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A Fuel-Based Inventory for Heavy-Duty Diesel Truck Emissions

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ABSTRACT

A fuel-based method for estimating heavy-duty diesel truck emissions is described. In this method, emission factors are normalized to fuel consumption; vehicle activity is measured by the amount of diesel fuel consumed. For the San Francisco Bay Area during summer 1996, on-road heavy-duty diesel trucks were estimated at the upper bound to emit 110 × 10^3 kg/day of nitrogen oxides (NO_x) and 3.7 × 10^3 kg/day of fine black carbon (BC) particles. These upper bound values were 2.3 and 4.5 times, respectively, the corresponding predictions of California's motor vehicle emission inventory model, MVEI 7G. Significant decreases in diesel truck activity and emissions, 70–80% below typical weekday levels, were observed in the Bay Area on weekends. Reductions in diesel NO_x and BC particle emissions on weekends may contribute to higher ambient ozone concentrations and higher organic carbon (OC) to BC ratios observed on weekends. Heavy-duty truck traffic peaks on weekdays during the middle of the day and falls off before the afternoon rush hour. Therefore, the diurnal pattern of heavy-duty truck travel may contribute to increases in ambient OC/BC ratios observed during late afternoon hours.

IMPLICATIONS

The emissions of nitrogen oxides and fine black carbon particles from heavy-duty diesel trucks may be understated in current emission inventories. The daily and weekly cycles of diesel truck activity differ from corresponding light-duty vehicle patterns. Weekend decreases in diesel truck activity and emissions may contribute to the observed "weekend effect" of higher ambient ozone concentrations in some urban areas on weekends. The contribution of secondary organic aerosol to total fine particle mass may have been overestimated in some cases.

INTRODUCTION

Heavy-duty diesel trucks (i.e., diesel-powered trucks with gross vehicle weight exceeding 3,860 kg, or ~4 tons) are an important source of fine particle and nitrogen oxide (NO_x) emissions.[1] Cass and Gray[2] estimate that during the 1980s, heavy-duty diesel engines accounted for 70% of total fine black carbon (BC) particle emissions from on-road vehicles in the Los Angeles area. Current estimates from California's MVEI 7G motor vehicle emission inventory model for the San Francisco Bay Area indicate that in 1996, heavy-duty diesel trucks contributed 74% of exhaust PM emissions and 18% of total NO_x emissions from on-road vehicles.[3]

Motor vehicle emissions are currently estimated using the travel-based MOBILE[4] and EMFAC[5] emission factor models in the U.S. and California, respectively. In this approach, estimates of vehicle travel are combined with emission factors expressed on a mass per unit distance traveled basis to obtain a motor vehicle emission inventory.

Traditionally, vehicle activity has been estimated using travel demand models.[6,7] Spatially- and temporally-resolved vehicle activity is predicted using socioeconomic data such as population, employment, automobile ownership, and income, combined with knowledge of travel times between points, available modes of transportation, and a description of the roadway network. Heavy-duty truck travel represents only a small fraction of total vehicle travel, so little effort has been made to describe truck travel explicitly within travel demand models.[7] In current modeling practice, it is common to estimate heavy-duty truck travel as a fixed percentage of predicted traffic volumes.[7] However, as noted by Schlappi et al.,[8] heavy-duty truck travel does not follow the same spatial and temporal patterns as light-duty vehicle travel. Consequently, heavy-duty truck activity estimates should not be based upon light-duty vehicle travel patterns.

Alternatively, measurements of vehicle kilometers of travel (VKT) for trucks may be used to estimate truck activity. In California, truck VKT is measured only on the state highway system, so reported truck VKT does not include all truck activity. However, truck VKT may be used in conjunction with statewide fuel sales to estimate total heavy-duty truck activity, using the amount of fuel consumed as a measure of activity. Accurate diesel fuel sales data are available at the state level, and truck VKT is reported at the county level.[9]

Light-duty vehicle emissions are regulated per unit distance of travel. Likewise, current emission inventory models rely on emission factors expressed per mile or kilometer traveled. In contrast, heavy-duty diesel truck emissions are regulated per unit of brake work output by the engine. A potentially large source of uncertainty in using MOBILE and EMFAC models to estimate heavy-duty truck emissions is the need to convert from gram per brake horsepower hour units (as meaured in the laboratory during engine dynamometer tests) to mass emission rates per unit distance traveled. Since heavy-duty trucks encompass a wide range of diesel engine sizes and gross vehicle weights, emission factors normalized to work output vary less than they would on a distance traveled basis. Furthermore, performance maps for heavy-duty diesel engines indicate that brake-specific fuel consumption (BSFC) varies only slightly as engine operating conditions change. For example, Heywood[10] presents the performance map for a 6.5-L diesel engine. Over a wide range of operating conditions, BSFC varied from 220 to 260 g/kW-h for this engine. Therefore, work output by the engine can be directly related to fuel input, and heavy-duty diesel engines are effectively regulated and designed to meet emission targets on a per unit of fuel burned basis.

