Unintended Environmental Impacts of Nighttime Metropolitan Freight Logistics Policies

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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 would increase the 24-hour average concentrations of diesel exhaust pollutants in many locations. This paper presents case examples of this phenomenon, which provide concentration and human intake estimates after temporal redistributions of daily logistics operations.

1. Introduction

Policies for shifting freight logistics operations away from highly impacting times and locations are receiving increased attention from policy makers and analysts (Sathaye et al., 2006). Such policies are not new, as records indicate their implementation as early as 2000 years ago; however increased noise near residences has similar historical longevity (Holguin-Veras, 2007). Despite this drawback, 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 indicates that logistics operations can be conducted at night without creating a detrimental noise problem (Forkert and Eichhorn, 2008). 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; Organisation for Economic Co-Operation and Development, 2003). Multiple studies provide estimates of emissions reductions as a result of shifting logistics operations to the night in specific contexts (Quak and de Koster, 2006; Warburton, 2001). One conference paper can be found which does make an estimate of pollutant concentrations, pointing out the potential for increases resulting from off-peak policies (Panis and Beckx, 2007). Concepts in this paper are discussed and built upon in this section of the paper, with an extension to estimate human health impacts. It should be noted that area-wide peak truck bans from highways are thought to be problematic, due to circumvention by use of smaller vehicles (Campbell, 1995), and the sparsity of locations where logistics vehicles comprise an impacting fraction of traffic (Grenzeback et al., 1990). Nevertheless, these analyses have taken many steps towards understanding the environmental impacts of off-peak policies, which is becoming increasingly important as the detrimental health impacts of diesel exhaust have become apparent (U.S. Environmental Protection Agency, 2002). However, the current analyses of off-peak policies generally neglect to incorporate the estimation of impacts.

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

1. Selection of feasible policies based on economic, political, administrative and social considerations

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[1] The term environment will not account for noise.

2. Prediction of adaptations by logistics operations

3. Prediction of the effects on traffic congestion

4. Prediction of effects on tailpipe emissions from passenger and freight logistics vehicles (and possibly life-cycle emissions)

5. Prediction of resulting pollutant concentrations through atmospheric modeling

6. Estimation of 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 most any city logistics policy. Most studies, including those aforementioned, analyze the first three steps in detail, with a fair number incorporating the tailpipe emissions component of the fourth. We additionally note the possibility that life-cycle emissions may be sensitive to certain policies (Facanha, 2006). However the last two steps are neglected, leaving significant questions about the accuracy of conclusions drawn about environmental impacts.

In this paper, we focus on concepts relating to the fifth step, which have been studied in depth by atmospheric scientists (McElroy, 2002; Seinfeld and Pandis, 1997). Many different aspects of atmospheric physics have been investigated, including 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 always either equivalent or more stable than those of the 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 its relevance apparent for the majority of metropolitan settings.

This paper makes the first investigation of this phenomenon and its influence on exhaust concentrations associated with nighttime city logistics policies in California. In Section 2, case examples are presented for two locations in California, contrasting the extent to which exhaust concentrations are affected depending on climate.

2. Case Examples

Pollutant concentrations resulting from trucks are measured in two locations for hypothetical scenarios in which truck trips are shifted out of daytime hours. The scenarios occur in California in the vicinity of Interstate 880 (I-880) in Oakland and Interstate 580 (I-580) in Livermore. The climates of these two locations contrast in that Oakland's is representative of coastal settings and Livermore's of inland settings. Inland climates are not equilibrated by the ocean, which changes temperature slower than land, and as result daily variations are typically more extreme. This phenomenon is made apparent by the probability distributions of hourly stability class for each location, as shown in Table 1. The letters represent stability classes ranging from A, the most unstable, to F, the most stable.

