ANALYSIS OF PARTICULATE MATTER EMISSION FACTORS IN THE PART5 MODEL

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Introduction

The EPA's PART5 model, similar in structure to the MOBILE5a model, calculates g/mi exhaust emissions of PM and SO_X from 12 classes of motor vehicles. It also calculates g/mi emissions of road dust and particles from tire wear and brake wear[1]. The g/mi emission factors of PART5 can be multiplied by estimates of VMT in a particular region to produce a total inventory of mobile-source PM emissions for the region. Because there are relatively few light-duty diesel vehicles and heavy-duty gasoline vehicles, virtually all on-road mobile-source PM comes from light-duty gasoline cars and trucks, and heavy-duty diesel vehicles (EPA, 1998b):

Contribution of different vehicle classes to total on-road mobile source PM:

[1]PART5 also estimates the amount of "indirect" sulfate, formed in the atmosphere from SO_2 emissions, on the assumption that 12% of the sulfur emitted as SO_2 becomes sulfur in ammonium sulfate or ammonium bisulfate (EPA, 1995c). However, indirect sulfate emissions are not counted as PM emissions in an emissions inventory. We treat them separately here, too.

	LDGVs	LDGT	HDGV	LDDV	LDDT	HDDV	total 10^3 tons
1987	18%	10%	3%	2%	1%	65%	360
1997	21%	15%	3%	2%	1%	58%	267

In this section, we argue that PART5 may under-estimate exhaust emissions of PM from light-duty gasoline cars and trucks, and heavy-duty diesel vehicles. Elsewhere, we argue that PART5 and AP-42 overestimate road-dust emissions (Delucchi and McCubbin, 1996). Because tirewear and brakewear emissions are much smaller than exhaust and road-dust emissions, we do not analyze the accuracy of the emission factors.

Overview of PART5 estimates of exhaust PM

Formally, PART5 calculates exhaust emissions of PM from each vehicle class, in a target year designated by the user:

$$EXPMF_{V,T} = \sum_{M} EXPM_{M,V} \cdot TF_{M,V,T} \qquad \textbf{(M1)}$$

where:

subscript V = the twelve classes of motor vehicles (light-duty and heavy-duty gasoline or diesel vehicles, two classes of light-duty gasoline trucks, light-duty diesel trucks, 3 classes of diesel vehicles between light- and heavy-duty, buses, and motorcycles)

subscript M = model year of vehicle (PART5 goes back 25 years from the target year T)

$EXPMF_{V,T}$ = the exhaust-PM emission factor for the fleet of vehicles of class V in user-designated target-year T (g/mi)

$EXPM_{M,V}$ = emissions from model year M of vehicle class V (g/mi)

$TF_{M,V,T}$ = of total vehicle-miles of travel by vehicle class M in target-year T, the fraction that is done by model-year M

In the case of gasoline vehicles, the total exhaust PM, EXPM in equation M1, is calculated as the sum of lead, direct sulfate, and carbon PM exhaust:

$$EXPM_{M,GV} = EXPB_{M,GV} + EXSO4_{M,GV} + EXC_{M,GV} \qquad \textbf{(M2)}$$

where:

$EXPB_{M,GV}$ = exhaust emissions of lead from model-year M of gasoline-vehicle class GV (g/mi)

$EXSO4_{M,GV}$ = direct sulfate emissions from model-year M of gasoline-vehicle class GV (g/mi)

$EXC_{M,GV}$ = exhaust emissions of particulate carbon from model-year M of gasoline-vehicle class GV (g/mi)

The parameter EXC is given in a table of g/mi emission rates organized by vehicle class, model year, and type of fuel and emission control equipment. The parameter EXSO4 is given in g/mi by type of emission control equipment and vehicle speed.

The calculation of the lead emission factor, EXPB in equation M2, is fairly complex (EPA, 1995c). However, in 1986 the lead content of "leaded" gasoline was decreased to 0.1 grams per gallon, and by 1991, sales of leaded gasoline were only 3% of total gasoline sales anyway (EPA, 1992a), with the result that from 1991 on, lead emissions from on-highway vehicles have been essentially zero (EPA, 1998b). Consequently, we do not discuss lead-particulate emissions further.

In the case of light-duty diesels, the parameter EXPM is given in a table of g/mi emission rates organized by vehicle class (light-duty diesel vehicles, and light-duty diesel trucks) and model year. However, as indicated above, in the summary of the EPA's *Emission Trends* estimates, there are so few light-duty diesel vehicles and trucks in the U. S. that presently, it is not worth analyzing the pertinent PART5 emission factors. We do not discuss them further here.

For other diesel-vehicle classes, the g/mi emission factor EXPM is calculated as:

$$EXPM_{M,DV} = EXPMB_{M,DV} \cdot CF_{M,DV} \qquad \textbf{(M3)}$$

where:

$EXPMB_{M,DV}$ = emissions from model-year M of diesel-vehicle class DV (g/brake-horsepower-hour [bhp-hr])

$CF_{M,DV}$ = bhp-hr/mi conversion factor for model-year M of diesel-vehicle class DV

The parameter EXPMB is given in a table of g/bhp-hr emission rates organized by vehicle class (class 2B of heavy-duty, light-heavy, medium-heavy, heavy-heavy, and buses) and model year[2].

Note that in the case of diesel vehicles, the total exhaust PM emission rate (EXPM or EXPMB), which comprises direct sulfate and carbon PM, is not a calculated value, but rather is a basic g/mi or g/bhp-hr number in a data table, whereas in the case of

[2]The values shown in Table 2 of the EPA's (1995c) *User's Guide* are for diesel vehicles that burn the high-sulfur fuel in use prior to 1993. To represent emissions from diesel vehicles that use the low-sulfur fuel mandated beginning in 1993, the EPA makes "appropriate adjustments" to the high-sulfur values.

gasoline vehicles the total exhaust PM (EXPM) *is* calculated as the sum of separately estimated components (lead, sulfate, and carbon).

As mentioned above, the fleet emission factors produced by PART5 are multiplied by total fleet travel to produce an estimate of total emissions:

$$EXPMT_T = \sum_V EXPMF_{V,T} \cdot VMT_{V,T} \qquad \textbf{(M4)}$$

where:

$EXPMT_T$ = total exhaust emissions of PM from motor vehicles in year T (grams)
$VMT_{V,T}$ = total vehicle miles of travel by vehicle class V in year T

We can see from equations M1-M4 that there are four potential general sources of error in the calculation of an emissions inventory: the basic emission factors by model year (EXPMB [heavy-duty diesel vehicles], EXSO4 [light-duty gasoline vehicles], and EXC [light-duty gasoline vehicles]), the bhp-hr/mi conversion factor (CF [heavy-duty diesel vehicles]), the travel fractions by model year (TF), and the total travel by vehicle class (VMT)[3]. In the following sections we discuss the accuracy of the basic emission factors. Recently, Browning (1998a, 1998b) has analyzed and updated the bhp-hr/mi conversion factors, so we do not consider them further here. Guensler et al. (1991) discuss the accuracy of travel statistics for heavy-duty vehicles in California.

Sulfate PM emissions from gasoline vehicles.

The sulfate emission rates in PART5 are based on relatively old data, and are given independent of the sulfur content of gasoline. They probably do not account fully for emissions from very old or malfunctioning vehicles, or from vehicles driven "off cycle". As a result, PART5 might overestimate sulfate emissions.

