission factors also vary by hourly average speeds, which are extracted from the PeMS database (PeMS, 2008). However, this has only a minor effect in the two scenarios considered in this paper, since hourly average speeds do not fall below 64 km/hr. Traffic speeds are considered further in section 3.

Values for the composite $DPM_{2.5}$ emission factor and hourly vehicle trips are then applied in the Caltrans line source dispersion model, Caline4 (Benson, 1984; Benson, 1992), to estimate concentrations at various receptor locations. Additional inputs to Caline4, such as aerodynamic surface roughness and hourly meteorology variables are extracted from meteorological data (Bay Area Air Quality Management District, 2008). The meteorological variables extracted are wind direction, wind speed, atmospheric stability class, standard deviation of wind direction and temperature. The mixing height is estimated according to the formula suggested by (Benson, 1984). All roadway geometry variables such as widths, lengths and locations of bridges are determined by use of Google Earth (Google, 2008a).

Concentrations of $DPM_{2.5}$ depend on emission factors, atmospheric stability, wind direction and wind speed. In accordance with the literature, the expected concentration is calculated based on a joint distribution of the three meteorological variables (Pfafflin and Ziegler, 2006). This allows for the estimation of a seasonal average based on a joint probability mass function (pmf) which is derived from the meteorological data. The pmf is created by categorizing wind speeds into 15 bins, each having an interval of 1 m/s and wind directions into 24 bins each having an interval of 15 degrees. Stability is categorized according to the six Pasquill classes. For each combination of these three variables, Caline4 is applied to estimate the concentration ($Conc^h$) for a given hour and receptor location. Subsequently, Eq. A.2 is used to calculate the expected concentration ($E[Conc^h]$) for each hour and receptor location.

The contribution of the $DPM_{2.5}$ concentration made by trucks is then calculated by multiplying $E[Conc^h]$ by the fraction of total emissions released by trucks (TC^h) during hour h. We note that Caline4 output $Conc^h$ values vary linearly with the input composite emission factor (Benson, 1984), so the value used for the car emission factor has no effect as long as TC^h is modified appropriately.

The 24-hour average $DPM_{2.5}$ concentration ($E\left[Conc^{24}\right]$) is then calculated according to Eq. A.3. $E[Conc^{24}]$ allows for comparison of the effects of shifting logistics operations from peak periods to the night.

Although $E[Conc^{24}]$ provides a basis for understanding the effects associated with off-peak operations, several additional factors influence health impacts (Marshall et al., 2006). In particular, hourly variations in breathing rates and time spent inside buildings (indoors) are likely to have significant impact. Values from previous studies are used for hourly breathing rates (Marshall, 2005) and fraction of time spent indoors (Klepeis et al., 2001). Based on previous estimates, we assume that the indoor exposure concentration is 2/3 of outdoor ambient concentrations (Lloyd and Cackette, 2001; Marshall et al., 2006). Eq. A.4 is used to estimate 24-hour average pollutant intake ($E[Intake^{24}]$) for an individual remaining at a single receptor throughout the day, with the assumption that all of his time is spent either indoors or outdoors.

2.2. Results

Figures 3 and 4 display estimates for $E[Conc^{24}]$ and $E[Intake^{24}]$ respectively, in Oakland for summer and winter at the receptor locations shown in Figure 2. Figures 5 through 7 present analogous information for Livermore. To allow for comparison, the results are produced for six different cases of daily truck trip distribution. These cases will be referred to alphabetically as case a through case f. Case a represents the status quo, which is based on the previously mentioned hourly truck trip distribution (Dreher and Harley, 1998). Case b is based on a 24-hour uniform hourly distribution of truck trips. For cases c through f, the same total number of truck trips are shifted out of peak periods, but the times of the assumed peak and off-peak periods differ. Accordingly, a different percent of trips is removed from the peak hours for each case (and this percent is uniform across peak hours for each case). Moreover, trips are assumed to be uniformly added to the off-peak hours. The percent of trips shifted, and peak and off-peak times are displayed in the Figures 3-4 and 6-7.

The receptor locations shown in Figures 2 and 5 are distributed to capture some of the potential variations in pollutant concentrations in residential neighborhoods due to wind direction and distance from the roadway. The only exception is receptor 4 in Figure 2, which is located to show how the effects of wind direction vary across seasons and potential influences on the health of port workers. The prevailing wind direction in Oakland is from the west, primarily because of the bay-breeze effect; however southwesterly winds are frequent, especially during the winter due to the Hayward Gap (Bay Area Air Quality Management District, 2010). Wind direction in the Livermore Valley is more variable and is generally highly dependent on local conditions. In the case of the data used for this study, the prevailing wind direction is generally from the west during the summer and the northeast during winter. The distance from each receptor to the nearest point on the highway is also shown in Figures 2 and 5.

For the remainder of section 2 we will refer to the percent changes in $E[Conc^{24}]$ and $E[Intake^{24}]$ for various cases versus case a, to draw comparisons relative to the status quo. Case c represents a situation in which truck trips are shifted out of daytime hours, similarly for examples to the congestion charging schemes in London (Transport for London, 2009) and Stockholm (Daunfeldt et al., 2009).

Results for case c, as shown in Figures 3 and 6, indicate that nighttime logistics operations cause significantly larger relative increases in $E[Conc^{24}]$ at receptor locations in Livermore than in Oakland, in accordance with the variations in stability class shown in Figure 1. In addition, the changes during the summer are larger due to greater diurnal variation in prevailing meteorology. This results from increased solar heating during summer, when there are more daylight hours and more intense sunlight during the day. The effect of wind direction is also notable, as the prevailing wind direction is from the southwest instead of northwest for a much higher fraction of the time during the night than the day in Oakland. Although concentrations at receptor 4 are generally low, the diurnal change in wind pattern results in a larger percent change in $E[Conc^{24}]$ at receptor 4 than the other receptors, since this intersection lies directly to the northwest of I-880. This fraction is also much greater during the winter than the summer. Case c, as shown in Figures 4 and 7, reveals that a shift of truck trips away from daytime hours does not generally improve $E[Intake^{24}]$ in Oakland, and is likley to worsen $E[Intake^{24}]$ in Livermore. These results are commensurate with the $E[Conc^{24}]$ increases shown in Figures 3 and 6.

Case d applies the peak and off-peak times currently utilized in the PierPASS system at the ports of Los Angeles and Long Beach (PierPASS, 2009). As can be seen in Figures 3 and 6, $E[Conc^{24}]$ for case d is generally less than that for case c, since case d shifts trips out of pre-dawn hours, when the ABL is very stable, and also the off-peak period begins slightly earlier, when the ABL is relatively unstable. However $E[Conc^{24}]$ for case d is greater than that for case a. Figures 4 and 7 show that $E[Intake^{24}]$ for cases a and d is comparable in Oakland, whereas $E[Intake^{24}]$ for case d is consistently higher than for case a in Livermore. These results indicate that the hours utilized in PierPASS are not likely to reduce DE concentrations and may worsen human intake in many locations.

Cases e and f utilize alternative times for peak and off-peak periods to show what types of policies are more likely to ameliorate impacts. Case e removes trips from pre-dawn hours and the morning commute period, and shifts them to the current PierPASS off-peak period. This results in comparable or lesser values of $E[Conc^{24}]$ and $E[Intake^{24}]$. These results differ from case d, since trips are not shifted away from the late morning and afternoon, when the ABL is unstable. Case f is the same as case e, except that the off-peak period to which truck trips are shifted ends at 22:00, corresponding to the decrease in port drayage activity after this time (BST Associates, 2008). The sharp drop in activity is associated with the 22:00-23:00 break taken by longshoremen. Although breathing rates are higher during the evening than the night, the results for case f generally indicate that there is a further reduction in $E[Conc^{24}]$ and $E[Intake^{24}]$ versus case e, since truck trips are shifted to earlier hours, when the ABL is less stable. Therefore, a focus on shifting off-peak operations to the evening instead of the night may allow both reduced health impacts and better utilization of labor.

In order to get a sense of the magnitude of the health implications of these results, we may compare $E[Intake^{24}]$ against those found in previous research. The mean $DPM_{2.5}$ intake for California's South Coast Air Basin has been estimated to be around 2 μg/hr (Marshall et al., 2006), which is likely of similar order of magnitude to that in the San Francisco Bay Area. Therefore, comparing this estimate with the results in Figures 4 and 7, the highways in the scenario locations are contributing significantly to excess $DPM_{2.5}$ intake measured at the receptor locations. This level of intake is likely to result in a measurable increase in lung cancer risk for the exposed populations (Marshall, 2005).