Previous studies have already demonstrated the utility of a fuel-based approach for estimating light-duty vehicle emissions.[11,12] As described by Singer and Harley[11] for light-duty vehicles, the advantages of the fuel-based approach include the fact that fuel-use data are readily available from tax records. Furthermore, emission factors normalized to fuel consumption vary considerably less over the full range of driving conditions than travel-normalized emission factors.[11,13] The fuel-based methodology applied to heavy-duty diesel trucks provides the same advantages.

The objectives of this study are to describe and apply a fuel-based method for estimating heavy-duty diesel truck exhaust emissions of fine BC particles and NO_x, compare fuel-based emission inventory estimates with California MVEI 7G model predictions, and describe weekly and diurnal patterns of heavy-duty truck activity and compare these with light-duty vehicle activity patterns.

METHOD

A fuel-based emission inventory for heavy-duty diesel trucks combines vehicle activity data (i.e., volume of diesel fuel consumed) with emission factors normalized to fuel consumption (i.e., mass of pollutant emitted per unit volume of fuel burned) to estimate emissions within a region of interest.

Vehicle Activity

At the statewide level, precise fuel consumption data are available through tax records.[14] The reported statewide fuel consumption can be apportioned to provide emission estimates for an individual air basin by month, day of week, and time of day. Spatially- and temporally-resolved use of diesel fuel was estimated using the following equation:

$$A_{i,j,k,l} = \left(\frac{D}{365}\right) f\, v_i\, m_j\, d_k\, h_{k,l} \tag{1}$$

where $A_{i,j,k,l}$ is the amount of fuel burned in air basin i during month j, day of week k, and hour l; D is the annual statewide volume of diesel fuel used by on-road vehicles; f is the fraction of on-road diesel fuel used by heavy-duty trucks; v_i is the fraction of statewide fuel use in air basin i; m_j is the ratio of daily fuel sales in month j to annual average daily sales; d_k is the ratio of fuel used on day k to the average weekly value; and $h_{k,l}$ is the fraction of total fuel use on day k that occurs during hour l. Methods for estimating the parameters needed in eq 1 are described below.

Emission Factors

Currently, the U.S. Environmental Protection Agency (EPA) uses a transient engine dynamometer test to measure emissions from individual heavy-duty diesel engines.[15] Emission factors obtained from engine dynamometer tests are reported in grams of pollutant emitted per unit of brake work performed by the engine. These emission factors can be normalized to fuel consumption as follows:

$$EI_P = \left(\frac{s_P}{BSFC}\right) \tag{2}$$

where EI_P is the emission index for pollutant P, in units of mass of pollutant emitted per unit mass of fuel burned; s_P is the brake specific pollutant emission factor obtained from the dynamometer test, expressed in g/kW-h units; and BSFC is the brake specific fuel consumption of the engine being tested, also in g/kW-h. California exhaust PM and NO_x emission standards for heavy-duty diesel trucks are presented in Table 1; these standards correspond to s_P in eq 2 above.

Emission factors for heavy-duty diesel trucks also can be calculated from measurements of exhaust pollutant concentrations. Heavy-duty diesel trucks emit only small amounts of hydrocarbons.[1] Therefore, by carbon balance, the mass of diesel fuel burned can be determined directly from exhaust emissions of CO_2 and CO. An emission index EI_P for pollutant P can be calculated using:

$$EI_P = \frac{\Delta[P]}{\Delta[CO_2] + \Delta[CO]} w_c \tag{3}$$

where $\Delta[P]$ is the exhaust concentration of pollutant P corrected for background levels and expressed in µg m^{-3}; $\Delta[CO_2]$ and $\Delta[CO]$ are the exhaust concentrations of CO_2 and CO less background, expressed in µg C m^{-3}; and w_C is the weight fraction of carbon in diesel fuel.

Vehicle Emissions

Exhaust PM and NO_x emissions are estimated by multiplying vehicle activity, as measured by the volume of fuel used, by emission factors expressed per unit volume of fuel burned.

APPLICATION

The methodology described above was applied to the San Francisco Bay Area for summer 1996. Fuel sales D for use in eq 1 were estimated from diesel fuel tax data by projecting 1985-1995 historic fuel sales data forward to 1996.[16] The linear best-fit equation had a positive slope of 47,000 gallons per year and was used to estimate total diesel fuel sales of 2.1 × 10^9 gallons in California for 1996. Based on International Fuel Tax Agreement returns, Beile[17] reports that an additional 202 × 10^6 gallons of diesel fuel were purchased out-of-state and used in California, whereas 33 × 10^6 gallons of diesel fuel purchased within California were used out-of-state. Therefore, diesel fuel sales within California were augmented by net imports of 170 × 10^6 gallons.