In PART5, LDGVs that have catalytic converters with air emit 16-25 mg/mi sulfate, and all other LDGVs emit 1-5 mg/mi sulfate (EPA, 1995c). The calculated LDGV fleet-average emission rate for the 1990s is on the order of 10 mg/mi sulfate. These rates are identical to those in the 1985 4th edition of EPA's *Compilation of Air Pollutant Emission Factors* for mobile sources (EPA, AP-42, vol. 2, 1985), which, in turn, come from the 1981 version of AP-42, and from a 1983 EPA report on particulate emissions from motor vehicles. It therefore is likely that the emission rates in PART5 are based on tests of late-70s vintage vehicles with late-70s gasoline. If so, the PART5 emission factors might not be accurate for 1990s vehicles and fuel.

There is some evidence that PART5 overestimates sulfate emissions from LDGVs. Sagebiel et al. (1996) measured exhaust emissions from 23 high-mileage, in-use LDGVs (model years 1976-1990), over the IM240 emissions test, and found an average

[3]As noted above, we have dropped light-duty diesel vehicles and trucks, and emissions of lead, from the analysis. We also drop emissions from heavy-duty gasoline vehicles, because they contribute so little to total PM emissions from motor vehicles (EPA, 1998b).

sulfate (anion) emission rate of only 0.17 mg/mi[4]. There was no appreciable trend with respect to model year. This average implies that less than 0.5% of the sulfur in the gasoline was converted to sulfur in SO_4. Watson et al. (1994c) measured the composition of $PM_{2.5}$ from approximately 600 LDGVs tested in 1989-1990 at an I&M facility in Phoenix, Arizona, and found that SO_4^{2-} was only 2.3% of the total mass of $PM_{2.5}$. Pierson and Brachaczek (1983) measured emissions from vehicles in the tunnels in Pennsylvania in 1975-1979, and found sulfate (SO_4^{2-}) emissions of 5 mg/mi (7% of total PM) for LDGVs and 68 mg/mi (5% of total PM) for HDDVs. By comparison, PART5 reports that direct sulfate emissions from LDGVs are more than 50% of total exhaust PM in the 1990s. Finally, emissions of *total* PM from late-model, new, properly functioning LDGVs are in the range of 2-3 mg/mi (Cadle et al., 1998b; Mulawa et al., 1997; EPA, 1993c) -- less than the PART5 sulfate emission rate alone.

Another, related line of reasoning suggests that PART5 overestimates sulfate emissions from LDGVs. The PART5 *Users Guide* implies (probably mistakenly) that 2% of the sulfur in gasoline is converted to sulfur in SO_4 (EPA, 1995c, p. 53), and clearly assumes that 2% of the sulfur in diesel fuel is converted to SO_4 (EPA, 1995c, p. 57). Assuming a sulfur content of 340 ppm by weight (EPA, 1995c) and a fuel economy of 22 mpg, a conversion of 2% of S-fuel to S-SO_4 results in a sulfate emission rate of 0.003 g/mi -- considerably lower than the rate reported by PART5. With reformulated "phase II" gasoline, which the EPA (1995c) assumes has a sulfur content of 138 ppm, the emission rate at 2% conversion would be 0.001 g/mi -- an order of magnitude lower than the rate reported by PART5[5].

Drive-cycle effects. How might differences between real-world driving and the test cycle affect emissions? In the sections that follow, we argue that the PART5

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[4]For one of the vehicles, the measured sulfate emission was greater than what could have been produced if all of the sulfur in the gasoline had been converted to sulfate. The authors speculate that some material had "built up over time and was dislodged during the test" (p. 81). We have excluded this vehicle from our averaging.

[5]In its calculations of S-SO_2 emissions, as the difference between total fuel-S and sulfate-S, PART5 assumes that the sulfate "particles" are droplets of sulfuric acid dissolved in water H_2O:H_2SO_4 [7:1, v/v]). This implies that the basic sulfate emission factors in PART5 (e.g., 16-25 mg/mi for vehicles with catalytic converters with air emit) include the weight of 7 water molecules and H_2 for every SO_4 group. If this is correct -- if the basic sulfate emission factors do include this weight -- then, for the purpose of comparing the PART5 "suflate" emission factors with the "sulfate" emissions data presented here, we should multiply emissions of SO_4 (which is what we present) by the ratio of the weight of the sulfuric acid droplet to the weight of SO_4, 2.33.

It is not clear whether the basic sulfate emission factors are for SO_4, or sulfuric acid droplets H_2O:H_2SO_4 [7:1, v/v]. The 4th edition of AP-42, which is the source of the PART5 factors, does not speak to the matter. We note, though, that all of the PM data we have seen report the weight of S or SO_4, not the weight of droplets of sulfuric acid.

emission factors do not fully reflect emissions from old or malfunctioning vehicles, or from vehicles driven in ways not represented in the emission test cycles. Old vehicles, malfunctioning vehicles, and vehicles driven "off cycle" (e.g., with very hard accelerations) generally burn fuel less completely, on account of lower combustion temperatures, less oxygen, or poisoned catalysts, and as a result emit more organic PM. However, it is not immediately clear how lower temperatures and oxygen levels, or poisoned catalysts, would affect emissions of particulate sulfate. Essentially all particulate sulfate comes from the fuel sulfur, which is a fixed quantity that is apportioned at the tailpipe between H_2SO_4, SO_2, H_2S, and other sulfur compounds. A decrease in the amount of oxygen available, or a reduction in the efficiency of the catalytic converter, might reduce the formation of the more oxidized species, such as H_2SO_4, and increase emissions of H_2S. If so, then on account of this effect, the "in-use" fleet of LDGVs, driven in the real world, would emit less sulfate then PART5 predicts.

The foregoing data analysis suggests to us that PART5 might overestimate direct sulfate emissions from LDGVs, especially LDGVs of model year 1981 and later. More clearly, the data indicate that the ratio of sulfate PM to total PM in PART5 is much too high. To resolve this, we need measurements of H_2S, H_2SO_4, and other sulfur emissions from a wide range of vehicle types, vintages, and ages, driven under a wide range of conditions.

Emissions of nitrate, salt, and metal PM.

As indicated in equation M2, PART5 estimates emissions of lead, sulfate, and organic PM. It apparently does not include emissions of direct nitrate or salts, such as chloride. In their tests of 23 in-use LDGVs, Sagabiel et al. (1996) (see the discussion above) measured an average nitrate emission rate of 0.04 mg/mi, and an average chloride emission rate of 0.10 mg/mi. Although these rates obviously are quite small, they are together comparable to the sulfate emissions measured by Sagabiel et al. (1996). More significantly, Watson et al. (1994c) measured the composition of $PM_{2.5}$ from approximately 600 LDGVs and 80 HDDVs tested in 1989-1990 at an I&M facility in Phoenix, Arizona, and found the following contributions to the $PM_{2.5}$ mass:

	LDGVs	HDDVs
carbon	43.6%	73.0%
NO_3^-	3.9%	0.3%
SO_4^{2-}	2.3%	2.4%
NH_4^+	1.7%	0.9%
silicon	1.6%	0.5%
sulfur	1.0%	1.2%
other metals	~3-4%	~1-2%
hydrogen, oxygen, nitrogen..	remainder (not measured)	remainder (not measured)

These results show clearly that LDGV emissions of nitrate, ammonium, and metal[6] PM, which PART5 does not count, are together several times larger than emissions of sulfate PM, which PART5 does count. This omission might cause PART5 to significantly underestimate total PM emissions from LDGVs[7].

Organic PM and total PM from gasoline vehicles.

The PART5 emission factor. As mentioned above, organic PM emissions from gasoline vehicles are presented in a table of g/mi emission rates organized by vehicle class (LDGVs, LDGT I, LDGT II, and HDGV), model year, and type of fuel and emission control equipment (leaded gasoline, unleaded gasoline and no catalyst, unleaded gasoline and catalyst without air, and unleaded gasoline and catalyst with air). We may ignore the emission factors for vehicles using leaded gasoline, vehicles without a catalytic converter, and heavy-duty gasoline vehicles, because PM emissions from these sources are minor (EPA, 1998b). We thus focus on the emission factors for light-duty vehicles and trucks equipped with a catalytic converter.