Figure 2. I-880 and receptor locations 1-4 in Oakland

Source: (Google, 2008b)

Figure 3. Estimated $DPM_{2.5}$ concentrations in Oakland

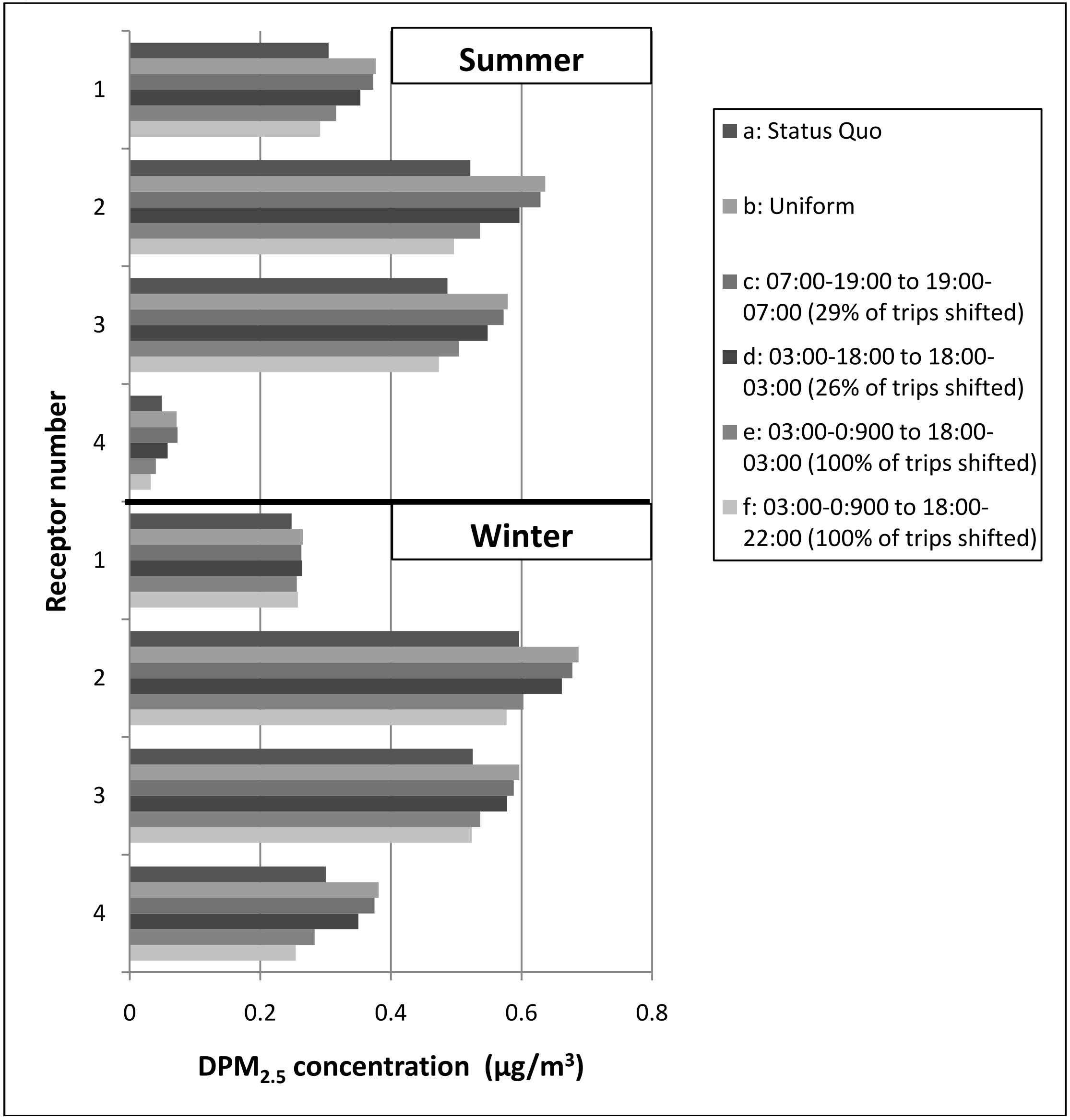


Figure 4. Estimated individual $DPM_{2.5}$ intake in Oakland

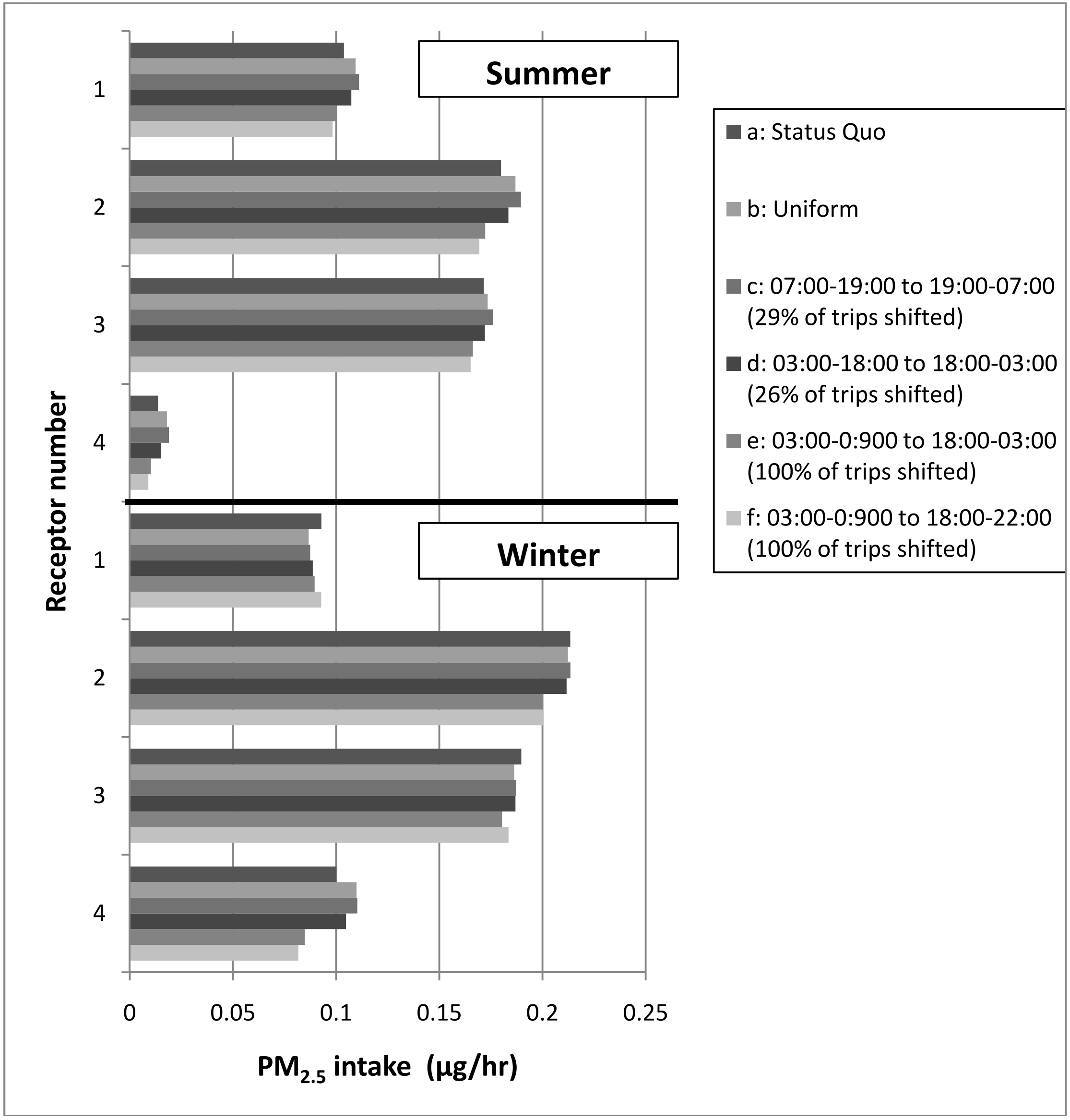


Figure 5. I-580 and receptor locations 1-3 in Livermore

Source: (Google, 2008b)

