Analysis of MOBILE6.2's PM Emission Factor Estimating Function

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ABSTRACT

Since 1995, PART5 was used to estimate exhaust, brake wear and tire wear particulate matter (PM) emission factors. The US Environmental Protection Agency (EPA) released the MOBILE6.2 (M6.2) model in February 2004. M6.2's PM module incorporates some of PART5 algorithms with MOBILE6 default data. This paper summarizes the basic differences between the models capabilities. Then, emission factor results from the models were analyzed to compare PM emission factors versus calendar year and vehicle speeds. Results showed slight differences in emissions factors. The differences might be explained by the use of different vehicle registration default data (especially in the heavier vehicle classes), different assumptions in the number of wheels per vehicle class, and M6.2's capability to model sulfur.

Understanding the PM module of M6.2 under various conditions becomes critical, as the model will now be used for both PM State Implementation Plans and transportation conformity for PM areas. For this purpose, parameters such as fuel physical properties, vehicle activities, and environmental conditions were tested. Results indicated that emission factors tend to decrease for both PM2.5 and PM10 in later calendar years, apparently due to more stringent vehicle emissions and fuel standards. It

was found that RVP, gasoline sulfur content, vehicle speeds, minimum and maximum temperature, and roadway facility types had negligible effects in PM emission factors, but PM emission factors are highly sensitive to diesel sulfur content.

INTRODUCTION

On February 24, 2004, the US Environmental Protection Agency (EPA) released its latest version of the MOBILE6.2.03 (M6.2) model. Among other updates, M6.2 integrates a new function for the calculation of highway mobile source particulate matter (PM) emissions. In addition, the EPA released its official policy guidance on the use of M6.2 for State Implementation Plans (SIPs) and Transportation Conformity.[1] In the guidance, EPA indicated that they would be publishing a Federal Register notice of availability in the near future to approve M6.2 and the November 2003 AP-42 re-entrained dust method for official purposes. Upon publication of the Federal Register notice, M6.2 will become EPA's approved motor vehicle emission factor model for estimating PM emissions from passenger cars, motorcycles, light-duty and heavy-duty trucks by state and local agencies outside of California.

Prior to M6.2, particulate matter emission factors from gasoline and diesel vehicles were calculated using PART5 (released by EPA in 1995). This paper begins with a comparison between both models. This section summarizes the basic differences between M6.2 and PART5 capabilities in terms of pollutants reported, and the differences in output results. The models used for this analysis were M6.2 (draft version released in October 31, 2002), and PART5. The comparison of the two models is followed by a sensitivity analysis that will allow the users to understand the relative impact of selected parameters on the resulting emission factors.

COMPARISON OF M6.2 AND PART5

The M6.2 particulate matter module incorporates many of PART5 algorithms, but uses the updated M6.2 default data (vehicle registration, diesel fractions, fuel economy, and mileage accumulation rates). Table 1, summarizes information from PART5 and M6.2's users manuals, showing the major differences between both models' in terms of pollutants reported.

As noted in Table 1, many of the emission factor algorithms did not change from PART5 to M6.2. There were also changes in the pollutants reported. M6.2 includes ammonia, which is one of the precursor pollutants to PM2.5. On the other hand M6.2 does not include the capability of estimating the emission factors for indirect sulfate and the re-entrained road dust as the result of motor vehicle activity. The EPA requires that indirect sulfate now be handled with air quality modeling, rather that as mobile source emissions.[2] In a similar manner, the EPA finalized in February 2004, new methods for the estimation of re-entrained road dust emissions from cars, trucks, buses, and motorcycles on paved and unpaved roads which are incorporated in the November 2003 edition of Chapter 13 of Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources.

M6.2 also refined some of PART5's algorithms. For example, PART5's did not account for different sulfur levels of gasoline and diesel fuel. PART5 does not allow the user to input values for the gasoline sulfur content, and fixes this parameter to 343.0 ppm or 138.0 ppm for calendar years 2000 or later. For diesel, PART5's sulfur content is fixed to 500.0 ppm.[3] A significant change is M6.2's capability to allow user inputs for fuel sulfur content allowing the modeling of the effects of different fuels and changes in EPA's fuel regulations.

Table 1. Pollutants reported.