PART5 assumes that all light-duty, catalyst-equipped cars and trucks of model year 1981 and later emit 4.3 mg/mi organic PM (EPA, 1995c). This emission factor is invariant with respect to user-specifiable inputs for the drive cycle (cruising or transient), vehicle speed, altitude (high or low), and inspection & maintenance (I&M) (in force or not) (EPA, 1995c). It is not a function of the age of the vehicle. For any scenario for the year 1990 or later, for any region of the country, light-duty gasoline vehicles and trucks will emit nearly or exactly 4.3 g/mi organic PM.

According to the EPA's (1995c) *User's Guide,* the organic-PM emission factors for gasoline vehicles were determined on the basis of the factors in AP-42, volume 2 (EPA, 1985) and the "updated information" in the EPA's (1993a) *Motor-Vehicle Related Air Toxics Study.* Comparing the factors in PART5 with the data and factors in the other EPA (1985, 1993b) reports, it appears that the PART5 factors for vehicles using leaded gasoline and vehicles without catalytic converters come from AP-42, volume 2 (EPA, 1985), and that factors for vehicles with catalytic converters come from the *Motor-Vehicle Toxics* study (EPA, 1993a). Appendix H of the latter study (EPA, 1993a) summarizes the results of nine studies of PM emissions from light-duty gasoline cars and trucks. Three of these studies were published after the 4th edition of AP-24 (EPA, 1985) and present

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[6]Cadle et al. (1997b) and Pierson and Brachaczek (1983) also report emissions of metals.

[7]Recall that for HDDVs, the basic emission factor in PART5 is for total PM. Thus, as long as the tests upon which the PART5 factor is based did indeed measure all PM, there is no problem of omission. However, PART5 also apportions the total exhaust PM into two components: direct sulfate PM and organic PM. For this apportioning, PART5 assumes that total PM = sulfate PM + organic PM. The results of Watson et al. (1994c) indicate that it would be better to apportion the total to sulfate PM, organic PM, and "other," which would be some 4% of the total.

emissions data for cars of model year 1981 and later. The average emission rate in all three studies was 5 to 10 mg/mi, depending on how one does the averaging, and whether the highest emitting vehicle is included. However, in the study that the EPA (1993a) gives the most weight to, the average emission rate was 2 mg/mi. Given that studies in the EPA (1993a) apparently report total PM, it is not clear how the how the PART5 organic-PM emission factors were derived from them. Presumably, all of the measurements in the three studies were taken over the Federal Test Procedure (FTP).

Now, given this, how might the PART5 emission factor for organic PM (and total PM) be in error? In general, there are three ways: 1) the vehicles tested in the three studies from which the PART5 emission factor apparently was derived might not be representative of the in-use vehicle fleet, in regards to characteristics that affect g/mi emissions; 2) driving in the real world might differ from the driving in the FTP, in ways that affect g/mi emissions of PM; and 3) future vehicles might have emissions different from those of the tested vehicle of the PART5 database.

We believe that there are more high-emitting vehicles in the real world than were tested in the PM emission tests, and that there is more high-emitting driving in the real world than in the FTP, but that PM emission rate for new vehicles generally has been declining, and will continue to decline, with model year.

Were the vehicles tested representative of the in-use fleet, with regards to characteristics that affect g/mi emissions? We believe that the most serious problem with the PART5 emission factor is that it is based on emissions from properly functioning, well-maintained, and in most cases new vehicles. In the real world there are malfunctioning, poorly maintained, old vehicles, and although there are only a small number of them, they emit so much more than do properly functioning new vehicles that they can raise the fleet-average emission rate appreciably. There is by now considerable evidence that a small number of vehicles emit large amounts of PM, and cause the in-use fleet-average PM emission rate to exceed that assumed in PART5.

Recently, the Desert Research Institute (Sagebiel et al. 1996) measured exhaust emissions from 23 high-mileage, in-use light-duty gasoline vehicles (model years 1976-1990), over the IM240 emissions test, and found that PM exhaust emissions: A) varied by over two orders of magnitude, and B) generally were much higher than predicted by PART5 (Table 1). These results are important because they pertain to high-mileage in-use vehicles, pulled off of the road and tested without modification. Six of the vehicles smoked visibly, and emitted about ten times more PM than did vehicles that didn't smoke. Even the non-smoking vehicles, however, emitted considerably more PM than predicted by PART5 (50 mg/mi in the tests versus 20 mg/mi predicted by PART5 -- see Table 1).

Several other studies report similar results for light-duty gasoline vehicles. Hanson and Rosen (1990) measured aerosol black carbon in the exhaust of gasoline vehicles driving up a hill in Berkeley in 1985, and found that emissions varied by more than two orders of magnitude, and that 20% of the vehicles -- the "high emitters" -- accounted for 65% of the emissions. Miguel et al. (1998) measured emissions of particulate PAH and solid carbon (carbon black) from vehicles in the Caldecott Tunnel

in the San Francisco Bay Area in 1996, and estimated an average emission rate of 17 mg/mi for LDGVs -- much higher than the PART5 predictions about 4 mg/mi, for all organic PM, in 1996. (See also Table 3).

In a study of smoking light-duty vehicles in Los Angeles, researchers found that the PM mass emission rate ranged from 29 to 1,651 mg/mi, with many emission rates one to two orders of magnitude above the EMFAC-prediction of 10 mg/mi (Cadle et al., 1997a). Similarly, a fleet of 103 in-use, high-emitting light-duty vehicles in Orange County, California, tested in 1995 on a transportable dynamometer, emitted an average of 138 mg/mi (Cadle et al., 1997b) -- about an order of magnitude higher than the PART5 prediction for total PM. The average emission rate for smoking vehicles was 395 mg/mi. The vehicles averaged 12.3 years old, and had an average of 126,000 miles. Another recent study in the South Coast Air Basin found that 1.1 to 1.8% of the light-duty vehicles emitted visible smoke, in the range of 64 to 2,3223 mg/mi, with an average of 399 mg/mi, over the FTP (Durbin et al., 1999). Cadle et al. (1997b) conclude that "it is clear that the current in-use, high-mileage, older vehicles can have significantly higher PM-10 emission rates than new vehicles, and higher than the rates used in the EPA...model" (p. 3408).

Cadle et al. (1998b) measured PM_{10} emissions from a sample of in-use light duty gasoline and diesel vehicles tested over the FTP in the Denver, Colorado area. New light-duty gasoline cars and trucks (MY 1991-1996) emitted only 2.8 mg/mi PM_{10} in the summer, but 24.9 mg/mi in the winter. Older gasoline LDVs emitted considerably more; for example, MY 1981-1985 vehicles emitted about 48 mg/mi in all seasons. Smoking vehicles emitted 330 mg/mi. Most of the PM emissions were attributed to the cold-start phase of the driving cycle. With a series of assumptions that they acknowledge "could result in a low estimate of real-world PM emissions" (p. 136), the authors estimate a fleet-average year-round emission rate of about 36 mg/mi, including emissions from smoking gasoline vehicles and a few light-duty diesel vehicles. (The most critical assumption is that smoking gasoline vehicles contribute only 0.1%.) By contrast, PART5, specified for the year 1996, an altitude of 5500 feet, I&M, and reformulated gasoline, estimates that light-duty gasoline cars and trucks emit a VMT-weighted average of 16 mg/mi, and that the entire light-duty fleet, including light-duty diesels, emits 17 mg/mi. Thus, PART5 underestimates a "conservative" estimate of in-use total PM_{10} emissions from LDVs in Denver by at least a factor of two. If smoking gasoline vehicles contribute more than 0.1% of VMT, then the underestimation by PART5 is considerably worse.

