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Particulate Emission Rates from Light-Duty Vehicles in the South Coast Air Quality Management District

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This paper presents the results of a particulate emission rate study conducted on 129 light-duty gasoline and 19 light-duty diesel vehicles for the Coordinating Research Council's (CRC's) Project E-24-2. Total particulate emission rates for newer gasoline vehicles were low (<3 mg/mi) with modest increases with vehicle age and older technology. Average FTP particulate emission rates as a function of model year for gasoline vehicles were found to be 2.5 mg/mi for 1991 and newer models, 14.4 mg/mi for 1986−1990 models, 49.0 mg/mi for 1981−1985 models, and 33.8 mg/mi for 1980 and older models. High gaseous emitters were found to have approximately 5−10 times the particulate emission rates of normal emitters. The diesel vehicles had an average particulate emission rate of 561 mg/mi. It should be noted that the light-duty diesel vehicles were predominantly older, pre-1985 vehicles; the 1985 and newer diesel vehicles had substantially lower particulate emissions, i.e., less than 100 mg/mi. Emission inventory estimates in the South Coast Air Basin based on the fleet emission rates were higher (3.42 tons/day of PM for light-duty passenger cars) than those obtained using the default values in EMFAC7G (1.96 tons/day of PM), due primarily to the contribution of high emitters.

1. Introduction

A large and robust database is critical to understanding the contribution of light-duty vehicles to present and future $PM_{2.5}$ emission inventories. Several studies have shown that particulate emission rates from properly functioning/modern gasoline-fueled vehicles are small–i.e., on the order of 1−5 mg/mi (*1*−*3*). Studies of in-use vehicles indicate somewhat higher particulate emission rates. Hildemann et al. tested seven 1977−1983 catalyst-equipped in-use vehicles and obtained an average $PM_{2.0}$ emission rate of 17.6 mg/mi (*4*). Gertler et al. measured the average PM_{10} emission rate of heavy- and light-duty vehicles passing through the Fort McHenry Tunnel during July 1993 and obtained a fleet average emission rate for light-duty vehicles of 15 $\pm$ 60 mg/mi (*5*). In other recent work, Schauer et al. (*6, 7*) measured particulate emissions for a small fleet of gasoline and medium-duty diesel vehicles with an emphasis on developing species profiles and measuring gas-phase, semivolatile and particle-phase organic compounds. Several recent studies have concentrated on determination of the particulate mass emission rates of high emitter vehicles (*8*−*12*). Dickerson et al. measured PM_{10} emissions of 1510 mg/mi, with a range of 100−16 760 mg/mi (*8*). Sagebiel et al. reported PM_{10} emission rates from 23 1976−1990 vehicles that were recruited as part of the Clark and Washoe Remote Sensing Study (CAWRSS) in Nevada (*9*). The average PM_{10} emission rate for all 23 vehicles was found to be 183 mg/mi as determined using the IM240 test cycle. The average emission rate for six smoking vehicles in that group was 558 mg/mi, while that for the nonsmoking vehicles was 51 mg/mi. A more recent study conducted in conjunction with the Orange County Remote Sensing Study measured PM_{10} emissions from 103 vehicles recruited on the basis of high HC or CO emissions (*10*). The average PM_{10} emissions rates for vehicles identified as nonsmoking and smoking were 94 and 395 mg/mi, respectively. Durbin et al. measured the particulate emission rates from 23 smoking vehicles recruited in the South Coast Air Quality Management District (SCAQMD) (*11, 12*). The average Federal Test Procedure (FTP) emission rate from these vehicles was found to be 399 mg/mi with a range from 64 to 2323 mg/mi. These recent studies have added significantly to the database on the particulate emission rates from malfunctioning and high emitter light-duty vehicles. There is still a need, however, to develop a larger database on particulate emission rates from the full range of the in-use light-duty vehicle fleet.

From September of 1996 to August of 1997, the University of California, Riverside, Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) conducted an extensive study of particulate emission rates from a wide range of in-use light-duty passenger cars and trucks. This work was conducted as part of a program cosponsored by the Coordinating Research Council (CRC), the SCAQMD, and the National Renewable Energy Laboratory (NREL) (*13*). This work was coordinated with CRC studies performed in Colorado as part of the Northern Front Range Air Quality Study (NFRAQS) (*14*) and at the Southwest Research Institute (SwRI) (*15*). For this project, FTP particulate emission rates were characterized for 129 gasoline and 19 light-duty diesel vehicles, along with the fractions of particulate below 2.5 and 10 μm mean aerodynamic diameter. These particulate emission results were used to develop particulate emissions inventory estimates using the California Air Resources Board's (CARB's) EMFAC7G model, which were compared with current inventory estimates.