In California, diesel fuel used by off-road vehicles is not taxed.[18] Therefore, the value of D obtained from tax records includes only diesel fuel used by on-road vehicles. MVEI 7G estimates[3] indicate that for summer 1996 in the Bay Area, light-duty vehicles accounted for 4% of taxable diesel fuel use. Therefore, the parameter f in eq 1 was taken to be 0.96. (According to MVEI 7G estimates,[3] buses accounted for 6% of on-road diesel fuel consumption; this non-taxable fuel use was not included in the value of D described above.)

The parameter v_i needed in eq 1 was estimated using the fraction of statewide heavy-duty diesel truck travel that occurs in the Bay Area. The California Department of Transportation (Caltrans) measures truck travel on the state highway system at statewide and county levels and reports travel data by axle class.[9] The fraction v_i was computed by summing measured travel by trucks with three or more axles in the nine-county Bay Area and dividing by the statewide total for the same classes of trucks. By this method, it was estimated that the Bay Area accounted for 12% of statewide total truck travel. However, for two of the nine counties, only the urbanized portions are included in the Bay Area Air Basin. Together, these counties (Solano and Sonoma) accounted for 21% of measured Bay Area diesel truck travel. Measured truck travel was adjusted using MVEI 7F estimates of the fraction of heavy-duty truck VKT falling within the urbanized areas of Solano (69%) and Sonoma (79%) counties. The final estimate for v_i used in eq 1 was 11%.

Monthly on-road diesel fuel sales data for California[19] were used to quantify the seasonal variations in truck travel. Calculated values of m_j for 1993 varied from a low of 0.85 to a high of 1.23, with an average of 1.0 and standard deviation of 0.12. It appears that some variations may be a result of fuel sales being reported quarterly instead of monthly. In the present study, a uniform distribution of diesel fuel sales throughout the year was assumed (i.e., $m_j = 1.0$ in eq 1).

Hourly and daily truck counts at weigh-in-motion sites were used to determine d_k and $h_{k,l}$ in eq 1. Weigh-in-motion sensors consist of a magnetic induction loop and a pressure-sensitive bending plate, both of which are embedded in the roadway. The magnetic induction loop senses the presence of a vehicle and the bending plate measures weight per axle. By using the induction loop and bending plate together, it is possible to count passing vehicles and to classify the vehicles by weight and number of axles. Weigh-in-motion data for use in this study were provided by Caltrans for two heavily traveled Bay Area freeways: Interstate 880 in Hayward and Highway 101 in Burlingame. Hourly vehicle counts from these sites for northbound and southbound traffic were provided by axle class for a two-week period in summer 1996.[20]

To make use of the weigh-in-motion data, it was necessary to determine what fraction of vehicles counted in each axle class met the definition of a heavy-duty diesel truck. The 1992 Truck Inventory and Use Survey[21] was used to determine these fractions. Analysis of truck census data for California indicated that none of the 2-axle, 4-tire trucks surveyed were heavy-duty diesel; 43% of the 2-axle, 6-tire trucks were heavy-duty diesel; and >90% of all trucks with three or more axles were heavy-duty diesel.

The ratio of fuel used on day k to the average daily use of fuel, d_k in eq 1, was estimated as the average diesel truck count on day k divided by the average daily truck count for all days

Table 1. California exhaust emission standards for heavy-duty diesel engines.[39]

Model Year	NO_x	Particulate Matter
	(g/bhp-hr)[a]	
1985-1986	10.7[b]	–
1987-1990	6.0	0.60
1991-1993	5.0	0.25
1994-1996	5.0	0.10

[a] In the United States, heavy-duty diesel engine emissions are regulated per unit of brake work output by the engine; standards are stated in g/bhp-hr units. Emission standards may be converted to g/kW-hr by multiplying the above values by a factor of 0.75.

[b] Prior to 1987, a 13-mode steady-state test procedure was used that differs from the current transient test procedure.[15] The NO_x standard in California was 5.1 g/bhp-hr under the old procedure. Sawyer and Johnson[1] estimate that this value is equivalent to 10.7 g/bhp-hr under current test procedures.

of the week combined. The fraction of total fuel use on day *k* that occurs during hour *l*, $h_{k,l}$ in eq 1, was estimated using the fraction of diesel truck counts from weigh-in-motion sites on day *k* that were measured during hour *l*.