The findings of Mulawa et al. (1997) are similar to those of Cadle et al. (1998b). Mulawa et al. (1997) tested 10 in-use LDGVs, model years 1977 to 1994, and found that PM emissions increased with decreasing temperature, and that virtually all of PM emissions in the FTP occurred during the cold-start phase of the test, due, they assume, to enrichment. Recent model-year vehicles (1987, 1989, and 1994) with low mileage emitted averaged 2.5 mg/mi at 75^{o} F, but 11.7 mg/mi at 20^{o} F. Earlier model-year vehicles with higher mileage generally emitted more PM.

Williams et al. (1989a, 1989b) measured PM emissions from "in-use" gasoline and diesel vehicles in Australia. The light-duty gasoline and diesel vehicles were tested over an urban cycle equivalent to the U. S. FTP. (The tests on HDDVs are discussed below.) Most of the vehicles were model years from the late 1970s to the mid 1980s. PM emissions from LDGVs ranged from 50 to 290 mg/mi (average 113 mg/mi), and PM emissions from LDDVs ranged from 290 mg/mi to 1,400 mg/mi (average of 595 mg/mi). PM emissions from LDGVs were correlated with NMHC emissions, and PM emissions from diesel vehicles were correlated with NMHC and CO emissions. Emissions were higher in the cold-start portion of the drive cycle.

Do vehicles emit more PM in real-world driving than in the FTP? As by now is well known, the official emissions test cycle, the FTP, has three shortcomings: it does not include accelerations hard enough to induce "command enrichment," it underestimates the number of cold starts, and it generally is performed with the air conditioning off.

During a hard acceleration, the air/fuel ratio is reduced, to increase the charge density and hence power output. With less oxygen available, less of the fuel is completely oxidized to H_2O and CO_2, and more is only partially oxidized or not oxidized at all, and emitted as HC, CO, and organic particulate. Similarly, during a cold start, the air/fuel ratio is reduced, and the catalyst is cold and relatively inefficient at oxidizing HC, CO, and organic particulates. And the use of air conditioning places an additional burden on the engine that can increase the likelihood of command enrichment.

Recent evidence supports the proposition that PM emissions are higher during hard accelerations and cold start than over the entire FTP. The tests by Mulawa et al. (1997) and Cadle et al. (1998b), cited above, found that PM emissions increased with decreasing temperature, and that virtually all of PM emissions in the FTP occurred during the cold-start phase of the test.

The correlation between HC and PM emission (Mulawa et al, 1997; Sagabiel et al., 1996; EPA, 1993a; Williams, 1989a, 1989b), and the evidence that HC emissions increase under enrichment, suggest that PM emissions increase under enrichment. In direct support of this, Fanick et al. (1996) found that a 1994 Ford Taurus using reformulated gasoline emitted almost 4 times more PM under fuel-rich driving conditions (such as occur during hard accelerations) than under FTP/stoichiometric conditions. Mulawa et al. (1997) conclude that "rich-operating, high-emitters can be expected to have high PM emissions" (p. 1302).

Will PM emissions change in the future? As noted above, PART5 assumes that all catalyst-equipped LDGVs of model-year 1981 and later, and all catalyst-equipped LDGTs of model-year 1987 and later, emit 4.3 mg/mi organic PM, everywhere, all the time. However, the studies cited above indicate clearly that relatively new, properly functioning LDGVs of about model year 1990 and later, tested over the FTP at low altitude and warm temperatures, emit on the order of 2-3 mg/mi *total* PM, and hence slightly less organic PM (Cadle et al., 1998b; Mulawa et al., 1997; EPA, 1993c). Furthermore, if PM emissions remain correlated with HC emissions, then future

decreases in HC emissions can be expected to be result in decreases in [organic] PM emissions.

At a minimum, PART5 should have more model-year categories, perhaps corresponding to years in which the HC standards change, with progressively lower "base" organic PM emission rates. As discussed below, it would be best if this were done as part of an overhaul of PART5 to make it function more like MOBILE6.

Light-duty gasoline vehicle summary.

The foregoing analysis indicates the following problems with PART5, and possible solutions:

- PART5 may overestimate sulfate emissions, and probably overestimates the ratio of sulfate to total PM -- especially for more recent vehicle model years. *PART5 should estimate sulfate emissions as a function of the sulfur content of the fuel and the age and model-year of the vehicle.*
- PART5 does not include emissions of nitrate or metal PM. *These should be added.*
- The PART5 emission factors for organic and total PM do not account for high-emitting vehicles, or high-emitting driving or conditions. On the other hand, they do no account for reductions in PM emissions related incidentally to reductions in HC emission standards. *PART5 should estimate organic (or total) PM emissions as a function of the age and model year of the vehicle (accounting for changes in the HC standard), the ambient temperature, the drive cycle (accounting for "off-FTP" driving), and the probability of malfunctions or poor maintenance that lead to unusually high emissions.*

We believe that the most significant problem with PART5 is its failure to account for high-emitting vehicles and driving conditions, and that as a result of this, PART5 underestimates real-world, in-use emissions. Cadle et al. (1998b) agree:

> ..the failure [of PART5] to include high emitters will result in a significant underestimation of the light-duty fleet average PM-10 emission rate (p. 3).

If we assume that some of the fleet are old or malfunctioning vehicles ("super-emitters"), then the total levels of emissions are much higher than those predicted by PART5. About 10% of the fleet are super-emitters (the results from Sagebiel et al. suggest that the fraction of super-emitters could be higher)[8], and super-emitters emit roughly five to ten times more than normal vehicles. If we start with the assumption that the "normal" vehicles emit about 15 mg/mi g/mi, as assumed by PART5 for 1990 calendar years, we end up with LDGV fleet emissions being 1.4 to 1.9 times higher than predicted by PART5.

[8] Regarding CO emissions, Ross et al. (1995) classify vehicles in two groups: 90% of the vehicles emit CO at about the normal FTP-measured rate, and 10% emit at a much higher rate.

PM emissions from heavy-duty diesel vehicles.

The PART5 emission factors. As explained above (equation M3), PART5 contains a table of total PM emission factors, in g/bhp-hr, for HDDV vehicles. These factors, and the corresponding PM emission standards (Davis, 1998) for four classes of HDDVs are as follows (g/bhp-hr):

	2B heavy	light-heavy	medium-heavy	heavy-heavy	PM standard
pre-1987	0.52	0.52	0.69	0.64	none
1988-1990	0.51	0.51	0.48	0.44	0.60
1991-1993	0.29	0.29	0.27	0.27	0.25
1994 +	0.10	0.10	0.09	0.08	0.10

Note that the emission rates for the years 1988 on follow the emission standards: the three model-year categories in PART5 are the same as the model-year groups for the emission standards, and the PART5 emission rates are close to the corresponding PM standards. Apparently, the PART5 emission factors for the years 1988 on are estimated on the basis of the engine-certification tests submitted by manufacturers to demonstrate compliance with the standards (EPA, 1993c). The use of the certification data implies an assumption that heavy-duty diesel engines maintained and driven in the real world will, over their entire lives, have the same emissions as new engines tested for compliance over the heavy-duty transient cycle (HDTC) (Walsh, 1995). Needless to say, we will want to examine this assumption.