M6.2 Pollutants	Part5 Pollutants	Description [Sources: PART5 and M6.2 users manuals]
OCARBON (Organic CO)	SOF (soluble organic fraction)	Organic Carbon of diesel exhausts particulate emissions. Other than name change, no other change was done.
ECARBON (Elemental & residual CO)	RCP (remaining carbon portion).	Elemental and residual Carbon of diesel exhausts particulate emissions. Other than name change, no other change was done.
GASPM	Carbon	Organic, elemental, and residual Carbon of gasoline exhausts particulate emissions.
SO_4	DIS	Direct Gasoline Sulfate Particle emissions: same algorithm, but now M6.2 calculations account for different fuel sulfur content.
Not available	INS	Indirect sulfate: sulfate formed in the air from vehicle emissions. In PART5 it is calculated based on measurements of ambient sulfur from 11 cities in the US. It also assumes that 12% of gaseous SO_2 reacts in the atmosphere to form SO_4.
Lead	Lead	Gasoline Lead particulate emissions based on fuel content. Both models assume that post 1975 model year vehicles, and after 1991 calendar years, are free of lead.
NH3	Not Available	Only gaseous ammonia directly emitted directly from a vehicle tailpipe are considered in Ammonia emission factors. Estimates are based in a 1981 report (EPA/AA/CTAB/PA/81-20).
BRAKE	BRAKE	PM emission factors from brake wear. The brake wear calculation portion of PART5 was not updated.
TIRE	TIRE	PM emission factors from tire wear. The tire wear calculation portion of PART5 was not updated.
Total PM	Total PM	Total PM includes: exhaust PM, indirect sulfate, brake-wear and tire-wear.
Not available	Fleet average unpaved road dust	PART5's calculation of fugitive dust from paved and unpaved roads was removed in M6.2.
Not available	Fleet average paved road dust	
SO_2	SO_2	Gaseous Sulfur Dioxide: same algorithm, but now M6.2 calculations account for different fuel sulfur content.

In terms of user-required inputs, there are also some differences between PART5 and M6.2. PART5 basic inputs include: region, calendar year of evaluation, speed cycle (transient or cruise) and vehicle average speed. M6.2's PM input file contain: minimum and maximum temperature, fuel RVP, calendar year, particle size, diesel sulfur content, and base particulate emission factors contained in six external files. These commands were added to supply the other inputs needed by PART5's algorithms.

As mentioned before, M6.2 is now the approved model for estimating PM2.5 emissions for SIP and transportation conformity purposes. As many areas are currently using PART5 for their emissions analyses, they will be interested in examining what the impacts on emissions estimates are by switching from PART5 to M6.2. This information might be useful when deciding if they need to revise their PART5-based PM budgets with M6.2.

Emissions Comparison by Calendar Years

The comparison of the emission results from the M6.2 PM module and PART5 are conducted under various conditions. First, PART5 and M6.2 results were compared for calendar years 2002 to 2020 and are for PM2.5 and PM10. For this purpose, we adopted the following assumptions:

1. Exhaust Emission Factor: M6.2 exhaust emission factors were calculated as:

$$\textit{Total Exhaust DIESEL PM} = \textit{OCARBON} + \textit{ECARBON} \tag{a}$$

$$\textit{Total Exhaust GASOLINE PM} = \textit{GASPM} \tag{b}$$

$$\textit{Total PM emissions} = (a) + (b) + \textit{lead} + \textit{SULFATE}$$

2. Calendar year: Emissions were aggregated for all vehicle classes, and are presented for calendar years 2002-2020, in one year increments.

3. Model inputs:
    a. Vehicle speed: an average speed of 19.6 mph (PART5's default) for all facilities was used for calculations.
    b. Vehicle registration distribution, diesel fractions, and Mileage accumulation: output emission factors were calculated using M6.2 and PART5's default values.
    c. Inspection and Maintenance (I/M) programs, anti-tampering (ATP) programs, and reformulated gasoline programs: no I/M, ATP, and reformulated gasoline programs were assumed. In PART5, I/M programs only affect lead particulate emissions. Due to the declined use of leaded gasoline, both M6.2 and PART5 show zero lead emissions after calendar year 1991. Therefore, the effect of I/M programs in the analysis of calendar years 2002-2020 will be none.
    d. Gasoline sulfur content: 138.0 ppm (PART5's calendar years 2000 and later default value) was used for all M6.2 runs.
    e. Diesel sulfur content: 500.0 ppm (PART5's default value) was used for all M6.2 runs.
    f. Temperature: effects of ambient temperature on particulate emission levels were not modeled. Neither PART5 nor M6.2 are sensitive to such effects.
    g. Altitude: altitude does not affect PART5 emissions.

The following set of figures, shows the comparison of both models outputs in six categories.

1. Total Emissions

Figure 1. Total exhaust PM emissions factors from M6.2 and PART5 for all vehicle classes.