Table 1 – Stability Class Probability Distribution During the Summer

Source: (Bay Area Air Quality Management District, 2008)

Time	Stability Classes	A	B	C	D	E	F
00:30	Oakland	0	0	0	0.492	0.209	0.299
	Livermore	0	0	0	0.095	0.167	0.738
12:30	Oakland	0.061	0.148	0.361	0.430	0	0
	Livermore	0.535	0.307	0.155	0.003	0	0

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 currently the fourth busiest port in the United States (Port of Oakland, 2008). Recognizing the environmental impact associated with ports, the California Air Resources Board (CARB) has recently conducted a comprehensive study of diesel PM impacts on the health of Oakland residents, based on current logistics operations (California Air Resources Board, 2008b). The Port of Oakland has also conducted a trial 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).

Similar to CARB's study, the case examples in this paper focus on estimates of PM concentrations. More specifically, concentrations of PM2.5, an Environmental Protection Agency (EPA) criteria pollutant, are estimated, since many studies indicate that the fine particle regime is the main contributor to human health impacts (Pope and Dockery, 2006). In addition, PM2.5 concentrations are expected to be strongly correlated with concentrations of other toxic constituents of diesel exhaust such as aldehydes and polycyclic aromatic hydrocarbons, as PM concentrations have historically been used as a surrogate (U.S. Environmental Protection Agency, 2002).

2.1. Methodology and Data

Multiple data sources and models are applied to estimate concentrations near I-880 and I-580. These are grouped into those related to traffic and dispersion modeling.

2.1.1. Traffic

Traffic information is extracted from California Department of Transportation (Caltrans) data (California Department of Transportation, 2007), which provides average annual daily aggregate and truck traffic. This daily information is then converted to an hourly format by assuming a weekday hourly trip distribution. This distribution is derived from weigh-in-motion data (Avis, 1996) for Monday through Thursday on San Francisco Bay Area highways and has been used in previous research (Dreher and Harley, 1998). Composite exhaust PM2.5 emissions factors are then estimated based on CARB's 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 a composite emissions factor for a specific location and hour of the day is shown in Eq. 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 more than 5-axle classes to the EMFAC2007 heavy-heavy-duty class. Cars are included, since increased vehicle flow causes more unstable air conditions over the roadway. We note that the emissions factors also vary by hourly average speeds extracted from the PeMS database (PeMS, 2008). However this has only minor effect in the two case examples, since hourly average speeds do not fall below 40 mi/hr ~ 64 km/hr.

$$EF = \frac{{}_{C}Q \times {}_{C}EF + \sum_{n=2}^{N} {}_{T}Q_n \times {}_{T}EF_n}{{}_{C}Q + \sum_{n=2}^{N} {}_{T}Q_n} \qquad \text{Eq. 1}$$

$EF = composite\ emissions\ factor$

${}_{T}EF_n = logistics\ vehicle\ emissions\ factor\ for\ axle\ class\ n$

${}_{C}EF = passenger\ vehicle\ emissions\ factor$

${}_{T}Q_n = hourly\ trips\ made\ by\ trucks\ of\ axle\ class\ n$

${}_{C}Q = hourly\ trips\ made\ by\ other\ vehicles\ (primarily\ cars)$

$N = number\ of\ truck\ axles\ in\ highest\ axle\ class$

2.1.2. Dispersion Modeling

Values for EF, ${}_{C}Q$ and ${}_{T}Q_n$ are then applied in the Caltrans line source dispersion model, Caline4 (California Department of Transportation, 1984), to estimate concentrations at various receptor locations. Additional inputs, such as surface roughness and hourly climate variables are extracted from Bay Area Air Quality Management District (BAAQMD) meteorological data (Bay Area Air Quality Management District, 2008). The climate variables extracted are wind direction, wind speed, atmospheric stability class, wind direction standard deviation and temperature. The mixing height is calculated according to the formula suggested in the Caline4 manual (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 PM2.5 are primarily dependent on atmospheric stability, wind direction and wind speed. In accordance with the literature, the expected concentration is calculated based on a joint distribution of these three 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 BAAQMD data. The pmf is created by categorizing wind speeds by 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 seven Pasquill classes. The formula used to calculate the expected concentration for a given hour and receptor location is shown in Eq. 2. Values for $Conc_h$ are computed by using Caline4.