2. Experimental Procedures

2.1. Vehicle Fleet Description and Recruitment. Light-duty gasoline-fueled vehicles tested in this program were recruited in conjunction with a larger testing program to develop a modal emissions model sponsored by the National Cooperative Highway Research Program (NCHRP) (*16*). The NCHRP project recruited over 300 vehicles grouped according to a vehicle/technology matrix based on their estimated relative gaseous emission contribution to the mobile source inventory. A 129 vehicle subset of the NCHRP fleet was used for this project. Table 1 presents a summary by model year, fuel type, and vehicle category of test vehicles. The gasoline fleet is approximately equally split between passenger cars and trucks. Gasoline vehicles were also classified as normal and high emitters, as listed in Table 1, and discussed further in section 3.1.1. In addition to the gasoline vehicles recruited in conjunction with NCHRP, a fleet of 19 light-duty diesel-

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TABLE 1. Vehicle Fleet Breakdown by Model Year, Vehicle Type, and Fuel Type

vehicle/fuel type	1991–1997	1986–1990	1981–1985	pre-1980
total light-duty gasoline	61	33	21	14
light-duty gasoline cars	34	15	10	8
light-duty gasoline trucks	27	18	11	6
normal emitter gasoline	56	22	8	4
high emitter gasoline	5	11	13	10
light-duty diesel	1	0	12	6

fueled passenger cars was recruited for testing. The light-duty diesel fleet was almost exclusively passenger cars. Due to the vehicle population characteristics in California, the light-duty diesel fleet is dominated by pre-1986 vehicles. It should be noted that particulate emission results for newer light heavy-duty diesel pick-up trucks were obtained as part of another CE-CERT study (*17*).

Since the NCHRP project required the testing of both normal and high gaseous emitter vehicles, several sources were used to identify and recruit vehicles. Vehicles were randomly recruited by telephone/mail solicitation based on the categorization of vehicles in the vehicle/technology matrix. The California Department of Motor Vehicles (DMV) provided a database of vehicle registration in the SCAQMD, which also was used for recruitment. This database was current up to 1996 and provided license plate numbers, vehicle identification numbers (VINs), and owner information (e.g., address). For high gaseous emitter vehicles, several recruitment techniques were used. These included identification of high gaseous emitters with CE-CERT's remote sensing van, contacts with local car dealers and rental car agencies to identify vehicles brought in by customers for emissions related repair and high mileage vehicles suspected to be high emitters, and use of a high emitter profile developed from inspection and maintenance data. Light-duty diesel vehicles were recruited separately from the NCHRP program. The light-duty diesel vehicles were identified using the DMV database and were recruited randomly by mail solicitation.

2.2. Vehicle Testing. All vehicles were tested over the Federal Test Procedure (FTP) to obtain mass emission rates for total particulate matter, total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), and nitrogen oxides (NO_x). THC emissions for diesel vehicles were determined from continuously integrated measurements through a heated sample line as specified in the Code of Federal Regulations (CFR) (*18*). Additional particulate sampling was added to the FTP test procedures to meet the program objectives, as discussed below. Each vehicle was tested over a single FTP after an overnight soak at a temperature of 72 ± 2 °F. To provide a more accurate portrayal of in-use emissions, vehicles were not preconditioned over the LA-4 driving schedule prior to testing. All vehicles were tested with the fuel in the tank at the time the vehicle was received. The fuels were California Phase 2 reformulated gasoline (RFG), with the exception of two out-of-state vehicles, and California reformulated diesel. Average gasoline characteristics in the SCAQMD during the vehicle testing period were 0.62 vol % benzene, 18.2 vol % aromatics, 4.8 vol % olefins, 1.99 wt % oxygen, and 20.4 ppm sulfur, consistent with California Phase 2 RFG. For the light-duty diesel vehicles, a composite fuel sample consisting of equal portions of fuel from each of the diesel test vehicles was submitted for analysis. The resulting analysis for the composite diesel fuel sample showed it to contain 22.9 wt % aromatics, 4.15 wt % polynuclear aromatics (PNA), and 0.0149 wt % sulfur with a cetane number of 51.6.