Heavy-duty diesel truck emissions were measured at the Caldecott tunnel on Highway 24 between Oakland and Orinda, CA, in summer 1996. The tunnel consists of three two-lane traffic bores, with eastbound traffic running uphill on a grade of 4.2% at moderate speeds of ~60 km/h. Particle- and gas-phase pollutant concentrations were measured in background air and inside two eastbound tunnel bores: one bore was influenced by heavy-duty diesel truck emissions, and a second bore was reserved for light-duty vehicles. The contribution due to light-duty vehicle emissions was subtracted from measured pollutant concentrations in the truck-influenced tunnel bore, using the method described by Miguel et al.[22] The fine particle BC emission rate for heavy-duty diesel trucks was calculated using eq 3; the result was 1.4 ± 0.2 g per kg of fuel burned.[22] A similar analysis for NO_x resulted in an emission index of 40 ± 7 g per kg of fuel burned.[23] Emission factors used in this study were expressed per unit volume of fuel burned and computed by multiplying the above values by typical diesel fuel density of 0.83 kg/L.[10]

RESULTS

Weigh-in-motion traffic count data were analyzed to determine weekly and diurnal patterns in light- and heavy-duty vehicle activity. Daily total light-duty vehicle travel varied only slightly between weekdays and weekends, as shown in Figure 1. In contrast, diesel truck activity on weekdays was 128% of the weekly average, but dropped to 39% and 24% of weekly average values on Saturdays and Sundays, respectively.

Figure 2 shows the percent of daily total traffic occurring at each hour, separately for light-duty vehicles and for heavy-duty diesel trucks, averaged over all five weekdays in the Bay Area. Light-duty vehicle traffic peaks during both the morning and evening rush hours centered at 7 a.m. and 5 p.m., respectively. In contrast, diesel truck traffic peaks around midday and falls to lower levels during the afternoon rush hour.

The fraction of weekday truck travel occurring during each hour was similar at both Bay Area weigh-in-motion sites, as shown in Table 2. Truck activity patterns observed in the Bay Area were similar to patterns observed in southern California at a weigh-in-motion monitoring site located on Interstate 710 in Long Beach (see Table 2).

The fuel-based emission inventory methodology described above was applied to calculate fine BC particle and NO_x emissions from heavy-duty diesel trucks in the Bay Area in 1996. Emission factors and activity data were combined to calculate the emission inventory presented in Table 3. The fuel-based inventory estimates for diesel truck emissions of NO_x and fine BC particles on a typical weekday are 2.3 and 4.5 times, respectively, the corresponding MVEI 7G estimates.

DISCUSSION

Differences between MVEI 7G and fuel-based emission estimates may arise in part because of differing estimates of weekday activity for heavy-duty trucks. However, after MVEI 7G fuel use is increased to match the higher weekday diesel fuel consumption estimates of this study, the fuel-based inventory still differs from MVEI 7G: NO_x emissions are 1.9 times and fine BC particle emissions 3.6 times the corresponding MVEI 7G estimates. Consequently, uncertainty in emission factors also contributes significantly to the differences between fuel-based and MVEI 7G emission estimates. When compared to

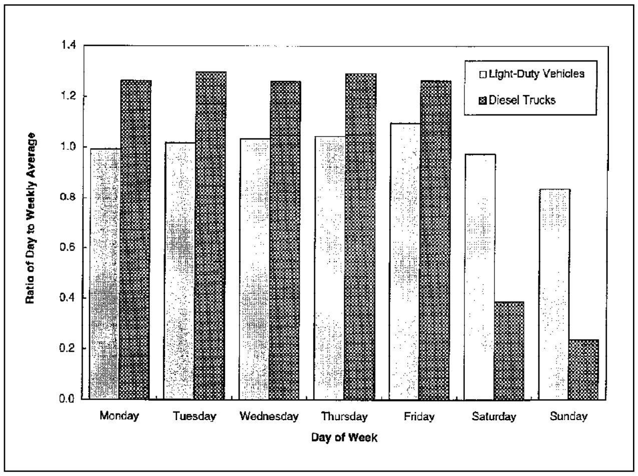

Figure 1. Ratio of daily total to weekly average traffic counts by vehicle class. Bay Area weigh-in-motion data[20] were used to compute the ratios. The ratios were calculated by dividing the total count for day *k* by the weekly average count for each vehicle class.

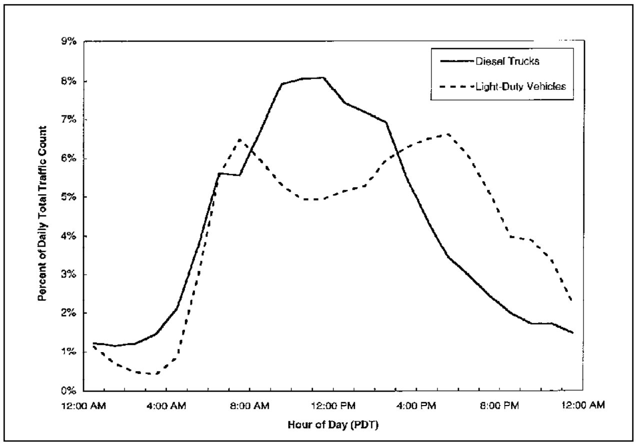

Figure 2. Hourly traffic counts as a percentage of the total daily count, calculated separately for each vehicle class. Based on hourly Caltrans traffic count data for the Bay Area from summer 1996 for weekdays only.[20] Traffic counts for each 1-hour interval were divided by the 24-hour total count for each vehicle class and then averaged over all five weekdays.