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

$Conc_h(sc, wd, ws, \bar{I})$
$= concentration\ at\ particular\ receptor\ location\ and\ hour\ for\ stability\ class\ sc,$
$wind\ direction\ wd, wind\ speed\ ws, and\ a\ vector\ of\ constant\ inputs\ \bar{I}$

$p(sc, wd, ws) = probability\ mass\ function$

$SC = set\ of\ stabiltiy\ classes$

$WD = set\ of\ wind\ direction\ bins$

$WS = set\ of\ windspeed\ bins$

The 24-hour average concentration is then calculated according to Eq. 3. ${}_{24}Conc$ allows for comparison of the effects of shifting logistics operations to the night and is used by the EPA in the designation of National Ambient Air Quality Standards (U.S. Environmental Protection Agency, 2008).

$$E[{}_{24}Conc] = \sum_{h=1}^{24} E[Conc_h] \qquad \text{Eq. 3}$$

${}_{24}Conc = 24\text{-}hour\ average\ concentration$

Finally, the contribution of the PM2.5 concentration made by trucks is calculated by multiplying $E[{}_{24}Conc]$ by the fraction of total emissions released by trucks (TC). We note that Caline4 output $Conc_h$ values vary linearly with the input EF (Benson, 1984), so the value used for ${}_{C}EF$ has no effect as long as TC is modified appropriately.

2.2. Results

Table 2 and Table 3 display values for $E[Conc^{24}]$ and $E[Intake^{24}]$ respectively, in Oakland for summer and winter at the receptor locations as shown in Figure 1.

Table 4, Table 5 and Figure 2 present analogous information for Livermore. The percent shifts in the second columns of Table 2 through Table 5 indicate that the concentrations and intakes for each corresponding row are based on that percentage of hourly truck trips being removed from the hours of 7:00 to 17:00, and being uniformly added to remaining hours of the day. The rows denoted by “Uniform” in these tables indicate that the concentrations are calculated based on a 24-hour uniform hourly distribution of truck trips.

Table 2 and Table 4 indicate that nighttime logistics operations cause significantly higher percent changes in $PM_{2.5}$ concentrations in Livermore than in Oakland, in accordance with the variations in stability class as shown in Table 1. The elasticity of $E[Conc^{24}]$ with respect to truck trips shifted is generally around twice as high in Livermore versus Oakland. In addition, the changes during the summer tend to be more severe due to greater diurnal climatic variation. This extreme variation results from increased solar heating as the angle of the Earth's axis with respect to the sun causes longer daylight hours and more intense sunlight during the day. The effect of wind direction is also notable, which is exemplified by the higher percent change in concentrations at the corner of Maritime & 14th St. than the other Oakland receptors. This occurs since this intersection lies directly to the west of I-880 and the prevailing wind direction is from the East a much higher fraction of the time during the night than the day in Oakland. This fractions is also much greater during the winter than the summer.

Table 3 and Table 5 show that off-peak policies do not generally improve intake of $PM_{2.5}$ in Oakland and are very likley to worsen helath impacts in Livermore. These results are commesurate with the concentration increases of Table 2 and Table 4 make apparent the stark effects of atmospheric stability.