Particulate samples were collected using a 10-in. diameter dilution tunnel for gasoline vehicles and a 12-in. diameter dilution tunnel for diesel vehicles. Each tunnel is fitted with three sampling probes located approximately 10 tunnel diameters downstream of the exhaust mixing flange. Dilution rates of 350 standard cubic feet per min (SCFM) and 856 SCFM were used, respectively, for the gasoline and diesel vehicles. Samples for total particulate mass determination were collected on 47 mm, 2.0 μm Gelman Teflon membrane filters using a primary and a back-up filter. Samples were drawn at flow rates of 47 lpm for gasoline and 20 lpm for diesel fueled vehicles through isokinetic samples probes using a mass flow controlled pump. The relatively high tunnel flow rates and low sample flow rates for the diesel vehicles were used to help prevent filter clogging during testing.

Size segregated samples were collected with a Micro-Orifice Uniform Deposit Impactor (MOUDI). Uncoated aluminum foils were used for the impaction substrates together with 47 mm, 2.0 μm pore size Gelman Teflon membrane after-filters. It should be noted that particle bounce can occur in impactors when using uncoated substrates, resulting in lower mass median diameters (*19*). This problem has not been extensively studied or documented for vehicle exhaust particulates sampled with a MOUDI, however. MOUDI flow rates were maintained at 30 lpm with a mass flow controlled pump. For 16 of the gasoline-fueled vehicles and all 19 of the light-duty diesel fueled vehicles, full MOUDI characterization was obtained with cut-points of >18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, 0.10, 0.056, and <0.056 μm aerodynamic diameter. For the remainder of the gasoline fueled vehicles, only the first five stages of the MOUDI were utilized together with the after-filter to obtain results on the percentage of total mass emissions below 10 and 2.5 μm aerodynamic diameter.

Teflon membrane and aluminum MOUDI substrates were weighed before and after sampling to determine the collected mass using an ATI Orion ultramicrobalance. The microbalance is located in an environmental weighing chamber maintained at a temperature of 25 ± 0.5 °C and a relative humidity of 40 ± 5%. The precision for the gasoline particulate mass emission rates is approximately 0.3 mg/mi at two σ with minimum detection limits of approximately 0.3–0.4 mg/mi. Tunnel blanks for mass emission measurements were collected daily for the gasoline tunnel and weekly for the diesel tunnel throughout testing. Tunnel blanks were converted to mass emission rates based on sample flows and the length of the testing period. Particulate mass emission rates were corrected based on the average equivalent mass emission rates. Tunnel blanks were 0.2 ± 0.2 mg/mi for the gasoline tunnel and 0.4 ± 0.5 mg/mi for the diesel tunnel during the period of testing.

In addition to the particulate mass emission and size samples, samples were collected for the determination of metals and trace elements, inorganic ions, elemental and organic carbon, polynuclear aromatic hydrocarbons (PAHs), steranes, and hopanes. A detailed discussion of the sampling procedures and results for chemical analyses are presented elsewhere (*13*).

3. Emissions Test Results and Discussion

3.1. Particulate and Gas-Phase Mass Emission Results. *3.1.1. Particulate Emission Results.* A summary of the FTP weighted

TABLE 2. FTP Weighted Particulate Emission Rates

category	no. of veh	particulate emission rates av PM mg/mi	median mg/mi	max. PM mg/mi	min. PM mg/mi
gasoline					
pre-1981	14	33.8	34.3	72.5	6.4
1981−1985	21	49.0	14.7	388	0.4
1986−1990	33	14.4	3.4	200	0.3
1991−1997	61	2.5	1.2	27.7	0.0
light-duty diesel	19	561	485	1608	15.5

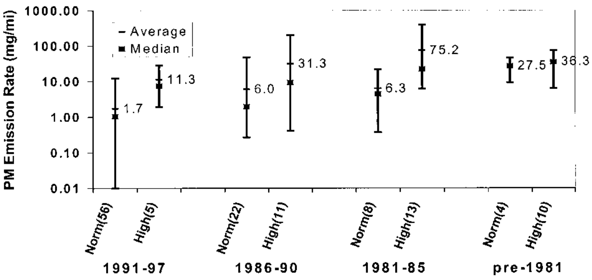

FIGURE 1. Comparison of FTP weighted particulate emission rates for normal and high emitter light-duty gasoline vehicles.