Table 2. Hourly heavy-duty diesel truck traffic counts as a percentage of the daily total diesel truck count for average weekday conditions.

Time of Day (PDT)	Interstate 880 Hayward	Highway 101 Burlingame	Interstate 710 Long Beach
12-1 AM	1.1 ± 0.3	1.4 ± 0.2	0.9 ± 0.2
1-2 AM	1.0 ± 0.2	1.3 ± 0.1	0.9 ± 0.2
2-3 AM	1.1 ± 0.1	1.4 ± 0.2	0.8 ± 0.2
3-4 AM	1.4 ± 0.2	1.5 ± 0.1	0.9 ± 0.1
4-5 AM	2.3 ± 0.1	1.9 ± 0.2	1.2 ± 0.1
5-6 AM	4.2 ± 0.3	3.2 ± 0.1	2.3 ± 0.1
6-7 AM	5.5 ± 0.5	5.7 ± 0.4	4.1 ± 0.2
7-8 AM	5.4 ± 0.4	5.8 ± 0.3	5.2 ± 0.2
8-9 AM	6.6 ± 0.3	6.8 ± 0.3	6.6 ± 0.2
9-10 AM	7.8 ± 0.4	8.1 ± 0.5	8.1 ±0.5
10-11 AM	8.3 ± 0.2	7.9 ± 0.2	8.7 ± 0.4
11-12 AM	8.0 ± 0.3	8.2 ± 0.5	9.2 ± 0.3
12-1 PM	7.4 ± 0.2	7.4 ± 0.1	7.5 ± 0.2
1-2 PM	7.2 ± 0.3	7.2 ± 0.3	7.6 ± 0.5
2-3 PM	7.2 ± 0.3	6.7 ± 0.2	8.0 ± 0.3
3-4 PM	5.7 ± 0.3	5.3 ± 0.3	7.2 ± 0.3
4-5 PM	4.5 ± 0.2	4.3 ± 0.2	6.1 ± 0.1
5-6 PM	3.4 ± 0.2	3.5 ± 0.2	4.1 ± 0.1
6-7 PM	3.1 ± 0.3	2.9 ± 0.2	2.9 ± 0.2
7-8 PM	2.5 ± 0.1	2.4 ± 0.3	2.4 ± 0.2
8-9 PM	1.9 ± 0.2	2.1 ± 0.2	1.7 ± 0.2
9-10 PM	1.6 ± 0.2	1.8 ± 0.2	1.6 ± 0.2
10-11 PM	1.6 ± 0.3	1.9 ± 0.2	1.2 ± 0.2
11-12 PM	1.3 ± 0.3	1.6 ± 0.4	1.1 ± 0.1

the emission factors derived from measurements at the Caldecott tunnel and used here in the fuel-based method, it appears that MVEI 7G uses lower emission factors for both NO_x and fine BC particles.

The fuel-based inventory developed in this study uses tunnel-derived emission factors to represent all Bay Area driving. Since vehicles are driving on a 4.2% uphill grade in the Caldecott tunnel, the question of whether emission factors might be different under other driving conditions must be addressed.

Pierson et al.[13] report that heavy-duty truck NO_x emission rates, when normalized to fuel consumption, were the same for uphill and downhill traffic in the Fort McHenry tunnel and for level driving in the Tuscarora tunnel. The heavy-duty truck emission factor of 34 g NO_x per kg of fuel burned reported by Pierson et al. is similar to the value used in the present study. These findings support the extrapolation of heavy-duty vehicle NO_x emission factors measured in the Caldecott tunnel to other driving conditions.

The fine BC particle emission factor used in the present study is similar to the value of 0.95 g per kg of fuel burned reported by Rogak et al.[24] for heavy-duty trucks driving in the nearly level Cassiar tunnel in Vancouver, Canada. Further study is needed of the variability in emission factors as a function of engine load. Despite the normalization to fuel consumption, the Caldecott tunnel-derived emission factors for both BC and NO_x are for uphill loaded-mode driving and should be viewed as upper bound values.

Another source of uncertainty in comparing fuel-based emission estimates to MVEI 7G predictions results from use of size distribution and chemical composition profiles to determine the fine BC particle fraction of total exhaust PM emissions. BC emission factors determined by Miguel et al.[22] were based on $PM_{1.3}$ sampling (i.e., a 1.3-µm aerodynamic diameter cutpoint was used). Current California inventories specify that sub-micron particles account for 92% of exhaust PM mass from heavy-duty diesel trucks.[25] While it is clear that almost all diesel exhaust PM consists of sub-micron particles, the BC fraction of exhaust PM is less certain. Current inventories assume that BC accounts for 26% by mass of diesel exhaust PM emissions.[25] These size distribution and chemical composition factors were applied to the MVEI 7G estimate of total heavy-duty diesel exhaust PM emissions to compute the fine BC particle emissions shown in Table 3.

Table 3. On-road heavy-duty diesel truck emissions in the San Francisco Bay Area, summer 1996.