Figure 1 - I-880 and Receptor Locations in Oakland

Source: (Google, 2008b)

Table 2 – Estimated $PM_{2.5}$ Concentrations ($\mu g/m^3$) and Percentage Change in Oakland

	Receptor:	1		2		3		4	
	Location:	Maritime & West 14th St.		Willow & 11th St.		West Oakland BART		Lowell Park	
Winter	0% Shift	.30	0%	.53	0%	.60	0%	0.25	0%
	25% Shift	.35	17%	.57	8%	.66	10%	.26	4%
	100% Shift	.49	63%	.71	34%	.83	38%	.30	20%
	Uniform	.38	27%	.60	13%	.69	15%	.27	8%
Summer	0% Shift	.049	0%	.49	0%	.52	0%	0.30	0%
	25% Shift	.064	31%	.55	12%	.60	15%	.35	17%
	100% Shift	.11	124%	.72	47%	.81	56%	.49	63%
	Uniform	.072	47%	.58	18%	.64	23%	.38	27%

Table 3 - Estimated Individual $PM_{2.5}$ Intake ($\mu g/hr$) and Percentage Change in Oakland

	Receptor:	1		2		3		4	
	Location:	Maritime & West 14th St.		Willow & 11th St.		West Oakland BART		Lowell Park	
Winter	0% Shift	1.5	0%	2.8	0%	3.1	0%	1.4	0%
	25% Shift	1.6	6%	2.8	0%	3.1	0%	1.3	-3%
	100% Shift	1.8	24%	2.7	-3%	3.1	0%	1.2	-13%
	Uniform	1.6	10%	2.7	-1%	3.1	0%	1.3	-6%
Summer	0% Shift	0.20	0%	2.5	0%	2.6	0%	1.5	0%
	25% Shift	0.25	24%	2.5	2%	2.7	4%	1.6	5%
	100% Shift	0.39	94%	2.6	5%	3.0	12%	1.8	17%
	Uniform	0.27	32%	2.5	2%	2.8	5%	1.6	6%

Figure 2 - I-580 and Receptor Locations in Livermore

Source: (Google, 2008b)

Table 4 - Estimated $PM_{2.5}$ Concentrations ($\mu g/m^3$) and Percentage Change in Livermore

	Receptor:	1		2		3	
	Location:	R. Henry Maitland Park		Wattenburger Park		Bill Clark Park	
Winter	0% Shift	0.54	0%	0.34	0%	0.51	0%
	25% Shift	0.65	20%	.40	18%	0.60	18%
	100% Shift	.95	76%	.57	68%	.86	69%
	Uniform	.71	31%	.43	26%	.65	27%
Summer	0% Shift	0.19	0%	0.31	0%	.51	0%
	25% Shift	0.27	42%	.39	26%	0.53	4%
	100% Shift	.47	147%	.62	100%	.85	67%
	Uniform	.31	63%	.44	42%	.60	18%

Table 5 - Estimated Individual $PM_{2.5}$ Intake (µg/hr) and Percentage Change in Livermore

	Receptor:	1		2		3	
	Location:	R. Henry Maitland Park		Wattenburger Park		Bill Clark Park	
Winter	0% Shift	2.6	0%	1.7	0%	2.5	0%
	25% Shift	2.8	9%	1.8	6%	2.6	7%
	100% Shift	3.5	35%	2.1	25%	3.2	29%
	Uniform	2.9	13%	1.8	9%	2.7	11%
Summer	0% Shift	0.79	0%	1.4	0%	1.9	0%
	25% Shift	1.0	27%	1.6	15%	2.2	16%
	100% Shift	1.6	108%	2.2	58%	3.0	61%
	Uniform	1.1	40%	1.7	23%	2.3	24%

3. Conclusion

Although the environmental impacts of nighttime policies have many influences, this paper focuses on concentrations of logistics vehicle exhaust, showing that in many settings increases are likely to cause unintended public health impacts. This phenomenon is more likely to occur in inland climates during the summer in California or, more generally, those that exhibit significant diurnal variation. The effect of ABL stagnancy has implications for logistics facilities and other modes of transportation as well. For examples, off-peak policies to induce temporal spreading of passenger commute trips, airport activities or maritime shipping could cause increased average pollutant concentrations. Nevertheless, nighttime policies are currently being directed at metropolitan logistics operations. In accordance with this trend and mounting environmental concerns, this paper highlights the importance of extending impact assessments of city logistics policies beyond tailpipe emissions alone.

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