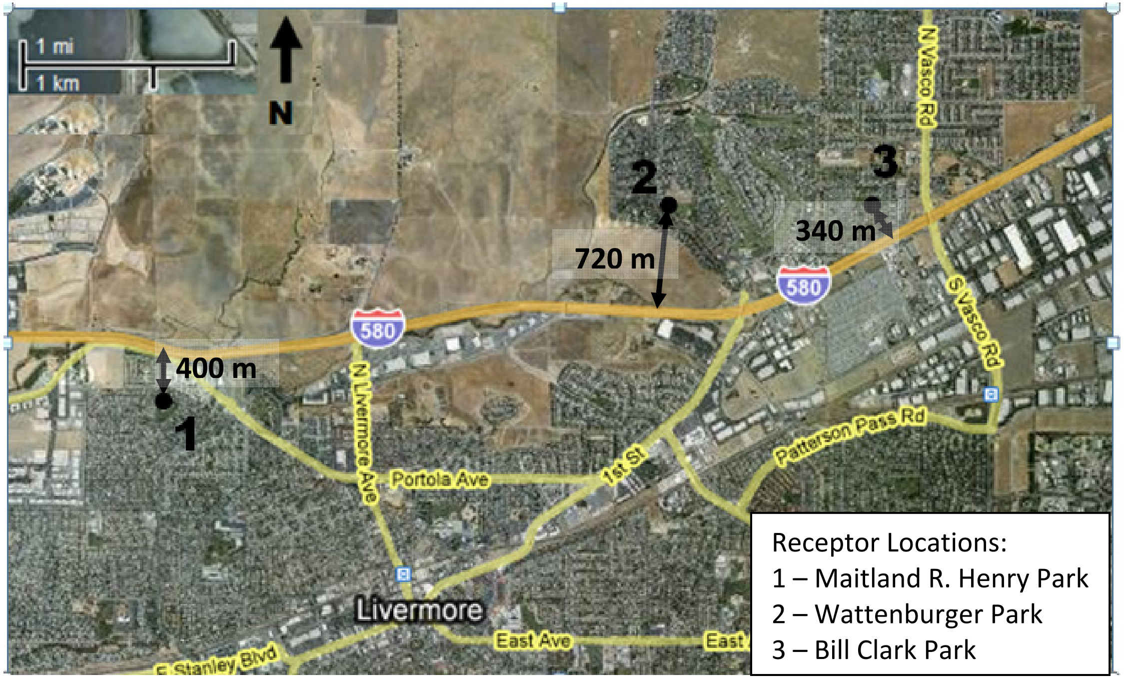


Figure 6. Estimated $DPM_{2.5}$ concentrations in Livermore

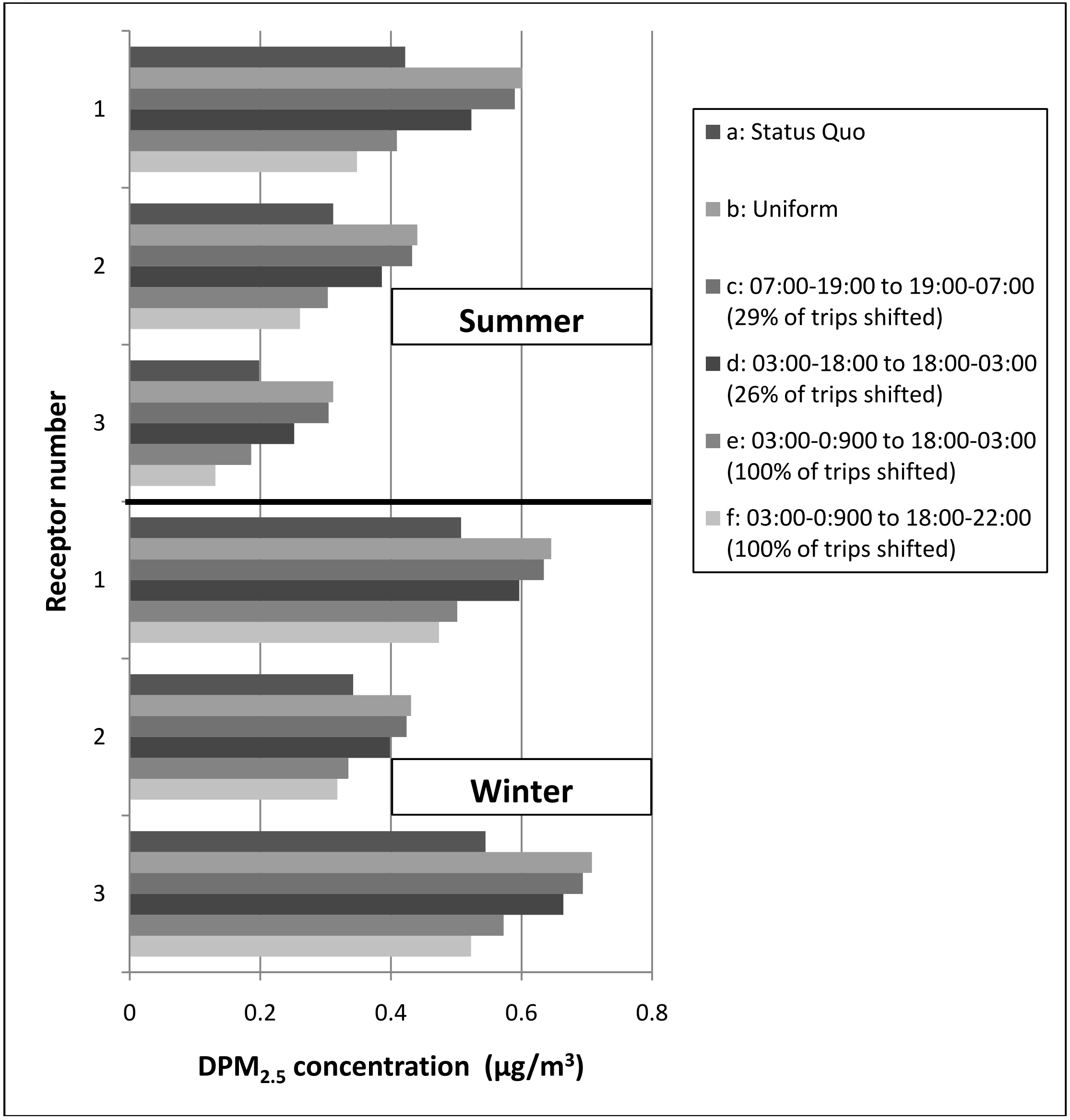
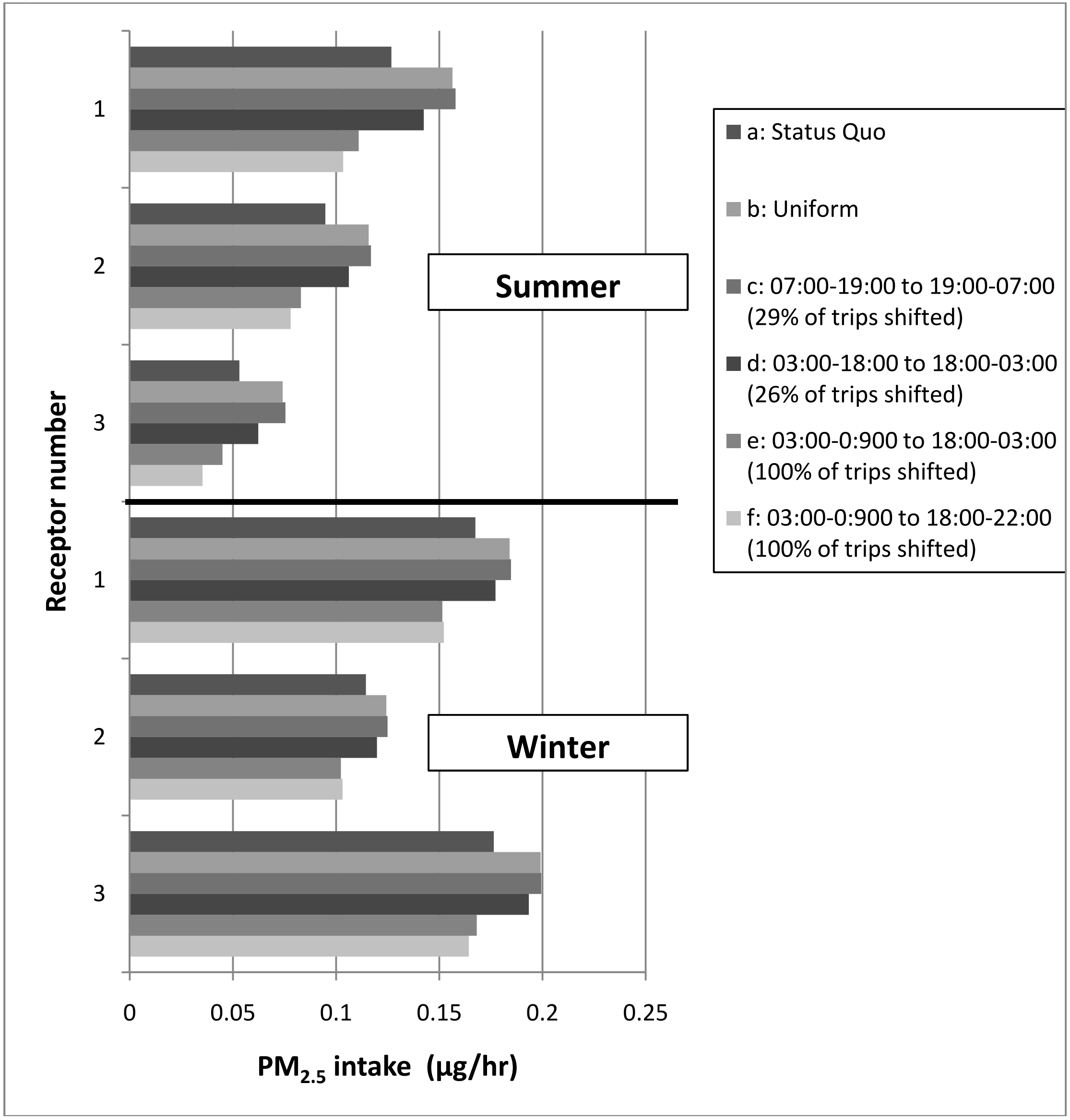


Figure 7. Estimated individual $DPM_{2.5}$ intake in Livermore



3. Accounting for the effects of traffic congestion

In section 2, we presented multiple scenarios, showing the effects of hourly variations in prevailing meteorology. However, as traffic speeds on the highway segments studied undergo little variation, only cursory investigation of congestion effects was made. As previously mentioned, congestion mitigation is a primary aim of policies for shifting freight trips to off-peak hours. Therefore, in section 3, we incorporate traffic considerations to provide further analysis of the types of situations in which unintended environmental impacts are likely to occur.