	Fuel-Based Inventory[a]			MVEI 7G	Weekday Ratio:
	Weekday	Saturday	Sunday	Weekday	Fuel-Based to MVEI 7G
Diesel Fuel Used (10^3 L/day)	3200	980	600	2600	1.2
NO_x (10^3 kg/day)	110	33	20	48	2.3
Fine BC particles (10^3 kg/day)	3.7	1.1	0.70	0.83[b]	4.5

[a] Calculated using Caldecott tunnel-derived emission factors of 40 g NO_x and 1.4 g of fine BC particles per kg of fuel burned (see text), and a typical diesel fuel density of 0.83 kg/L.

[b] For consistency with the fuel-based inventory, the MVEI 7G estimate was adjusted to include only particles with aerodynamic diameter of 1 µm or less. Sub-micron particles were estimated to account for 92% of total diesel exhaust PM mass.[25] Current California inventories assume that black carbon accounts for 26% of total diesel exhaust PM emissions.[25]

Weekend Effects

Analysis of weigh-in-motion truck count data for the Bay Area revealed a sharp decline in heavy-duty vehicle travel on weekends, which is clearly observable in Figure 1. The fuel-based emission inventory presented here highlights important differences between weekday and weekend emissions from diesel trucks. Decreases in off-road mobile source and stationary source activity may also contribute to weekday and weekend differences in air pollutant emissions. For example, decreases in emissions from off-road construction equipment on weekends could augment the emissions reductions from on-road diesel trucks.

Altshuler et al.[26] have reviewed ambient ozone concentrations for Northern California locations including the Bay Area and report that, on average, ozone concentrations are higher on weekends than on weekdays. Similar findings have been reported for other locations, such as Los Angeles.[27,28] Changes in heavy-duty diesel truck NO_x emissions between weekdays and weekends described in this study may contribute to the observed phenomenon of higher ozone concentrations on weekends. Heavy-duty diesel truck NO_x emissions in the Bay Area decrease relative to typical weekday conditions by ~70% and ~80% on Saturday and Sunday, respectively. Under California urban conditions, with low VOC-to-NO_x-concentration ratios in ambient air, Altshuler et al.[26] argue that lowering NO_x emissions may lead to increased ozone concentrations.

Changes in exhaust emissions due to reduced diesel truck activity may lead to lower ambient fine particle concentrations on weekends. Since BC particles scatter and absorb light efficiently and are present in high concentrations in urban areas, they are an important cause of visibility impairment.[29] Therefore, reductions in exhaust PM emissions from diesel trucks may lead to improved visual range on weekends relative to typical weekday conditions.

Sensitivity analyses conducted on atmospheric photochemical mechanisms indicate that urban ozone formation is strongly influenced by the rates of NO_2 and formaldehyde photolysis.[30,31] Therefore, because BC particles absorb light, ground-level sunlight intensity and photolysis rates may increase on weekends when BC particle concentrations are lower. Consequently, another contributing factor to the weekend effect may be that lower fine particle emissions from diesel trucks lead to increased photolysis rates and ozone formation on weekends.

Secondary Organic Aerosol

The differences shown in Figure 2 between hourly activity patterns for heavy-duty diesel trucks and light-duty vehicles are consistent with findings reported for the Bay Area by Schlappi et al.[8] The truck activity pattern is also consistent with the weigh-in-motion truck count data from southern California shown in Table 2 and with reported truck activity patterns from other locations nationally.[32,33]

Differences in the diurnal patterns of travel by light-duty and heavy-duty vehicles complicate the use of BC as a tracer for directly emitted organic carbon in secondary organic aerosol studies. Previous studies[29,34-36] have used the ratio of ambient organic carbon (OC) to BC concentrations to estimate the contribution to OC from secondary organic aerosol formation. In such studies, a baseline OC/BC ratio is computed from known primary source emissions within the air basin. When the baseline ratio is exceeded in ambient air samples, the excess OC is attributed to secondary organic aerosol formation.

Source tests have shown that the BC fraction of total fine carbonaceous particle emissions is higher in diesel exhaust than it is in gasoline exhaust. Hildemann et al.[37] report that BC accounted for 11% and 33% of fine carbonaceous particle emissions from non-catalyst and catalyst-equipped gasoline-powered vehicles, respectively, versus 55% BC in diesel engine carbon particle emissions. Likewise, Watson et al.[38] report a lower BC fraction, 31% of total fine carbon particles, in gasoline engine exhaust compared to 45% BC in diesel engine exhaust emissions. Therefore, differences in the diurnal patterns of light- and heavy-duty vehicle activity may also contribute to variations in the ambient OC/BC ratio. As shown in Figure 2, diesel truck emissions fall off by mid-afternoon on weekdays, while at the same time, light-duty vehicle emissions are increasing. Therefore, the ratio of OC/BC in primary source emissions varies throughout the day.