particulate emissions results for the gasoline and diesel vehicles is presented in Table 2. Average, median, maximum, and minimum FTP weighted particulate emission rates are presented by model year categories for the light-duty gasoline-fueled vehicles. Since all but one of the light-duty diesel vehicles are pre-1986, these results are presented as one total. The results presented in Table 2 show that the average particulate emission rates for newer gasoline vehicles (1991−1997) are low with a fairly steady trend of increased emissions with increasing vehicle age. This is not unexpected given the improvements in technology over time and vehicle deterioration as a function of age. As indicated by comparison of the average and median emission rates for the 1981−1985 and 1986−1990 model year categories, the average emission rate for these categories is strongly influenced by high emitters. Removal of the two highest-emitting vehicles reduces the fleet average for the 1981−1985 model year category to 16.6 mg/mi, while removal of the highest emitting vehicle reduces the fleet average for the 1986−1990 model year category to 8.6 mg/mi.

The average emission rates for the diesel vehicles are approximately 1−2 orders of magnitude higher than those of the gasoline vehicles. Newer light-duty diesels had considerably lower particulate emission rates than the average would imply. In particular, two 1985 diesel vehicles had emission rates of 70.1 and 15.5 mg/mi, and a 1993 diesel vehicle had an emission rate of 86.6 mg/mi. The diesel vehicle with an emission rate of 15.5 mg/mi was equipped with a particulate trap.

Figure 1 compares the FTP weighted particulate emission rates for the gasoline vehicles characterized as normal and high gaseous emitters. These vehicles were classified based on categories used in the larger NCHRP study, with high gaseous emitters defined as those having two times the HC or CO or four times the certified NO_x emission level for tier 0 vehicles. For tier 1 vehicles, high gaseous emitters were defined as those having 1.5 times the certified HC, CO, or NO_x emission level. Results are presented as average, median, and range of particulate emission rates. Normal emitter vehicles newer than the 1981 model year have low emission levels, with all of the average emission rates less than 6.3 mg/mi. For 1981 model year and newer vehicles, the high gaseous emitters in the same categories have particulate

TABLE 3. Comparison of FTP Weighted Particulate Emission Rates for Light-Duty Gasoline Cars and Trucks

model year	vehicle	particulate emission rates av mg/mi	median mg/mi	max. mg/mi	min. mg/mi
pre-1981	cars(8)	31.5	26.9	67.5	6.4
	trucks(6)	36.8	36.7	72.5	13.5
1981−1985	cars(10)	48.6	13.2	325	0.4
	trucks(11)	49.3	15.1	388	1.3
1986−1990	cars(15)	17.2	1.9	200	0.3
	trucks(18)	12.2	4.9	54.5	0.4
1991−1997	cars(34)	1.8	0.8	27.7	0.01
	trucks(27)	3.5	1.9	13.3	0.5

TABLE 4. FTP Weighted THC Emission Rates

category	no. of veh	THC emission rates av g/mi	median g/mi	max. g/mi	min. g/mi
gasoline					
pre-1981	14	5.06	2.92	24.58	0.44
1981−1985	21	2.07	1.65	8.71	0.30
1986−1990	33	0.96	0.54	6.06	0.20
1991−1997	61	0.34	0.20	3.50	0.06
light-duty diesels	19	0.54	0.38	1.43	0.11

TABLE 5. FTP Weighted CO Emission Rates

category	no. of veh	CO emission rates av g/mi	median g/mi	max g/mi	min. g/mi
gasoline					
pre-1981	14	63.9	25.2	332	6.17
1981−1985	21	29.6	18.8	118	2.39
1986−1990	33	9.48	7.08	31.4	0.54
1991−1997	61	2.77	1.90	13.1	0.65
light-duty diesel	19	1.90	1.47	7.81	0.86

TABLE 6. FTP Weighted NO_x Emission Rates

category	no. of veh	NO_x emission rates av g/mi	median g/mi	max. g/mi	min. g/mi
gasoline					
pre-1981	14	2.14	1.64	6.16	0.43
1981−1985	21	1.46	1.03	5.11	0.11
1986−1990	33	1.08	0.73	7.15	0.22
1991−1997	61	0.48	0.32	4.85	0.08
light-duty diesel	19	1.53	1.58	2.83	0.69

emission rates approximately 5−10 times those of the normal emitters. For vehicles older than the 1981 model year, there is a much smaller difference between the normal and high emitter category.

Table 3 compares the FTP weighted particulate emission rates for gasoline-fueled passenger cars and trucks. Interestingly, very little difference is seen in the average particulate emission rates for passenger cars and trucks in the same model year categories, although in many cases there are significant differences in emission control technologies and certification level.