The analysis of section 2 is based on real-world scenarios, whereas in section 3 we utilize a more conceptual approach, in that hypothetical examples are used to develop insights. A graphical tool, in the form of a $DPM_{2.5}$ concentration isopleth diagram, is used to analyze the various examples. This type of diagram can be used in future analyses of nighttime logistics policies. We note that this paper does not account for congestion within terminals, for which other mitigation methods such as appointment systems are applicable (Giuliano and O'Brien, 2007). A list of variables used in section 3 is shown in Table B.1, since they are referred to multiple times in the text.

3.1.Methodology

The examples analyzed in section 3.2 are based on a one-direction, three-lane link with a wind direction of 270°, as depicted in Figure 8. Although the implications of the analysis of a single link may at first seem limited, we note that logistics vehicles generally comprise an impacting fraction of traffic only at specific locations (Grenzeback et al., 1990) and the importance of hot spot analysis for considering DE impacts (McEntee and Ogneva-Himmelberger, 2008). In addition, the analysis of a single bottleneck has often been used to develop intuition for more complicated scenarios (Daganzo, 1995; Newell, 1987). In particular, the main concepts of this section can be extended to lengthy arterials and networks through the use of the macroscopic fundamental diagram (Daganzo, 2007; Geroliminis and Daganzo, 2007; Geroliminis and Daganzo, 2008).

The fundamental diagram (FD) displayed in Figure 9 is assumed to represent possible traffic states on the link. The FD is widely used to depict the relationship between traffic flow and density for a link (Daganzo, 1997). The triangular FD is often used as an approximation and retains the necessary features for the purposes of this section. The approximation has also been shown to be empirically realistic

(Banks, 1989) and has been applied in seminal works on traffic flow theory (Newell, 1993). The FD in Figure 9 is defined by the following parameters:

free-flow speed $(s_f) = 97\ km/hr$

jam density $(k_j) = 375\ car/km$

capacity flow $(q_c) = 6000\ car/hr$

critical density $(k_c) = 63\ car/km$

backward wave speed $(w) = 19\ km/hr$

The geometric interpretations of these parameters are shown in Figure 9. The total initial trip demand ($Z_{CT}^{M}(FS^{O})$) is assumed to be 6000 in units of cars. FS represents the fraction of trips shifted out of peak hours, and FS^{O} is used to denote the case in which $FS = 0$ to simplify notation. Freight vehicles are assumed to make up 20% of this demand in units of vehicles, and subsequently make up 43% in units of cars. The passenger car equivalent is assumed to be $PCE = 3$ to convert between passenger and freight vehicles.

Figure 8. Example link, receptor and wind direction

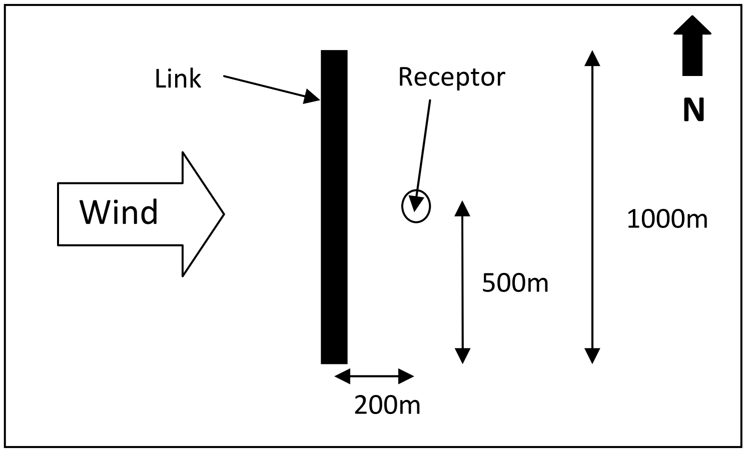
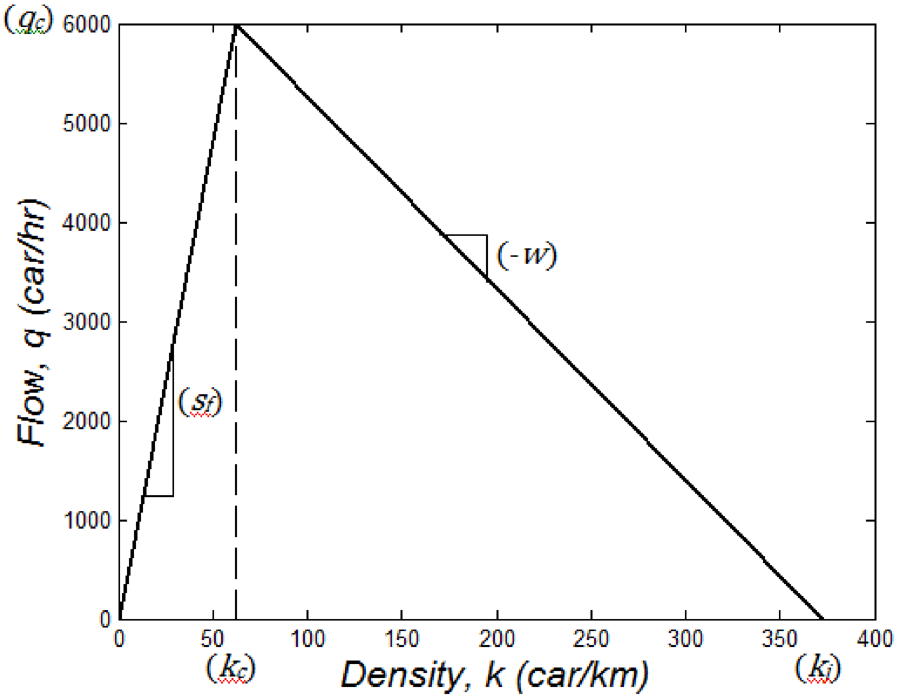


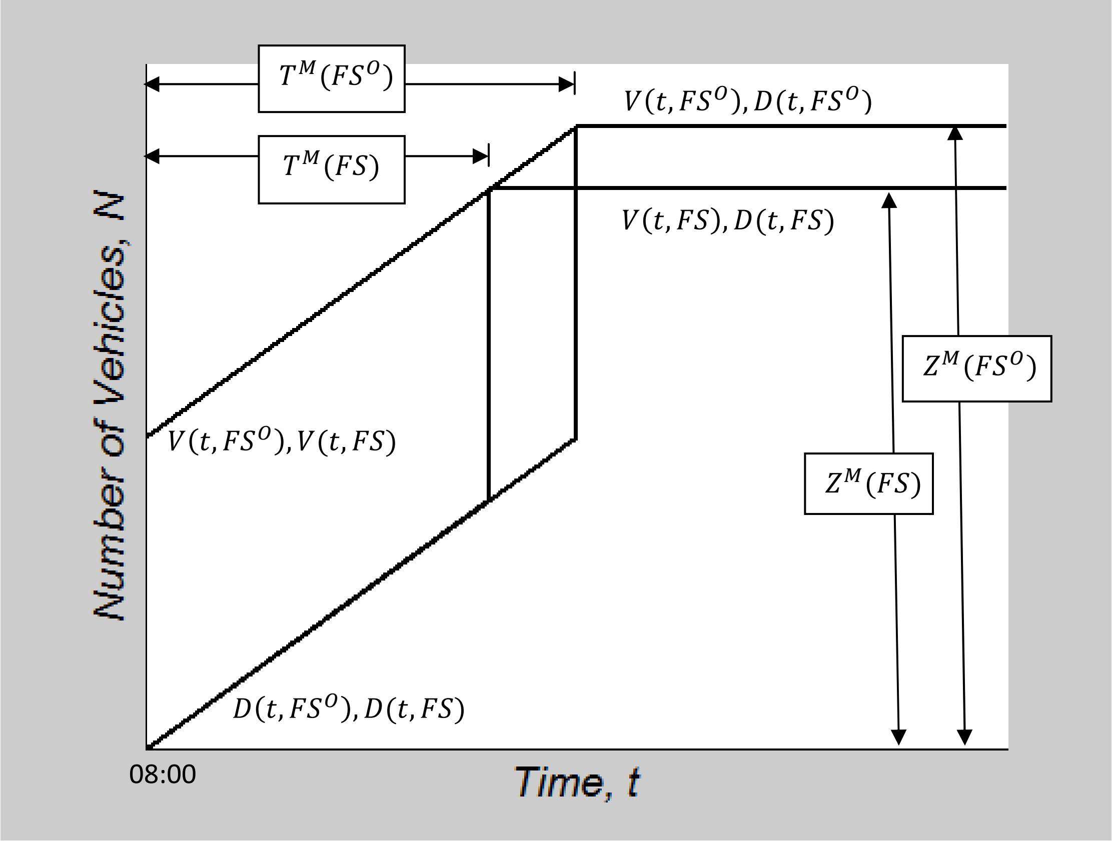
Figure 9. Example fundamental diagram



Vehicles are assumed to use the link shown in Figure 8 during the morning commute hour, starting at 08:00 and also during the night starting at 00:00. The demand at 08:00 corresponds to the morning commute problem with a single bottleneck, which has received much attention (Lago and Daganzo, 2007; Vickrey, 1969) as a basis for analyzing peak-period congestion. Freight trips are shifted from this demand at 08:00 to travel at 00:00. Flow on the link is assumed to be constrained by a bottleneck at one end of the link and vehicles arrive at the back of the queue at the opposite end. Vehicles do not enter or exit the link at any other locations.