Turpin and Huntzicker[35,36] measured ambient OC and BC concentrations in southern California during summer and fall of 1987. By analyzing OC/BC ratios, Turpin and Huntzicker concluded that secondary organic aerosol contributed significantly to total OC concentrations on days with high levels of photochemical activity. The highest secondary OC contributions were reported to occur from 4-6 p.m. at Claremont, which was later than the time of the observed ozone peak. Another contributing factor to the observed increases in OC/BC ratios late in the afternoon may have been a shift in the composition of fine carbon particle emissions. As shown in Figure 2, diesel truck activity drops off after ~3 p.m. relative to earlier hours and drops even more when considered relative to the increase in light-duty traffic during the 4-6 p.m. period. This shift in the mix of gasoline versus diesel traffic would lead to an increase in the OC/BC ratio in fresh fine particle emissions.

Turpin and Huntzicker[35] also reported weekend OC/BC ratios almost double the weekday ratios in August 1987. During the weekend days sampled, BC concentrations were as expected, lower than on weekdays due to lower weekend truck travel. Consequently, the elevated OC/BC ratio observed on weekends can be explained at least in part by changes in vehicle activity patterns described in this study.

CONCLUSIONS

A fuel-based approach to estimating emissions from diesel trucks was described and applied to the San Francisco Bay Area for summer 1996. Heavy-duty diesel trucks were estimated at the upper bound to emit 110×10^3 kg/day of NO_x and 3.7×10^3 kg/day of fine BC particles on weekdays. Emissions declined by 70–80% on weekends. Weekday emissions of NO_x and fine BC were found to be at most 2.3 and 4.5 times, respectively, the predictions of MVEI 7G.

Weekday versus weekend differences in heavy-duty diesel truck travel and NO_x and exhaust PM emissions may contribute to the higher ambient ozone concentrations and higher OC/BC ratios observed on weekends. Furthermore, the decrease in heavy-duty diesel truck travel and increased light-duty vehicle activity observed on weekday afternoons may contribute to increases in ambient OC/BC ratios observed during the afternoon peak traffic period (4-6 p.m.).

The fuel-based method provides a useful, independent check on traditional travel-based emission inventory models. Improvements to the activity data underlying emissions estimates for heavy-duty diesel trucks have been described. Emission inventories would benefit from further measurements of in-use heavy-duty diesel truck emissions. We encourage the measurement and reporting of fuel consumption in future emission factor studies so that the fuel-based emission inventory approach may be further developed.