The emission rates for pre-1987 vehicles apparently are based on the few available tests of in-use engines prior to 1987 (Guensler et al., 1991). In 1983 and 1984, the EPA tested 30 in-use heavy-duty diesel engines. The engines were removed from their chassis, and tested "as is" (i.e., without being tuned up) over the HDTC for new engines, on an engine dynamometer. The results for eight of the engines were problematic, and discarded. The results[9] for the remaining 22 engines were (Guensler et al., 1991):

9 medium -heavy engines	13 heavy-heavy engines
0.62 - 0.89 g/bhp-hr	0.58 - 2.14 g/bhp-hr

After these initial tests of the 22 engines "as received", the EPA tuned up and re-tested 7 of the medium-heavy and 6 of the heavy-heavy engines. After this tune up, the engines emitted more NO_X but less HCs (Guensler et al., 1991). Because PM emissions generally change in the same direction as do HCs, and in the opposite direction from NO_X, we can presume that the PM emissions also decreased after tune-up.

[9]It is not clear if this is TSP or PM_{10}.

It is not clear which set of test results -- before tune up, or after tune up -- the EPA used to establish its baseline emission factor. Guensler et al. (1991) speculate that the official emission factors are based on the results of the tests conducted *after* the engines were tuned up. In support of this, we note that PART5 factors shown above (0.69 g/bhp-hr for medium-heavy, and 0.64 g/bhp-hr for heavy-heavy), and the emission factor used for all heavy engines in the 4th edition of AP-42 (0.70 g/bhp-hr) (EPA, 1985), are at the low end of the range of results from the tests on the engines "as received".

Problems with the PART5 PM emission factors for HDDVs. Our analysis here considers the same issues analyzed with regards to LDGVs. First, we ask whether the tests from which the PART5 factors are derived included vehicles representative of the in-use fleet. Then, we discuss the reality of the test cycle, the HDTC. Finally, we briefly discuss emissions from future vehicles.

It seems clear that the in-use vehicles emit more PM than do the new, properly tuned vehicles that are tested for engine certification. In fact, the 1983/1984 EPA tests mentioned above showed that in-use vehicles tested "as received" emitted more PM than the same vehicles tested after being tuned up. Moreover, none of the vehicles tested for engine certification, and apparently none of the vehicles tested in the 1983/1984 tests, were high emitters: even the highest level measured in the EPA tests, 2.14 g/bhp-hr, is less than one would expect from a badly smoking engine. Given that the small amount of super-emitters that one typically observes in a fleet can significantly raise fleet-average emissions, the omission of super-emitting engines from the emissions tests will result in emission factors that significantly underestimate real-world emissions.

The 22 engines tested in 1983 and 1984 had accumulated from 29,000 to 410,000 miles at the time of testing (Guensler et al., 1991). It is not clear, however, if the mileage distribution was representative of the fleet average at the time, or if the EPA accounted for the effect of mileage in establishing its baseline emission factors (Guensler et al., 1991). In fact, in general, it is not clear if the vehicles selected were broadly representative of the in-use fleet.

Chassis dynamometer tests. Chassis dynamometer tests of heavy-duty vehicles also suggest that base emission factors in PART5 pertain to relatively new, properly functioning vehicles. The EPA has measured PM exhaust emissions from in-use heavy-duty diesel vehicles (HDDVs) and heavy-duty gasoline vehicles (HDGVs), driven over the transient test cycle on a chassis dynamometer (Black et al., 1984; Dietzmann et al., 1980). The test results, and the corresponding predictions from PART5, are shown in Table 2, part A. One perhaps can infer that PM emissions from the in-use HDDVs vehicles increase with increasing mileage, although so few vehicles were tested that inferences might not be reliable. At only 60,000 miles -- well below the midpoint of the life of an HDDV -- emissions already were at or above the level predicted by PART5. This suggests to us that a fleet of HDDVs, which on average has more than 100,000 miles of travel per vehicle, emits more exhaust PM than is predicted by PART5. Of the five HDGVs tested, four emitted close to the amount predicted by PART5, but three of

these had new or nearly new engines. The fifth HDGV emitted several times more PM than predicted by PART5. Thus, we expect, again, that a real in-use HDV fleet, with a substantial proportion of high-mileage vehicles (in the case of HDDVs, over 400,000 or 500,000 miles), and a few high-emitting vehicles, will emit considerably more PM than is predicted by PART5.

Williams et al. (1989b) tested 12 HDDVs, model years 1974-1985, over a multi-model steady-state drive cycle on chassis dynamometer, in Australia. PM emissions ranged from 1.3 g/mi to 11.5 g/mi, with an average of 3.4 mg/mi, or 2.6 g/mi without the highest emitter. PM emissions were correlated with NMHC and CO emissions. Because the HDDVs tested were not built for the U. S. market, and were not tested over the HDTC (although the Williams et al. [1989b] found that the vehicles had similar emission rates over a transient cycle), it probably is not sensible to compare the measured emissions with the predictions of PART5. Still, two conclusions can be drawn: first, the fleet-average emissions are quite high, and second, the single "super emitting" vehicle (11.5 g/mi) significantly raised the fleet average emission rate, from 2.6 g/mi to 3.4 g/mi.

Most recently, West Virginia University (WVU) has been testing heavy-duty diesel and alternative-fuel vehicles on a portable chassis dynamometer. The vehicles are tested on-site, over a variety of test cycles, including the Truck Central Business District Cycle, a 5-mile truck route, and WVUs own truck cycle. All of the vehicles are in the heavy-heavy class (the average gross vehicle weight is over 60,000 lbs). There is a relatively wide range of makes and ages. Results from 1993 and early tests are published in Wang et al. (1993); results from later tests are available on the web (see Table 2, part B). Nearly 100 PM emission results are available.

Table 2, part B, summarizes the results of the WVU tests, and compares the in-use emissions with the pertinent PART5 emission factor. We see that PART5 slightly overestimates emissions for model years 1988-1990, slightly underestimates emissions for model years 1991-1993, and significantly underestimates emissions from model years 1994 and later. Assuming that WVU did not test any super-emitters -- the highest emission rate in all the tests was only 2.74 g/mi, well below what a badly smoking vehicle emits -- we can infer that PART5 significantly underestimates in-use emissions from a fleet with small percentage of high-emitting vehicles.

Measurements of on-road emissions. We have found four studies of on-road emissions from HDDVs. In 1983, Pierson and Brachaczek measured the ambient airborne PM at the exit of the Allegheny and Tuscarora Mountain Tunnels on the Pennsylvania Turnpike, and with these and other data, back-calculated the HDDV emission rate[10]. More recently, Whittorf et al. (1994) and Gertler et al. (1995) reported the results of a similar experiment at the Fort McHenry Tunnel in Baltimore, Maryland.

[10]Pierson and Brachaczek (1983) summarize the method: "Known traffic and air fluxes are combined with net (tunnel minus intake) tunnel-air pollutant concentrations to derive mg/km emission rates of the various species observed. Correlation against the changing traffic composition gives emission-rate estimates resolved as to vehicle type" (p. 2).

Balogh et al. (1993) measured the PM concentration along a university road that had heavy bus traffic, and back-calculated the bus emission rate. Finally, Miguel et al. (1998) measured emissions of particulate PAH and solid carbon (carbon black) from gasoline and diesel vehicles in the Caldecott Tunnel in the San Francisco Bay Area in 1996

In Table 3, we compare the results of these studies with the estimates of the PART5 model specified for the same conditions. In all cases except two (gasoline vehicles in Pierson and Br., and diesel vehicles in Whittorf et al.) PART5 underestimates the "adjusted" on-road PM exhaust emission rate. (Details of the adjustments are given in the notes to Table 3.) Now, because the majority of emissions from super-emitters occur during transient driving, not during the high-speed cruising of the on-road tests, our adjustments of the reported on-road cruising emissions to levels that would have occurred in an on-road transient test do *not* include any "excess" emissions from super-emitting vehicles in the transient cycle. We believe that in the real world, with high-emitting vehicles in transient driving, the fleet average emission rate is even higher than indicated by the "adjusted" results of Table 3.