FS is increased from 0 to 1 to assess changes in the hourly concentration resulting from freight vehicles, averaged across the morning and night ($Conc^{MN}$). This reduction in the morning trip demand causes a change in the time ($T^{M}(FS)$) after 08:00 needed to serve this demand ($Z_{CT}^{M}(FS)$), as shown in Figure 10, which is a cumulative plot for the bottleneck. The cumulative plot is commonly used in dynamic traffic analysis (Daganzo, 1997). $V(t, FS)$ represents the virtual arrival curve, and $D(t, FS)$ the departure curve, as a function of time and FS. $Z_{CT}^{M}(FS)$ includes both passenger and freight trips. Note the sets of curves for FS^{O} and FS, when $FS > FS^{O}$, coincide along much of the plot.

Figure 10. Cumulative plot for bottleneck with instantaneous link loading



In Figure 10, the spatial extent of the queue, represented by the vertical distance between $V(t,FS)$ and $D(t,FS)$, is assumed to remain constant and equal to the length of the link throughout the duration of the morning analysis period. This is akin to assuming that the link is instantaneously filled and emptied of vehicles and that the arrival rate to the back of the queue is constant and equal to the departure rate at the bottleneck during the peak period. Another interpretation of this assumption is that the time during which the queue forms and dissipates is not accounted for and that the arrival rate is constant between these periods. Despite the lack of realism, this assumption is generally inherent in line source dispersion models, such as Caline4 (Benson, 1984), in which steady-state traffic is assumed.

The speed of traffic (S^M) in the queue is assumed to be constant throughout the peak period and across changes in FS. This is justified by empirical evidence which shows that the level of congestion on roadways tends to be unaffected by a reduction in trip demand, although the length of the peak period may be reduced (Small, 1992). The nighttime traffic speed (S^N) is assumed to be equal to s_f and the time to service night truck demand ($T^N(FS)$) is used analogously to the use of $T^M(FS)$. The assumptions inherent in this setup simplify the development of the examples in section 3.2 without hindering their purpose. Further investigation, related to the implications of relaxing traffic assumptions, can be found in a previous report (Sathaye et al., 2009a) which depicts the implications of a shortened peak period and associated decreasing marginal benefits.

3.2. Results

Figures 11, 13 and 14 present isopleth diagrams for $Conc^{MN}$ in units of $\mu g/m^3$. Isopleth diagrams display curves of constant $Conc^{MN}$ as a function of S^M and FS. The formulas used to calculate values for $Conc^{MN}$ are shown in Appendix B. Mean summer meteorological characteristics are assumed, with the exceptions of wind direction, which is assumed as 270°, and stability class, for which the median is used. For illustrative purposes, the concentration intervals between the isopleths in these diagrams are not constant. However, they are evenly spaced within two ranges of $Conc^{MN}$ values. The arrows on the diagrams point in the direction of decreasing $Conc^{MN}$.

A vertical slice of an isopleth diagram provides a description of how shifting logistics vehicles from morning to night would influence environmental impacts for a given traffic speed. Note, as previously mentioned, that empirical evidence indicates that trip demand reduction does not influence the congested traffic speed. Therefore, moving upward along a slice, in the direction of increasing FS, reveals whether or not an off-peak policy would be environmentally improving or damaging, depending on the changes in $Conc^{MN}$. A horizontal slice of an isopleth diagram describes the environmental impacts that would occur over a range of traffic speeds, but for a specific number of logistics trips shifted. Therefore the diagram can be use to analyze various traffic conditions, for a given meteorological setting. It could also be used to analyze the effects of an off-peak policy in conjunction with traffic control methods aimed at influencing traffic flows and speeds (Daganzo et al., 2002).

Multiple factors influence the form of isopleth diagrams. The main factors for the examples presented in this paper are S^M, S^N, and meteorological conditions during morning and night. These factors lead to regimes, characterized by the two arrows in Figures 11, 13 and 14. In the lower S^M regime (Regime I) off-peak policies improve $Conc^{MN}$, whereas in the higher S^M regime (Regime D), $Conc^{MN}$ increases and environmental damage occurs. Regime D corresponds to the examples of section 2.2, as the traffic speeds on those roadways was relatively high. S_{Trans} refers to the transition value of S^M at which $\partial Conc^{MN}/\partial S^M = 0$, as shown in Figure 11.

The reason for the existence of the two regimes is the variation in the morning emission factor (EF^M) with respect to S^M, as shown in Figure 12. The variations in the tradeoff between the change in morning average concentration ($Conc^M$) and that of the night ($Conc^N$) can be attributed to the variations in EF^M, since the morning and nighttime meteorological conditions, and nighttime emission factor (EF^N) are constant. (EF^N is constant, because S^N is assumed to be equal to s_f; meteorological conditions are constant, as previously specified.) Therefore, in the case of low S^M and a corresponding high EF^N, a shift to the night results in a reduction in $Conc^{MN}$, because the number of trips made with high EF^N is reduced. Accordingly, the contribution of $Conc^M$ to $Conc^{MN}$ has decreased more than that of $Conc^N$ has increased (the contributions of $Conc^M$ and $Conc^N$ instead of their values are considered, because they must be appropriately weighted to directly estimate $Conc^{MN}$, as the duration of $T^M(FS)$ and $T^N(FS)$ differ). To describe the tradeoff in other terms, in Regime I the low S^M values cause relatively high morning emission factors (EF^M); reducing the number of morning trips by shifting trips to the night period outweighs the effects of the stagnant nighttime ABL.

However, EF^M decreases with increasing S^M, as can be seen in Figure 12. As S^M increases and EF^M decreases, the tradeoff between $Conc^M$ and $Conc^N$ changes, causing improvements in $Conc^{MN}$ with respect to FS to diminish. For high values of S^M, the tradeoff is reversed and the effects of the stagnant nighttime ABL outweigh the relatively low values for EF^M. The tradeoff reversal occurs at S_{Trans}, leading to a regime change from Regime I to D. In regime D, $S^M > S_{Trans}$ and $Conc^{MN}$ increases with FS, since the contribution of $Conc^M$ decreases less than that of $Conc^N$ increases. Note that $Conc^{MN}$ also increases with S^M, for S^M greater than about 72 km/hr, since EF^M increases in this regime, in accordance with Figure 12. This results in the upside down u-shape of the isopleths around S^M = 72 km/hr.

Figure 11. DPM$_{2.5}$ Isopleths (µg/m^3) for summer in Oakland with free-flow speed, $s_f = 97\ km/hr$