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REFERENCES

1. Sawyer, R.F.; Johnson, J.H. In *Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects*; Health Effects Institute: Cambridge, MA, 1995; pp 67-81.
2. Cass, G.R.; Gray, H.A. In *Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects*; Health Effects Institute: Cambridge, MA, 1995; pp 127-137.
3. Fanai, A.K., Planning Division, Bay Area Air Quality Management District, San Francisco, CA, personal communication, 1997.
4. *User's Guide to MOBILE 4.1 (Mobile Source Emission Factor Model)*; U.S. Environmental Protection Agency. Office of Mobile Sources. Ann Arbor, MI, 1991; EPA-A-TEB-91-01.
5. "Predicted California On-Road Motor Vehicle Emissions; Volume I: EMFAC7G"; California Air Resources Board: Sacramento, CA, 1996.
6. Harvey, G.W.; Deakin, E. "A manual of regional transportation modeling practice for air quality analysis"; National Association of Regional Councils, Washington, DC, 1993.
7. *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use;* Transportation Research Board. National Academy Press: Washington, DC, 1995; Special Report 245.
8. Schlappi, M.L.; Marshall, R.G.; Itamura, I.T. "Truck travel in the San Francisco Bay Area," *Transportation Research Record* **1993**, *1383*, 85-94.
9. "Truck Kilometers of Travel on the California State Highway System, 1978-1993"; Office of Traffic Improvement. California Department of Transportation: Sacramento, CA, 1995.
10. Heywood, J.B. *Internal Combustion Engine Fundamentals*; McGraw-Hill Publishing Company: New York, 1988.
11. Singer, B.C.; Harley, R.A. "A fuel-based motor vehicle emission inventory," *J. Air & Waste Manage. Assoc*. **1996**, *46*, 581-593.
12. Black, D.R.; Singer, B.C.; Harley, R.A.; Martien, P.T.; Fanai, A.K. Presented at the 90th Annual Meeting of the Air & Waste Management Association, Toronto, Canada, 1997; Paper 97-RP143.03.
13. Pierson, W.R.; Gertler, A.W.; Robinson, N.F.; Sagebiel, J.C.; Zielinska, B; Bishop, G.A.; Stedman, D.H.; Zweidinger, R.B.; Ray, W.D. "Real-world automotive emissions—summary of studies in the Fort McHenry and Tuscarora Mountain tunnels," *Atmos. Env.* **1996**, *30*, 2233-2256.
14. *Highway Statistics 1995*; Office of Highway Information Management. Federal Highway Administration. United States Department of Transportation: Washington, DC, 1996.
15. Code of Federal Regulations, Title 40, Part 86, Subpart N.
16. "California Statistical Abstract"; California Department of Finance, Financial and Economic Research Unit: Sacramento, CA, 1996.
17. Beile, K., California State Board of Equalization, Sacramento, CA, personal communication, 1997.
18. "California Diesel Fuel Tax Law"; California State Board of Equalization: Sacramento, CA, 1997.
19. *Monthly Motor Fuel Reported by States;* Office of Highway Information Management. Federal Highway Administration. United States Department of Transportation: Washington, DC, 1995.
20. Avis, J., Traffic Control Section, California Department of Transportation, Sacramento, CA, personal communication, 1996.
21. *Truck Inventory and Use Survey*; United States Census Bureau; Washington, DC, 1992.
22. Miguel, A.H.; Kirchstetter, T.W.; Harley, R.A.; Hering, S.V. "On -road emissions of particulate polycyclic aromatic hydrocarbons and black carbon from gasoline and diesel vehicles," *Env. Sci. & Tech.* **1998**, *32*, 450-455.
23. Kirchstetter, T.W., Department of Civil and Environmental Engineering, University of California, Berkeley, CA, personal communication, 1997.
24. Rogak, S.N.; Pott, U.; Campbell, J.L.; Nejedly, Z. Presented at the 90th annual meeting of the Air & Waste Management Association, Toronto, Canada, June 1997; Paper WP96.02.
25. Allen, P.D., Technical Support Division, California Air Resources Board, Sacramento, CA, personal communication, 1997.
26. Altshuler, S. L.; Arcado, T.D.; Lawson, D.R. "Weekday vs. weekend ambient ozone concentrations: discussion and hypotheses with focus on northern California," *J. Air & Waste Manage. Assoc.* **1995**, *45*, 967-972.
27. Hoggan, M.; Hsu, M.; Kahn, M.; Call, T. Presented at the 82nd Annual Meeting of the Air & Waste Management Association, Anaheim, CA, 1989; Paper 89-125.5.
28. Current Air Quality, Appendix II, 1997 Air Quality Management Plan; South Coast Air Quality Management District: Diamond Bar, CA, 1996.
29. Larson, S. M.; Cass, G.R.; Gray, H.A. "Atmospheric carbon particles and the Los Angeles visibility problem," *Aerosol Sci. and Tech.* **1989**, *10*, 118-130.
30. Milford, J. B.; Gao, D.; Russell, A.G.; McRae, G.J. "Use of sensitivity analysis to compare chemical mechanisms for air quality modeling." *Env. Sci. & Tech.* **1992**, *26*, 1179-1189.
31. Vuilleumier, L.; Harley, R.A.; Brown, N.J. "First- and second-order sensitivity analysis of a photochemically reactive system (a Green's function approach)," *Env. Sci. & Tech.* **1997**, *31*, 1206-1217.
32. Grenzeback, L.R.; Reilly, W.R.; Roberts, P.O.; Stowers, J.R. "Urban freeway gridlock study: decreasing the effects of large trucks on peak-period urban freeway congestion," *Transportation Research Record* **1990**, *1256*, 16-26.
33. Rawling, F.G. In *Goods Transportation in Urban Areas*; Chatterjee, A.; Fisher, G.P.; Stanley, R.A., Eds.; American Society of Civil Engineers: New York, NY, 1989; pp 95-118.
34. Turpin, B.J.; Huntzicker, J.J.; Larson, S.M.; Cass, G.R. "Los Angeles summer midday particulate carbon: primary and secondary aerosol," *Env. Sci. & Tech.* **1991**, *25*, 1788-1793.
35. Turpin, B.J.; Huntzicker, J.J. "Secondary formation of organic aerosol in the Los Angeles Basin: a descriptive analysis of organic and elemental carbon concentrations," *Atmos. Env.* **1991**, *25A*, 207-215.
36. Turpin, B.J.; Huntzicker, J.J. "Identification of secondary organic aerosol episodes and quantitation of primary and secondary aerosol concentrations during SCAQS," *Atmos. Env.* **1995**, *29*, 3527-3544.
37. Hildemann, L.M.; Markowski, G.R.; Cass, G.R. "Chemical composition of emissions from urban sources of fine organic aerosol," *Env. Sci. & Tech.* **1991**, *25*, 744-759.
38. Watson, J.G.; Chow, J.C.; Lowenthal, D.H.; Pritchett, L.C.; Frazier, C.A.; Neuroth, G.R.; Robbins, R. "Differences in the carbon composition of source profiles for diesel- and gasoline-powered vehicles," *Atmos. Env.* **1994**, *28*, 2493-2505.
39. "Update on the Feasibility of Reducing NO_x and Particulate Matter Emissions from Heavy-Duty Vehicles"; California Air Resources Board, Mobile Source Division: Sacramento, CA, 1993.

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