The ratio of exhaust PM to road-dust PM in the emissions inventory versus the same ratio measured at ambient air-quality monitors. As discussed in Delucchi and McCubbin (1996), the ratio of emissions of road dust to exhaust emissions from highway vehicles, in the EPA's (1995d) emissions inventory, is many times higher than the ratio of dust to motor-vehicle exhaust at ambient air-quality monitors. If the ambient ratios are accurate, and if the differences between the ambient ratios and the emissions ratios cannot be explained entirely by differences in emissions dispersion (which, it seems, they cannot), then the AP-42-based estimates of road-dust emissions are too high, or the PART5-based estimates of highway-vehicle PM emissions are too low, or, most likely, both.

PART5 versus EMFAC7F. One basis, albeit still a weak one, for quantifying the degree to which PART5 underestimates exhaust emissions from HDDVs is a comparison of the PM emission factors from PART5 with the PM emission factors from California's emission-factor model, EMFAC 7F. We ran PART5 and EMFAC7F for the year 1990, and found that the EMFAC7F estimates of exhaust PM from HDDVs are about 1.8 times as high as the PART5 estimates (Delucchi and McCubbin, 1996). Although the EMFAC7F tirewear estimates are at least an order of magnitude higher than the PART5 estimates, this does not qualitatively affect the results since tirewear is a small fraction of emissions.

Why are CARB's EMFAC7F estimates higher than the EPA's PART5 estimates? According to Guensler et al. (1991), CARB had used the EPA's estimates until 1988, when CARB modified the EPA emissions factors to reflect inspection and maintenance practices in California. CARB developed its new estimates for EMFAC7F on the basis of a report by Radian Corporation, which reviewed the original data used to establish the EPA (PART5) factors, plus additional information. The Radian report apparently estimated a factor to adjust the EPA's estimates upwards to account for high emissions from poorly maintained vehicles (Guensler et al, 1991). This adjustment factor might

partially explain why the EMFAC7F estimates are so much higher than the PART5 estimates.

The drive cycle. Guensler et al. (1991) note that the trucks in the real world may idle more than is assumed in the HDTC, and that the emissions inventory apparently does not account for emissions from truck engines being run to provide auxiliary power for refrigeration and other purposes. If this is so, then the PART5 emission factors, which are based on HDTC tests, underestimate real-world emissions.

On the other hand, the EPA (1993a) cites a 1988 study by the University of Michigan that found that class VIIIB (heavy-heavy) trucks accumulated 73% of their mileage on freeways when in large urban areas -- much more than the 25% assumed in the HDTC. To the extent that PM emissions arise more from transients than from steady-state operation, and that freeway driving involves less transients, the underestimation of freeway driving will overestimate real-world emissions. However, it is not clear to what extent the freeway driving estimated by the University of Michigan is steady state. In many large urban areas, freeways are congested for many hours a day, and cause trucks to spend a lot of time idling and stopping and starting. These are conditions that increase g/bhp-hr emissions. Hence, it is not immediately clear to what extent, if any, the possible underestimation of freeway driving results in an overestimate of PM emissions.

Heavy-duty diesel vehicle summary

In summary, the HDDV PM emission factors in PART5 probably underestimate real-world emissions, most likely because the test database from which the PART5 factors were derived does not include a representative number of old, malfunctioning, poorly tuned, or inherently high emitting vehicles. In addition, the HDTC might not be representative of real driving conditions in the country; for example, there might be a lot more idling and hard accelerating in the real world than is present in the HDTC.

Our conclusion

The data reviewed above suggest that PART5 underestimates emissions from real on-road vehicles, primarily because PART5 seems to be based on low-mileage, properly functioning vehicle, and takes little, if any, account of super-emitters. Real-world emissions might be as much as a factor of 2 higher than estimated by PART5. The PART5 PM emission factors should be constructed like the MOBILE emission factors for HC, CO, and NO_X: as a function of the age and model year of the vehicle, the ambient temperature, the drive cycle (accounting for "off-cycle" driving), and the probability of malfunctions or poor maintenance that lead to unusually high emissions.

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ABBREVIATIONS

Vehicles

LDGV = light-duty gasoline vehicle (passenger vehicles, including station wagons and motorcycles)

LDGT = light-duty gasoline truck (light-duty gasoline trucks (trucks, vans, minivans, jeeps, and utility vehicles, that have a gross vehicle weight rating of 8,500 lbs or less and a curb weight of 6,000 lbs or less)

LDGT1 = LDGT with a weight rating of 6,000 lbs or less

LDGT2 = LDGT with a weight rating of 6,001 to 8,500 lbs

HDGT = heavy-duty gasoline truck (all other gasoline trucks, and buses)

LDDV = light-duty diesel vehicle (passenger vehicles, including station wagons)

LDDT = light-duty diesel truck (trucks, vans, minivans, jeeps, and utility vehicles, that have a gross vehicle weight rating of 8,500 lbs or less and a curb weight of 6,000 lbs or less)

HDDT = heavy-duty diesel truck (all other diesel trucks, and buses)

HDDV = heavy-duty diesel vehicle

LDV = light-duty vehicle (LDGV + LDDV)

HDV = heavy-duty vehicle (HDGV + HDDV)

VMT = vehicle miles traveled

Pollutants

CO = carbon monoxide

HC = hydrocarbons

NO_2 = nitrogen dioxide

NO_X = nitrogen oxides (including but not limited to NO_2)

NH_3 = ammonia

O_3 = ozone

PM = particulate matter

PM_{10} = particulate matter with a diameter of 10 microns or less

$PM_{2.5}$ = particulate matter with a diameter of 2.5 microns or less

Coarse PM_{10} = particulate matter with a diameter between 2.5 and 10 microns

SO_2 = sulfur dioxide

SO_X = sulfur oxides

SOA = secondary organic aerosols

TSP = total suspended particulates

VOCs = volatile organic compounds

Emissions tests

HDTC = Heavy-Duty Transient Cycle

FTP = Federal Test Procedure

TABLE 1. PM AND OTHER EXHAUST EMISSIONS FROM HIGH-MILEAGE, IN-USE LIGHT-DUTY GASOLINE VEHICLES COMPARED TO PART5 MODEL EMISSIONS

		Exhaust emissions (g/mi)			
	Miles	*PM_{10}*	*HC*	*CO*	*NO_x*
Average of all 23 vehicles[a]	105,691	0.18	3.52	45.03	1.72
Average of 6 smoking vehicles[a]	119,925	0.56	6.18	63.47	1.57
Average of 17 non-smoking vehicles[a]	100,667	0.05	2.59	38.52	1.78
PART5 Model[b]	n.a.	0.020	n.a.	n.a.	n.a.

n.a. = not applicable.

[a]From IM240 test results reported by Sagebiel et al. (1996).

[b]Sagebiel et al. (1996) tested 1976 to 1990 model-year vehicles, over the IM240 cycle, in Nevada. To replicate these conditions in PART5, we specified a 1989 fleet, a transient driving cycle, an average speed of 19.6 mph, low altitude, no inspection and maintenance, no reformulated gasoline, and a size-cutoff of PM_{10}. (Note that, because the drive cycle and average speed make no difference in the PART5 estimates, it is immaterial whether our cycle and speed assumptions match those of the IM240 test cycle used by Sagebiel et al. [1996].)