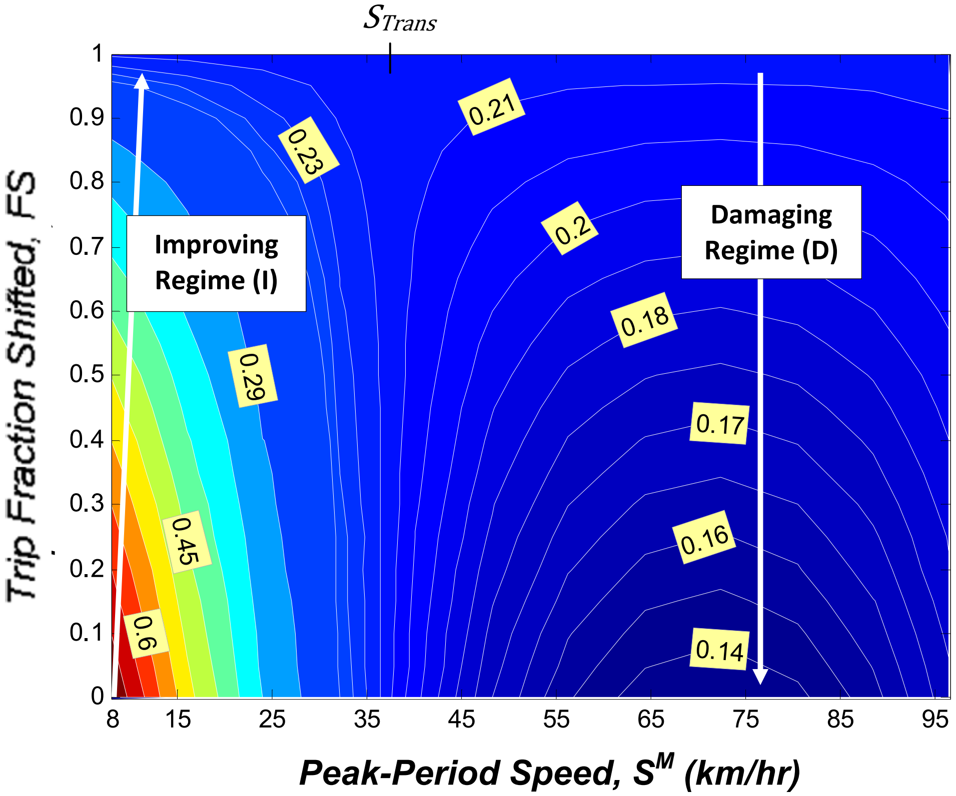


Figure 12. EMFAC2007 Heavy-heavy duty vehicle DPM$_{2.5}$ emission factors

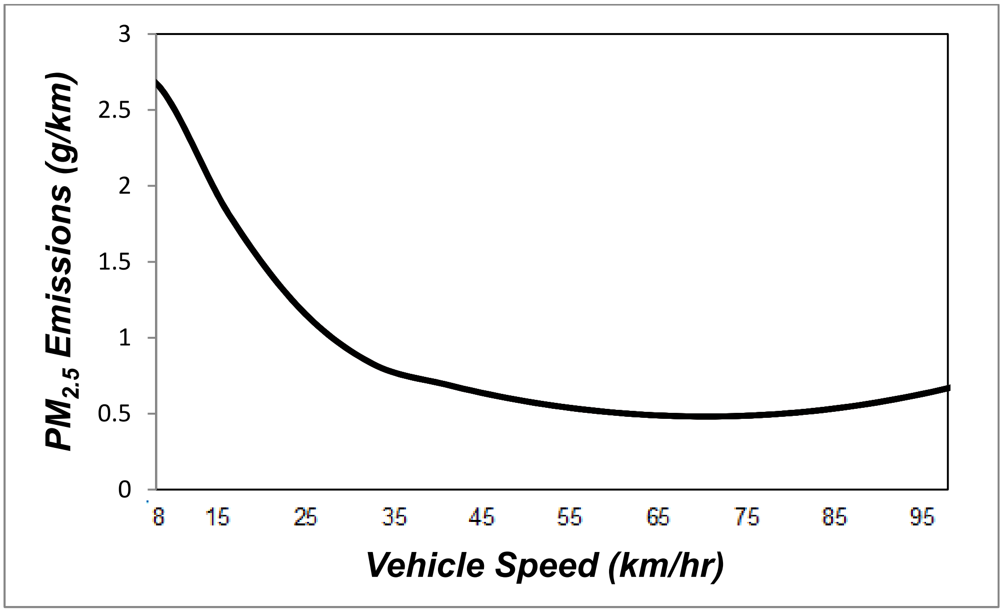


Figure 13 presents the resulting isopleth diagram for the same situation, except that s_f is 64 km/hr. This lower s_f represents the case of arterials, instead of freeways. The fundamental diagram is accordingly adapted so that q_c is reduced, and k_c increased. As can be seen, S_{Trans} is higher than for Figure 11, because the reduction in s_f from 97 km/hr to 64 km/hr causes a decrease in EF^N. This can be seen in the right of Figure 12. This reduction in EF^N makes nighttime freight logistics activities less environmentally damaging per trip shifted, than in the case of freeways. Specifically, the increases in $Conc^N$ are lower for arterials, whereas the decreases in $Conc^M$ are the same for all values of FS and $S^M \leq 64\ km/hr$. Therefore, as S^M increases, the increases in $Conc^N$ do not outweigh the decreases in $Conc^M$, until a higher value of S^M is reached, resulting in a higher S_{Trans}. This shows that nighttime policies are more likely to be beneficial for cases in which S^N is lower, such as arterials.

Figure 13. DPM$_{2.5}$ Isopleths (µg/m^3) for summer in Oakland with free-flow speed $s_f = 64\ km/hr$

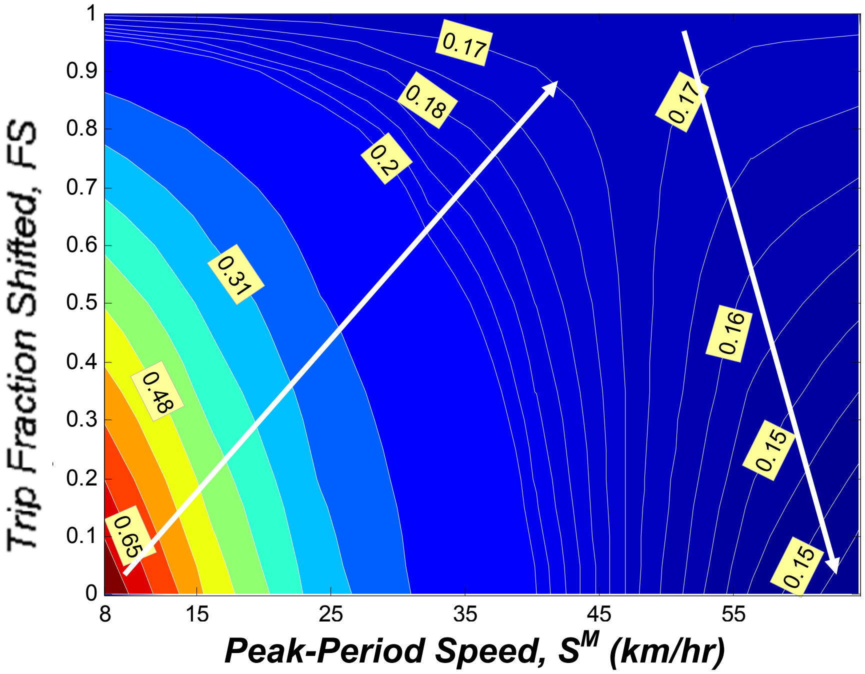
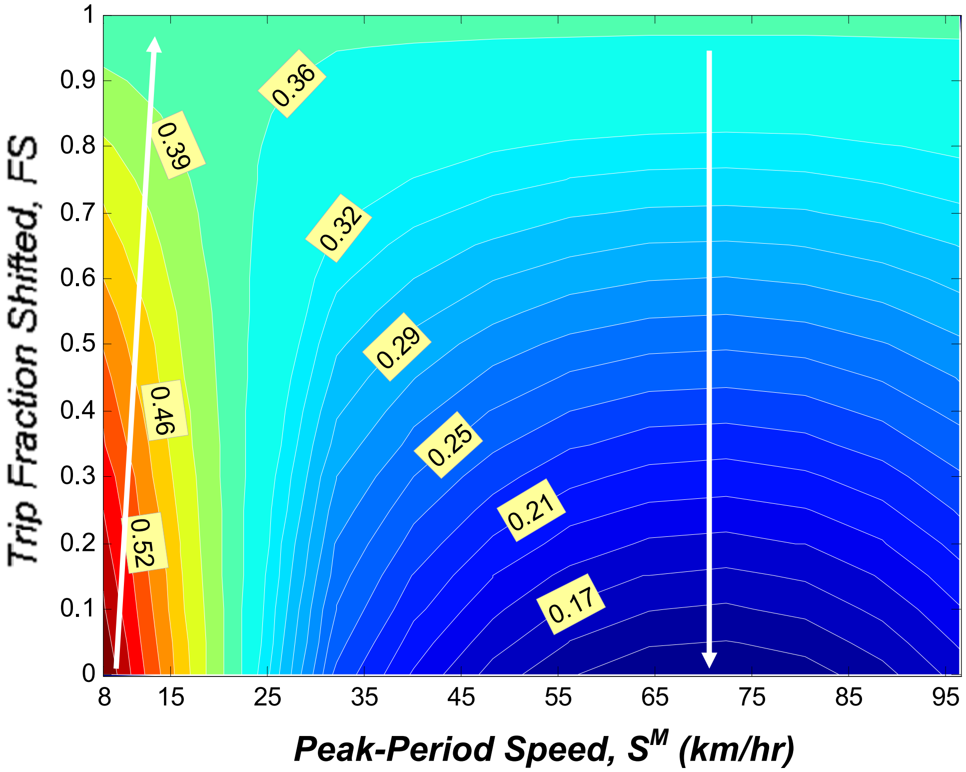


Figure 14 shows the isopleth diagram for summer conditions in Livermore. In comparison with Figure 11, a shift to nighttime operations by logistics vehicles results in greater increases in $Conc^N$, due to greater nighttime stability, whereas the decrease in $Conc^M$ is lower for all values of S^M and FS. Consequently, the value for S_{Trans} is lower for Livermore than Oakland (the tradeoff between $Conc^M$ and $Conc^N$ reverses at a lower S^M). Consistent with the higher changes in $E[Conc^{24}]$ values found for Livermore (Figure 6), these results indicate that unintended environmental impacts are more likely to occur in inland locations in California.