3.1.2. Gaseous Emission Results. Average, median, maximum, and minimum FTP weighted THC, CO, and NO_x emission rates by vehicle category are presented in Tables 4, 5, and 6, respectively. The average THC and CO emissions for the gasoline vehicles increase significantly for the older

TABLE 7. Percent of Particulate Mass Less Than 10 and 2.5 μm Aerodynamic Diameter

category	% less than 10 μm	% less than 2.5 μm
gasoline		
1991–97	83.2	73.6
1986–90	90.2	84.1
1981–85	94.9	89.0
pre-1981	96.1	91.7
light-duty diesel	99.4	95.1

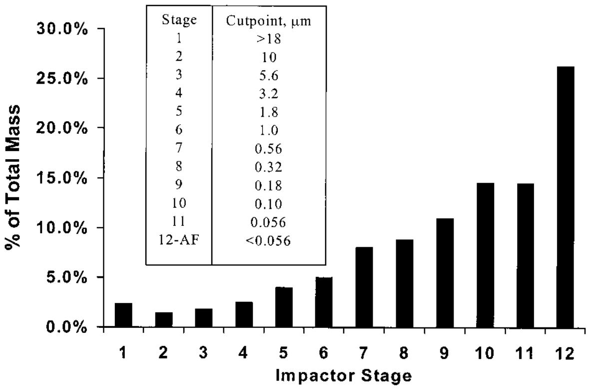

FIGURE 2. Composite gasoline MOUDI results.

model years and technologies. Average NO_x emissions for the gasoline vehicles also increase for older vehicles but not as significantly as for THC and CO emissions. As expected, the average THC and CO emission rates for the diesel vehicles were lower than those for the gasoline vehicles. Although both gaseous and particulate emissions tend to increase for older model years and emission control technologies, the linear correlations between gaseous and particulate emissions rates were weak for individual vehicles, with $R^2 = 0.17$ for THC and $R^2 = 0.11$ for CO. This indicates that the mechanisms that cause high THC or CO emissions are not necessarily directly related to the high particulate emissions.

3.2. Particle Size Distributions. Percentages of total particulate mass emissions below 10 and 2.5 μm mean aerodynamic diameter are summarized in Table 7. The majority of the particulate is below 2.5 μm mean aerodynamic diameter for all vehicle categories. Interestingly, there appears to be a modest trend toward a greater fraction of the particulate below 10 and 2.5 μm aerodynamic diameter with increased particulate emission rate. Thus, the diesel and older gasoline vehicle categories have the largest mass fraction of particulate below 2.5 μm. One possible explanation for this trend is that as the emission rates of engine-out particulate decrease, the relative contribution of re-entrained particulate, such as particle deposits in the exhaust system, to the total particulate increases.

Figures 2 and 3 present average composite MOUDI size distributions for 12 gasoline vehicles and 19 light-duty diesel vehicles, respectively. These composite averages were obtained by determining the percentage of mass on each stage for each vehicle and then averaging these percentages over all vehicles. The MOUDI spectra for four gasoline vehicles with particulate emission rates below 1.0 mg/mi were excluded from the composite spectra since it is difficult to obtain accurate size distributions with such low mass levels. The remaining 12 gasoline vehicles ranged in model year from 1972 to 1990 and had an average mass emission rate of 14.5 mg/mi with a range from 1.9 to 44.0 mg/mi (*13*). Average mass recoveries for the complete MOUDI samples were 78% for both the gasoline and diesel vehicles. Typically,

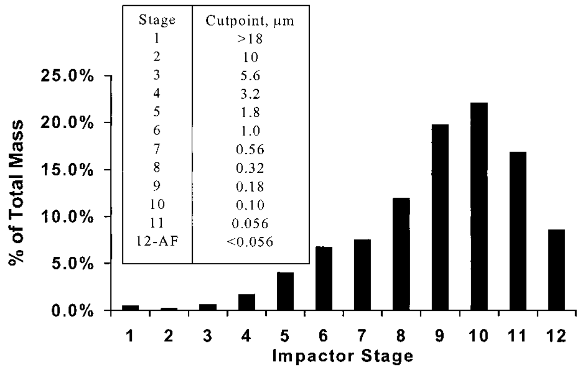

FIGURE 3. Composite diesel MOUDI impactor results.

some particle losses are observed during MOUDI operation, hence, the less than perfect mass recoveries are not unexpected. The particle losses do not, however, appear to have a significant impact on the overall size distribution, or the PM_{10} and $PM_{2.5}$ fractions, as discussed previously (*13*). Particle losses were not observed with the partial-stage MOUDI spectra collected for a majority of the gasoline vehicles, as the mass emission rates for these spectra were typically within $\pm$10–15% of those found for the Teflon membrane filters.