Seven of the 23 vehicles were light-duty gasoline trucks (LDGT1) and the rest were light-duty gasoline vehicles (LDGV), so we estimated emissions for both vehicle types and calculated a weighted average. We found 0.018 g/mi for LDGVs and 0.026 g/mi for LDGT1s, which gives a weighted average of 0.02 g/mi. We report exhaust emissions only, and exclude tirewear, brakewear and indirect sulfates.

TABLE 2. PM EXHAUST EMISSIONS FROM IN-USE HEAVY-DUTY VEHICLES TESTED OVER ON A CHASSIS DYNAMOMETER

A. TESTS OF PRE-1980 VEHICLES OVER THE HDTC

Vehicle	**Mileage**	**PM exhaust emissions** (g/mi)
Diesel[a]		
1979 Caterpillar 3208	7,000	1.0
1979 Mack ENDT 676	69,000	1.9
1979 Cummins Formula 290	26,000	1.6
1977 Detroit Diesel 8V-71	60,000	2.7
PART5 prediction[b]	*Calendar years 1979-1984*	*2.1*
Gasoline[c]		
1973 International Harvester Stake-Bed	105,000	0.3
1975 General Motors Stake-Bed	35,000	0.5
1980 General Motors Ryder Van	<10,000	0.3
1979 Ford Van	<10,000	2.1
1979 Ford Stake Bed (same engine as above)	<10,000	0.5
PART5 prediction[b]	*Calendar years 1979-1984*	*0.3 - 0.4*

[a]From Dietzmann et al. (1980).

[b]We run the PART5 model for two years: 1979 and 1984. The assumptions used in the model for both years are: transient cycle, speed of 19.6 mph, low altitude, no inspection and maintenance, no reformulated gasoline, and PM_{30}. We report exhaust emissions only, and exclude tirewear, brakewear and indirect sulfates. For HDGVs, we got 0.33 g/mi for 1984 and 0.44 for 1979 (which we rounded to 0.3 to 0.4); for HDDV we got 2.1 g/mi for both years.

[c]From Black et al. (1984). For each vehicle, Black et al. measured emissions at two test weights (about half of gross-vehicle weight, and about 3/4 of gross vehicle weight), and over two test cycles, the Heavy-Duty Transient Cycle (HDTC) and the Durham Road Route (DRR). We have reported the results for the heavier of the two vehicle weights, because it seemed more realistic, and for the HDTC, which was the official EPA test cycle. The DRR always produced lower PM emissions than did the HDTC , and in most cases the lighter configuration produced lower PM emissions than did the heavier configuration.

We have excluded results for a 1976 Ford with a gross vehicle weight of only 9,000 lbs.

TABLE 2. PM EXHAUST EMISSIONS FROM IN-USE HEAVY-DUTY VEHICLES TESTED OVER ON A CHASSIS DYNAMOMETER

B. PM EMISSIONS FROM 1980S AND 1990S IN-USE HEAVY-HEAVY DIESEL VEHICLES, TESTED ON THE WEST VIRGINIA UNIVERSITY PORTABLE CHASSIS DYNAMOMETER

Model year	Average in-use emissions (g/mi)[a]	PART5 emission factor (g/mi)[b]	Emission standard (g/mi)[c]	Ratio: in-use /PART5[d]
1987 and back	n.e.	2.05	none	n.e.
1988-1990	0.99	1.36	1.86	0.73
1991-1993	1.02	0.84	0.78	1.21
1994 +	0.50	0.25	0.31	2.02

[a]The average of all the tests of vehicles of a particular model-year class. Data from tests through 1993 are published in Wang et al. (1993); data from tests from 1994 on are available on the web at: www.ott.doe.gov/ohvt/heavy_vehicle/hv/emishdv.html. There were 23 data points from model years 1988-1990, 26 from 1991-1993, and 33 from 1994+ We used test data for trucks; there also are emissions data for buses, available from the same web site.

[b]The PART5 emission standard for heavy-heavy diesel vehicles, in g/bhp-hr (EPA, 1995c) multiplied by PART5 bhp-hr/mi conversion factor. Browning (1998a) reports that MOBILE5 uses a conversion factor of 2.99 for HDDVs with a gross vehicle weight (GVW) of 33,001 - 60,000 lbs, and a factor of 3.13 for HDDVs with a GVW of over 60,000 lbs, for the years 1987 to 1996. However, in PART5, the "heavy-heavy" class is all vehicles over 33,000 lbs (EPA, 1995c). The vehicles tested on the WVU portable chassis dynamometer had an average GVW of over 60,000 lbs. We assume a conversion factor of 3.1 for the years 1987-1996, and 3.2 for earlier years.

[c]The g/bhp-hr PM standards for heavy-duty diesel vehicles (Davis, 1998), multiplied by the assumed conversion factor of 3.1 bhp-hr/mi.

[d]The average emissions from the in-use vehicles divided by the PART5 emission factor.

TABLE 3. COMPARISON OF MOTOR VEHICLE PM EXHAUST EMISSIONS BACK-CALCULATED FROM FIELD STUDIES AND EMISSIONS CALCULATED BY THE PART5 MODEL (GRAMS/MILE)

	Pierson & Br. (1983)		Balogh et al. (1993)		Whittorf et al. (1994)		Miguel et al. (1998)	
PM size measured	*PM_{10}*		*$PM_{2.5}$*		*PM_{10}*		*$PM_{1.3}$*	
Gasoline vehicles[a]								
Study results (all PM)[b]	0.064		0.032		0.015		0.017	
Adjusted results (exhaust)[c]	0.100		0.044		0.023		0.060	
PART5 model (exhaust)[d]	0.133		0.016		0.016		0.012	
Diesel heavy vehicles[a]								
Study results (all PM)[b]	1.40		1.29		0.67		1.8	
Adjusted results (exhaust)[c]	2.18		2.01		1.04		4.1	
PART5 model (exhaust)[d]	2.07		1.63		1.47		1.14	
Gasoline and diesel fleet[e]	*20% diesel*	*7% diesel*	*6% buses*	*3% buses*	*30% diesel*	*7% diesel*	n.e.	n.e.
Study results (all PM)[f]	0.33	0.16	0.11	0.07	0.21	0.06	n.e.	n.e.
Adjusted results (exhaust)[c]	0.51	0.25	0.17	0.11	0.33	0.09	n.e.	n.e.
PART5 model (exhaust)[g]	0.52	0.27	0.12	0.07	0.45	0.12	n.e.	n.e.

[a]See the discussion of vehicle types in the notes to Table 16-5 of Delucchi and McCubbin (1996).

[b]Except in the case of Miguel et al. (1998), the values shown are the original authors' apportionment of *total* roadway PM emissions, including road dust and tirewear PM, to the two different vehicle classes. Generally, they did this by relating the variation in the measured PM level to the variation in the composition of the traffic. Miguel et al. (1998) measured only combustion particles, PAHs and black carbon.

In all of the studies, the measured PM apparently excludes indirect or secondary PM, such as ammonium sulfate. Pierson and Brachaczek (1983: 1) state that they exclude "photochemical or 'secondary' material", and Whittorf et al. (1994) seemed to have followed the method of Pierson and Brachaczek (1983). We suspect that this sampling method does not allow enough time for significant amounts of secondary material to form. Miguel et al. (1998) measured only PAH and black carbon particulate from combustion.

We assume all of the studies exclude brakewear PM, because the vehicles were cruising and hence rarely if ever braking.

The results in Whittorf et al. (1994) also are reported in Gertler et al. (1995).