Figure 14. DPM$_{2.5}$ Isopleths (μg/m^3) for summer in Livermore with free-flow speed, $s_f = 97km/hr$



4. Discussion

In this section, assumptions, sources of uncertainty and pertinent aspects for more detailed analysis in future assessments are discussed. These issues are grouped by the latter four steps of the assessment framework presented in section 1. We note that although step 1, which involves the assessment of adaptations by logistics operators, is not addressed directly it in this paper, it is likely to be one of the most uncertain aspects and require context-specific analysis. This is due to the nuances of logistics industry operations and business relationships (Holguin-Veras et al., 2006).

Considering step 2, average values for traffic speeds are straightforwardly used in section 2, and should not be a great source of uncertainty. For section 3, the average speed of traffic being modeled must be relatively homogeneous within the peak and off-peak periods for the isopleth diagram to be meaningful.

This should be reasonable for a single bottleneck and has also been identified as a feature of the macroscopic fundamental diagram (Geroliminis and Daganzo, 2008), allowing for extension of the isopleth diagram to be used for networks. For the analysis of multiple links or networks with inhomogeneous average speeds, multiple isopleth diagrams can also be used. Of course, this may seem to necessitate the use of a prohibitive number of diagrams; however, as previously mentioned, much of the concern regarding DE impacts is at specific locations.

Considering step 3, DPM emission factors are a potential source of uncertainty for two main reasons. The first has to do with whether the EMFAC2007 $DPM_{2.5}$ emission factors are valid for the area-wide drive cycles they are designed to represent (Lloyd and Cackette, 2001). Although the EMFAC2007 $DPM_{2.5}$ emission factors are area-wide estimates, they also fall within the range of those suggested by multiple empirical studies (Ban-Weiss et al., 2007; Kear and Niemeier, 2006). Therefore, for the analysis of section 2, which does not account for speed variations, uncertainties in EMFAC2007 should not affect the implications of the results. Similarly, the order of magnitude for EMFAC2007 $DPM_{2.5}$ emission factors is reasonable for section 3. However there is a second source of uncertainty for section 3, which has to do with whether EMFAC2007 $DPM_{2.5}$ emission factors are appropriate for project-level analysis. At the project level, changes in average traffic speed may not necessarily represent changes in time spent idling or spent in high-power transient driving mode, which greatly influence emission factors (Kear and Niemeier, 2006). Nevertheless, the parabolic shape of the $DPM_{2.5}$ emission factor curve, in which emission factor is a decreasing as a function of speed with the exception of very high speeds, should generally be valid for given traffic control conditions and facility type. This occurs since higher average speeds generally correspond to less time spent idling and in high-power transient driving mode per distance traveled. Therefore, although the exact shape of the isopleths would differ as a result of minor modifications to the emission factor curve shown in Figure 12, the general form of the isopleth diagrams should generally hold. Future applications of the isopleth diagram must ensure that the appropriate relationship between average speed and microscopic traffic phenomena, which influence emissions, is utilized. This will depend on traffic control conditions and facility type, which is a subject of ongoing research (Kear and Niemeier, 2006; Nesamani et al., 2007).

Considering step 4, the dispersion model and assumptions regarding wind direction in section 3 are potential sources of uncertainty. Caline4 is a standard model and has been validated for the estimation of pollutant concentrations for several pollutants; however results are inconclusive for $PM_{2.5}$ in dense urban areas (Chen et al., 2009). The main reasons for these mixed results are thought to be street canyon effects and the influence of traffic on atmospheric dispersion. The two scenario locations in this paper are residential neighborhoods made up mainly of detached houses. Therefore it is reasonable to assume that street canyon effects and the influence of traffic on dispersion patterns do not invalidate the use of Caline4 in this paper. Future work should utilize appropriate context-specific atmospheric dispersion modeling tools to determine the extent to which atmospheric stability influences DE concentrations in different settings. For section 3, wind direction is assumed constant to derive basic implications; however even if wind direction is realistically accounted for, the general form of the isopleth diagrams should not differ, since the parabolic emission factor curve and diurnal stability variation will be present. The only caveat is the extreme case in which S_{Trans} becomes very low or high, causing either the improving or damaging regime to be eliminated from the diagram.

We also note that future policy assessments can also account for DE concentrations resulting from port equipment and other transportation modes, such as maritime vessels. Although different emissions and dispersion models are necessary for such DE sources, the implications of atmospheric stability are similar, though generally less impacting on human health since they are likely to be further from affected populations (California Air Resources Board, 2008).

Considering step 5, uncertainty regarding $DPM_{2.5}$ exposure is primarily the result of two main issues. The first has to do with microenvironments. The methodology of this paper accounts for differences in indoor and outdoor exposure concentrations, but exposure is likely much higher for people who are in-vehicle near freight traffic, which occurs mainly during daytime hours (Marshall et al., 2006). This indicates that estimates of $E[Intake^{24}]$ for cases b through f in section 2 are biased upwards versus the population average. However this upward bias may not be that significant, since truck trips avoid commute periods when people are most likely to be in-vehicle, truck trips generally only share specific roadways with those of passenger, and most of people's time is spent indoors even during commute hours (Klepeis et al., 2001). The second source of uncertainty has to do with daily travel patterns, which are also not accounted for in section 2. The receptor locations are in predominantly residential neighborhoods, where there are likely to be more people during the night than the day. This indicates that estimates of $E[Intake^{24}]$ for cases b through f in section 2 are biased downwards versus the population average. Although these issues vary across locations and times, we note that a previous study shows that the biases associated with ignoring the in-vehicle microenvironment and travel patterns largely cancel out for the South Coast Air Basin (Marshall et al., 2006).

Finally, regarding step 5, we consider enhancing the isopleth diagrams to depict DPM intake, rather than concentration. Although S_{Trans} is likely to be different versus the concentration isopleth diagrams, the implications of the parabolic emission factor curve and atmospheric stability on the form of the isopleths, as discussed in section 3, should generally still hold. The only change is that in some cases intake may not be a parabolic function of speed if traffic control policies, which influence speed, greatly divert the location of emissions towards higher density populations (e.g. from freeways to on-ramps). As a result, the form of the isopleths could differ from those shown in section 3. In this case, multiple isopleth diagrams can be used if values for S_{Trans} are of primary interest. A single diagram can also still be used, although the form of intake isopleths may not be similar to those for concentrations shown in section 3. Nevertheless, this issue should not generally negate the implications of the diagrams in section 3, since future policy assessments are likely to focus on major roadways and networks, which will be the dominant source of DE concentrations in the study area.

5. Conclusion

This paper focuses on estimating the change in freight vehicle DE concentrations and human intake as a result of nighttime operating policies, indicating that increases in air pollution are likely to result in many metropolitan settings. Although there are many benefits of shifting operations to the nighttime, the results show the importance of carefully assessing the environmental impacts of nighttime freight operations. The potential for unintended impacts is shown to be more severe in inland locations during the summer for California, and more generally, locations that exhibit significant diurnal meteorological variation. However, environmental benefits are likely to occur if off-peak policies are directed at specific time periods, such as the morning commute period. In addition, benefits are more likely to occur for situations with relatively low peak-period traffic speeds, since this corresponds to high peak-period emission factors. The isopleth diagram, developed in this paper, provides a tool that can be utilized in the future to assess whether or not an off-peak policy is likely to cause environmental damage. Future policy analyses can incorporate these diagrams to provide a graphical representation of impacts for decision making. These results highlight the importance of conducting comprehensive assessments of logistics policies in the future, which account realistically for the complex nature of both transportation and environmental systems.

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Appendix A. Variables and equations for section 2

Table A.1. Variables used for section 2

BR^h	Breathing rate during hour h
$Conc^{24}$	24-hour average concentration
$Conc^h(sc, wd, ws, \bar{I})$	Concentration at particular receptor location and hour h for stability class sc, wind direction wd, wind speed ws, and a vector of constant inputs $\bar{I}$
EF_{CT}	Composite $PM_{2.5}$ emissions factor
e_C	Passenger vehicle $PM_{2.5}$ emission factor
e_{Tn}	Truck $PM_{2.5}$ emission factor for axle class denoted by n
γ^h	Ratio of indoor to outdoor $DPM_{2.5}$ concentration
$Intake^{24}$	24-hour average intake
N	Number of truck axles in highest axle class
$p(sc, wd, ws)$	Probability Mass Function
Q_{Tn}	Hourly trips made by trucks of axle class n
Q_C	Hourly trips made by passenger vehicles
SC	Set of stability classes
TC^h	Fraction of emissions released by trucks during hour h
θ^h	Fraction of time spent outdoors during hour h
WD	Set of wind direction bins
WS	Set of wind speed bins

Eq. A.1 through Eq. A.4 are used in section 2. For Eq. A.1, the Caltrans 2-axle and 3-axle classes are assumed to correspond to the EMFAC2007 medium-heavy-duty vehicle class, and the Caltrans 4-axle and 5 or more-axle classes to the EMFAC2007 heavy-heavy-duty class. Cars are included, since traffic flow influences the stability of air over the roadway.