The gasoline-fueled MOUDI results presented in Figure 2 show the largest single mass fraction to be on the after-filter (aerodynamic diameter <0.056 μm). The diesel vehicle results, on the other hand, show a maximum at approximately 0.10–0.18 μm, as shown in Figure 3. One possible explanation for the differences between the gasoline and diesel spectra is that greater numbers of particles are formed during the combustion process in a diesel engine, and these can more rapidly and readily coagulate into the accumulation mode. Differences in the combustion processes also could contribute to this effect. It should be cautioned, however, in comparing the gasoline and diesel size distributions, that there are also significant differences in the mass emission rates of vehicles tested which could contribute to some of the observed differences. In this regard, it is worth noting that a relatively high percentage of mass (32.1%) was observed on the after-filter for the lowest-emitting diesel vehicle (15.5 mg/mi). Although the MOUDI composite spectra show differences for the gasoline and diesel vehicles, the average mass median diameters are similar for gasoline and diesel vehicles. The average mass median diameter was 0.16 μm for the gasoline vehicles with a range from 0.05 to 0.70 μm. The average mass median diameter for the diesel vehicles was slightly greater at 0.20 μm with a range from 0.11 to 0.36 μm. It should be noted that these differences in the sub 1.0 μm range would not result in differences in the percentages of PM_{10} and $PM_{2.5}$ as presented in Table 7.

4. Emissions Inventory Estimates and Model Comparisons

It is important to compare the results of this work with results obtained from EMFAC7G. For the light-duty gasoline and light-duty diesel vehicles, emission inventory estimates were developed with EMFAC7G based on the testing results and compared with those obtained using the default emission factors. The resulting emissions inventory estimates are presented in Table 8 for the South Coast Air Basin for light-duty passenger cars and trucks in calendar year 1997. The CE-CERT results were developed by replacing the emission factors in the input files for the EMFAC7G model with values based on the testing results (where available). Emission factors for all model year groupings where the contribution of high emitters was significant were developed by population weighting the emission factors for high emitters and normal

TABLE 8. Comparison of Emission Inventory Estimates for South Coast Air Basin[a]

	light-duty passenger cars				light-duty trucks			
	gasoline			LDPC	gasoline			LDT
	non-cat.	cat.	diesel	total	non-cat.	cat.	diesel	total
EMFAC7G baseline	0.59	0.96	0.42	1.96	0.06	0.40	0.21	0.67
CE-CERT total fleet (weighted by emitter level)	0.33	2.59	0.50	3.42	0.04	0.62	0.23	0.89
CE-CERT normal emitter	0.59	0.55	0.50	1.64	0.05	0.44	0.23	0.72

[a] Tons/day. Calendar year 1997.

emitters. The high-emitter population estimates were based on data obtained through the Arizona inspection and maintenance (I/M) program (20). It should be noted that these comparisons include only exhaust particulate and not tire- or brake-wear particulate emissions, which were not addressed in this study.

The emission inventory estimates for light-duty passenger cars ranged from 3.42 tons/day using the test fleet average after population weighting the high and normal emitters to 1.64 tons/day using only the normal emitters in the test fleet. This is compared with the EMFAC7G baseline estimate of 1.96 tons/day. For the light-duty trucks, the emission inventory estimates range from 0.89 tons/day using the test fleet average after population weighting the high and normal emitters to 0.72 tons for the normal emitters. This is compared with the EMFAC7G baseline estimate of 0.67 tons/day for light-duty trucks.

It should be noted that these results do not include the effects of smoking vehicles. Previous studies have shown that smoking vehicles can have a significant impact on the particulate emissions inventory even though they represent only 1−2% of the total vehicle population. Previous estimates of the contribution of light-duty smoking vehicles (GVWR < 6000 lbs) ranged from 0.47 tons/day PM to 0.74 tons/day PM based on high and low population estimates and the median FTP emission rate (11). Overall, given the significant impact that high emitters can have on the overall fleet average, it is recommended that consideration be given to having either different emission categories for normal and high emitters or emission factors developed by weighting the distribution of normal and high emitters.

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