[c]To make the field-study measurements of emissions during cruising (see note d) comparable to the PART5 estimates of emissions from transient driving, we make the following changes to the field-study estimates: 1) In all cases, we increase the cruising emissions by 75% to make them comparable to transient emissions; 2) except in the case of Miguel et al. (1998), we reduce total emissions by 11% to remove road dust and tirewear to make them comparable to exhaust emissions (Miguel et al. did not measure road dust); and 3) in the case of Miguel et al., we increase LDGV emissions by a factor of 2, and HDDV emissions by a factor of 1.3, to account for exhuast PM other than carbon black and PAHs.

Thus, the "adjusted" study results are equal to the original study results multiplied by 1.56 (all except Miguel et al.), or, in the case of Miguel et al. (1998), by 3.5 (LDGVs) and 2.3 (HDDVs).

Adjusting cruise-cycle emissions to transient-cycle emissions. The objective here is to estimate what the vehicles in the three field studies would have emitted had they been following a transient cycle (as modeled in PART5) rather than cruising. To make this estimate, we first describe the transient test cycle upon which the PART5 estimates apparently are based, and then analyze the relationship between emissions during cruising, and emissions during transient driving.

Black et al. (1984) describe the heavy-duty transient cycle (HDTC) test. It is 1060 seconds with an average speed of 18.86 mph, and comprises the following three sub-cycles, one of which is repeated: i) NY non-freeway, 254 seconds, 7.56 mph average; ii) LA non-freeway, 285 seconds, 14.55 mph average; iii) LA freeway, 267 seconds, 44.93 mph average; iv) NY non-freeway again. A substantial amount of time -- over 300 seconds -- is spent at or near zero mph. (It thus appears that the HDTC is meant to be an "average" cycle.)

To adjust cruising emissions to transient emissions, we can compare emissions from the LA freeway portion of the HDTC with emissions from the entire HDTC. Dietzmann et al. (1980) report PM emission for the LA freeway sub-cycle and for whole HDTC, for four heavy-duty engines. PM emissions over the transient cycle were 10% to 60% (mid value of about 40%) higher than emissions over the LA freeway sub-cycle.

Black et al. (1984) report that the four heavy-duty gasoline trucks emit 3.3 times more HCs over the NY non-freeway cycle than the LA freeway cycle, 2.6 times more HCs over the LA non-freeway than the LA freeway, and 1.78 times more HCs over the whole HDTC than over the LA freeway cycle. They do not report PM emissions over the different sub-cycles of the HDTC, but they do report PM emissions for the HDTC versus another completely different drive cycle, the RDD. The relationship between PM-HDTC and PM-RDD is the same as the relationship between HCs-HDTC and HCs-RDD. This suggests that PM emissions would have behaved over the HDTC sub-cycles the same way that HC emissions did. This means that PM emissions in LA freeway would be 1.78 times less than in the whole HDTC. This 78% increase is similar to 10-60% increase found above.

However, vehicles cruising at constant high speed, as in the three field studies, should emit even less PM than vehicles following the LA freeway sub-cycle, which has a few transients itself. Overall, we believe that the Black et al. (1984) data and Dietzmann et al. (1980) data imply that PM emissions (from normal vehicles) during transient driving are 50% to 100% higher than PM emissions during cruising. For super-emitters, which presumably emit most of their "excess" emissions during transient driving, this ratio probably will be higher.

Finally, we note that Gertler et al. (1995) compared HC emissions from 5 heavy-duty diesel vehicles at steady 40 mph cruise and over a 5-peak drivecycle. Each peak had acceleration, steady cruise, deceleration, and idle. The HC emissions were 60% higher in the 5-peak cycle than at 40 mph cruise.

We infer from these studies that exhaust PM emissions over the transient cycle are 50% to 100% higher than exhaust emissions during cruising; we assume that they are 75% higher.

Road dust and tirewear adjustment. Because our purpose here is to check the accuracy of PART5's estimates of exhaust emissions, we must deduct road-dust and tirewear PM emissions from the total emissions measured in the field studies.

The Pierson and Brachaczek (1983) study allows us to calculate vehicle emissions excluding road dust (10% of total emissions) and tirewear (1% of total emissions). We assume the same percentages of road dust and tirewear apply to the Whittorf et al. (1994) and Balogh et al. (1993) studies.

[d]In order to compare the estimates of PART5 with the results of each field study, we specified the PART5 model to replicate the conditions of each study:

	Pierson & Br. (1983)	Balogh et al. (1993)	Whittorf et al. (1994)	Miguel et al. (1998)
Year	1977	1991	1993	1996
PM size class	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Drive cycle	cruise	cruise	cruise	cruise
Vehicle speed (mph)	55.0	40.0	55.0	42
I & M	no	yes	yes	yes
Reformulated gasoline	no	no	no	yes

Year: The year in which the measurements were taken.

PM size class: Whittorf et al. (1994) measured PM_{10}, Balogh et al. (1993) measured $PM_{2.5}$, and Miguel et al. (1998) measured $PM_{1.3}$. Pierson and Brachaczek (1983) measured "airborne" PM, but because about 95% of the measured PM was PM_{10}, we specified PART5 for PM_{10}.

Drive cycle: PART5 offers two choices: "cruise," and "transient". However, according to the PART5 users manual [EPA, 1995c], the choice of drive cycle affects lead emissions only. (Our runs of the model confirmed this.) But lead emissions are essentially zero after 1990, and hence the choice of drive cycle matters only as regards

Pierson and Brachaczek (1983), and Whittorf et al. (1994), measured PM along an expressway, along which vehicles obviously are "cruising." The study site of Balogh et al. (1993) was a two-lane road on a university campus, with a 2% grade. We assume that the vehicles were cruising at steady speed as they passed the monitors. (.)

Vehicle speed: Pierson and Brachaczek (1983) reported that vehicles approached the Allegheny and Tuscarora sampling sites at 55 mph, and went through the tunnel at 50 to 55 mph. We assume 55 mph. We also assume the normal expressway speed of 55 mph in the Whittorf et al. (1994) study. The vehicles at the campus study site of Balogh et al. (1993) probably were traveling at 30 to 35 mph, but up a 2% grade, which we assume is equivalent to 40 mph on flat ground. (The speeds in PART5 presumably are for level ground without a tailwind. However, such details don't matter, because the speed has almost no effect on emissions.) Miguel et al. (1998) state that vehicles in the Caldecott tunnel traveled 41-49 mph, and that "during all

sample periods,traffic inside the tunnel flowed smoothly, lacking heavy accelerations and stop-and-go driving" (p. 452).

Inspection & Maintenance, and reformulated gasoline: We have made assumptions that we believe are appropriate for the year of the study. Miguel et al. (1998) report that reformulated gasoline had been in use in California since 1996.

[e]PM emissions from traffic depends on the mix of heavy-duty diesel vehicles (HDDVs) and gasoline vehicles. In the case of Pierson and Brachaczek (1993), we consider one case with 20% HDDVs, which was the average mix in their study, and one with 7% HDDVs, which is about the national average on all roads (Table 16-5 of Delucchi and McCubbin). In the case of Balogh et al. (1993), we do not know the exact percentage of buses, and so consider two cases, one with 6%, and another with 3%. In the case of Whittorf et al. (1994), we consider one case with 30% HDDVs, which was the average in the study, and one with 7% HDDVs, which as just mentioned is about the national average on all roads.

[f]Equal to the HDDV or bus emission rate, from the original study, multiplied by the HDDV or bus fraction, plus the gasoline-vehicle emission rate from the original study multiplied by one minus the bus or HDDV fraction.

[g]Equal to the HDDV or bus emission rate, from the PART5 model, multiplied by the HDDV or bus fraction, plus the gasoline-vehicle emission rate from the PART5 model multiplied by one minus the bus or HDDV fraction.