$$EF_{CT} = \frac{Q_C \times e_C + \sum_{n=2}^{N} Q_{Tn} \times e_{Tn}}{Q_C + \sum_{n=2}^{N} Q_{Tn}} \qquad \text{Eq. A.1}$$

$$E[Conc^h] = \sum_{SC,WD,WS} Conc^h(sc, wd, ws, \bar{I}) \times p(sc, wd, ws) \qquad \text{Eq. A.2}$$

$$E[Conc^{24}] = \frac{1}{24} \times \sum_{h=1}^{24} TC^{h} \times E[Conc^{h}]$$ Eq. A.3

$$E[Intake^{24}] = \frac{1}{24} \times \sum_{h=1}^{24} (\gamma^{h} \times (1 - \theta^{h}) + \theta^{h}) \times BR^{h} \times TC^{h} \times E[Conc^{h}]$$ Eq. A.4

Appendix B. Variables and equations for section 3

Table B.1. Variables used for section 3

$Conc^h$	Caline4 output average $PM_{2.5}$ concentration for hour h
$Conc^Y$	Average $PM_{2.5}$ concentration during period Y, resulting from logistics vehicles
$D(t, FS)$	Departure curve
EF^Y	Composite $PM_{2.5}$ emission factor during period Y
e_X	$PM_{2.5}$ emission factor for vehicle type X
FS	Fraction of freight trips shifted to off-peak operations
k	Traffic density
k_c	Traffic critical density
k_j	Traffic jam density
N	Cumulative number of vehicles
O	Superscript used to denote original value of variable for FS^O (i.e. where $FS = 0$)
PCE	Passenger-car equivalent
Q_X^Y	Flow of vehicle type X during period Y
q	Traffic flow
q_c	Traffic capacity
S_{Trans}	Transition ${}_{M}S$ between improving and damaging traffic speed regimes
S^Y	Speed of queued traffic during period Y
s_f	Free-flow traffic speed
$T^Y(FS)$	Duration needed to serve traffic demand during period Y
T^{Yh}	Fraction of hour h used to serve trip demand during period Y
t	Time
TC^Y	Fraction of total traffic $PM_{2.5}$ emissions made by freight vehicles during period Y
TF^O	Fraction of peak-period trip demand comprised of freight vehicles for $FS = 0$ in units of passenger vehicles
TFV^O	Fraction of peak-period trip demand comprised of freight vehicles for $FS = 0$ in units of vehicles
$Time$	Averaging time for $PM_{2.5}$ concentration estimates
$V(t, FS)$	Virtual arrival curve for all vehicles
w	Traffic backward wave speed
X	$= \begin{cases} C\ if\ variable\ represents\ passenger\ vehicles \\ T\ if\ variable\ represents\ freight\ vehicles \\ CT\ if\ variable\ represents\ all\ vehicles \end{cases}$
Y	$= \begin{cases} M\ if\ variable\ represents\ peak\ period \\ N\ if\ variable\ represents\ night \\ MN\ if\ variable\ represnts\ average\ across\ peak\ period\ and\ night \end{cases}$
$Z_X^Y(FS)$	Trip demand during period Y for vehicle type X

The derivation of the formulas used to calculate $PM_{2.5}$ concentration values for the isopleths diagrams in section 3.2 can be seen in Eq. B.1 through Eq. B.12. Eq. B.1 is used to compute w based on q_c , k_j , k_c , which are assumed from the FD in Figure 9.

$$w = \frac{q_c}{k_j - k_c} \qquad \text{Eq. B.1}$$

w is then used along with k_c and q_c in Eq. B.2 to calculate Q_{CT}^M. S^M takes on a range of assumed values, in accordance with the horizontal axis of the associated isopleth diagram. Therefore, Eq. B.2 is applied for multiple values of S^M to compute the associated Q_{CT}^M values.

$$Q_{CT}^M = \frac{q_c + w \times k_c}{1 + w/S^M} \qquad \text{Eq. B.2}$$

TFV^O is then converted to its equivalent in units of cars, TF^O, by applying $PCE = 3$, as shown in Eq. B.3.

$$TF^O = \frac{TFV^O \times PCE}{TFV^O \times PCE + 1 - TFV^O} \qquad \text{Eq. B.3}$$

TFV^O is subsequently used to compute Q_T^M and Q_C^M, as shown in Eq. B.4 and Eq. B.5. The second case of each equation is used when $FS \times TF^O < 1$, representing a situation in which less than 100% of freight trips have been shifted. To maintain the generality of the equations, the first case formulas are shown for $FS \times TF^O = 1$, since otherwise the denominator could equal 0.

$$Q_T^M = \begin{cases} 0 & if\ FS \times TF^O = 1 \\ \dfrac{(1-FS) \times TF^O}{1-FS \times TF^O} \times Q_{CT}^M & otherwise \end{cases}$$ Eq. B.4

$$Q_C^M = \begin{cases} Q_{CT}^M & if\ FS \times TF^O = 1 \\ \dfrac{(1-TF^O)}{1-FS \times TF^O} \times Q_{CT}^M & otherwise \end{cases}$$ Eq. B.5

Q_{CT}^N, is assumed to be equal to both q_c and Q_T^N, since nighttime trip demand by cars is assumed to be 0. This is shown in Eq. B.6.

$$Q_T^N = Q_{CT}^N = q_c$$ Eq. B.6

EF^Y values for input to Caline4 are then computed as shown in Eq. B.7. Note that Y is used to save on notation, and indicates that the variable is computed for both morning and night.

$$EF^Y = \frac{\frac{e_T}{PCE} \times Q_T^Y + e_C \times Q_C^Y}{Q_T^Y + Q_C^Y}$$ Eq. B.7

$$where\ Y = \begin{cases} M\ if\ morning \\ N\ if\ night \end{cases}$$

EF^Y and the corresponding Q_{CT}^Y are then input into Caline4. TC^Y is then calculated through the use of Eq. B.8, to distinguish the PM$_{2.5}$ concentration resulting from freight vehicles, versus that from cars. TC^Y is later used in Eq. B.12.

$$TC^Y = \frac{\frac{e_T}{PCE} \times Q_T^Y}{\frac{e_T}{PCE} \times Q_T^Y + e_C \times Q_C^Y}$$ Eq. B.8

$T^M(FS)$ and $T^N(FS)$ are calculated as shown in Eq. B.9 and Eq. B.10.

$$T^{M}(FS) = \frac{Z_{CT}^{M} \times (1 - FS \times TF^{O})}{Q_{CT}^{Y}}$$ Eq. B.9

$$T^{N}(FS) = \frac{Z_{CT}^{M} \times (FS \times TF^{O})}{Q_{CT}^{Y}}$$ Eq. B.10

Caline4 concentration outputs, $Conc^{h}$, which vary with inputs Q_{CT}^{Y} and EF^{Y}, are applied in Eq. B.12 to estimate the average concentration, $Conc^{MN}$, over an assumed averaging period of time ($Time$). We assume $Time = 6\ hours$, since $T^{M}(FS)$ exceeds 4 hours for the slowest travel speed for which Caline4 is applied, 8 km/hr, and $T^{N}(FS)$ is always less than 1 hour. $T^{Yh}(FS)$ represents the fraction of an hour, denoted by h, that is used to service trip demand. $T^{Yh}(FS)$ is calculated using Eq. B.11. $T^{Yh}(FS)$ is equal to 1 for every hour except for the last hour of the morning commute and night traffic periods. We note that in the case that the duration of either of these periods is less than 1 hour, the associated value of $T^{Yh}(FS)$ would by default be less than 1 hour. Therefore, the first case of Eq. B.11 is applied when considering the last hour of the morning or night periods, or if they last less than 1 hour. $T^{Yh}(FS)$ can subsequently then be used to assign less weight to these hours as shown in Eq. B.12. The second case of Eq. B.11 is used for all other periods.

$$T^{Yh}(FS) = \begin{cases} T^{Y}(FS) - \lfloor T^{Y}(FS) \rfloor & if\ \lfloor T^{Y}(FS) \rfloor = h - s \\ 1 & otherwise \end{cases}$$ Eq. B.11

$$where\ s = \begin{cases} 0\ if\ Y = N \\ 8\ if\ Y = M \end{cases}$$

$$h = hour\ of\ the\ day\ assumed\ to\ be\ represented\ by\ an\ integer\ (e.g. 08{:}00\ to\ 09{:}00 \equiv 8)$$

Eq. B.12 is used to calculate $Conc^{MN}$. The inner summation adds the hourly $PM_{2.5}$ concentrations resulting from freight vehicles within either the morning or the night period. The outer summation is then used to add across both the morning and night. The sum is then divided by $Time$ to derive an average concentration, $Conc^{MN}$.

$$Conc^{MN} = \frac{\sum_{Y=\{M,N\}} \sum_{h=s}^{s+\lceil T^{Y}(FS) \rceil} Conc^{h}(Q_{CT}^{Y}, EF^{Y}, \bar{I}) \times T^{Yh}(FS) \times TC^{Y}}{Time} \qquad \text{Eq. B.12}$$