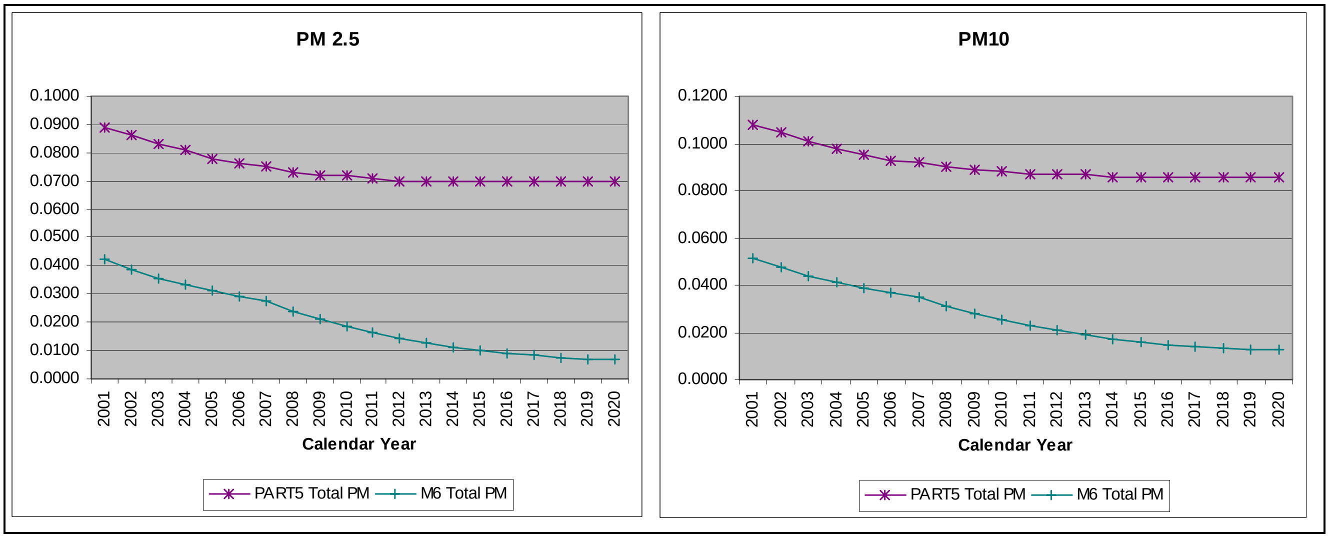


Figure 2. SO_2 emissions factors from M6.2 and PART5 for all vehicle classes.

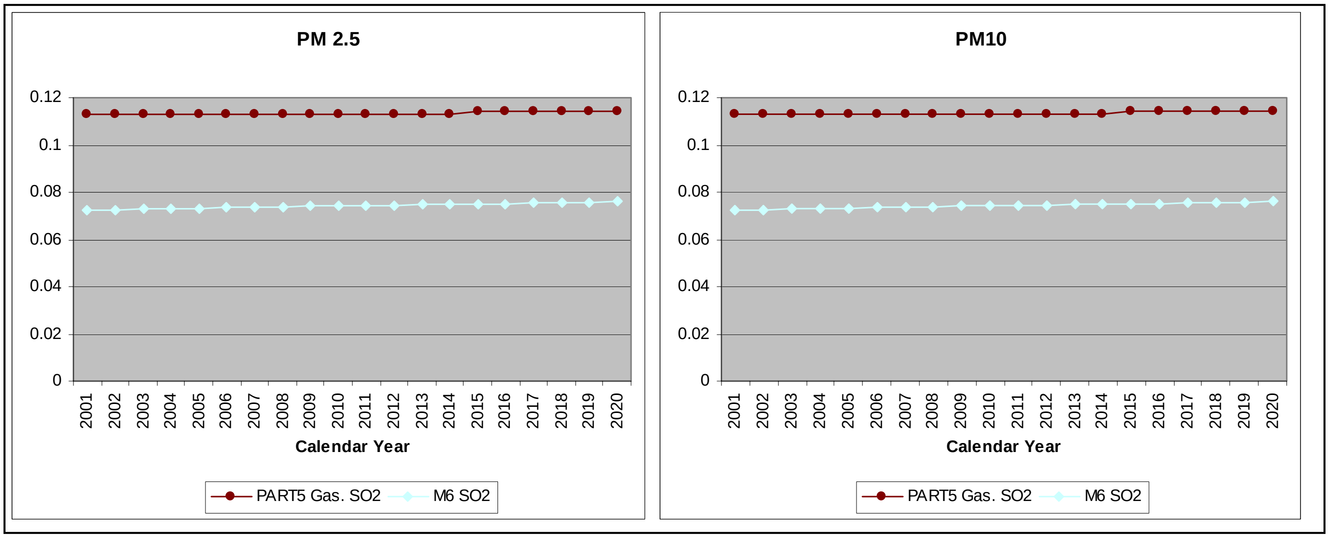
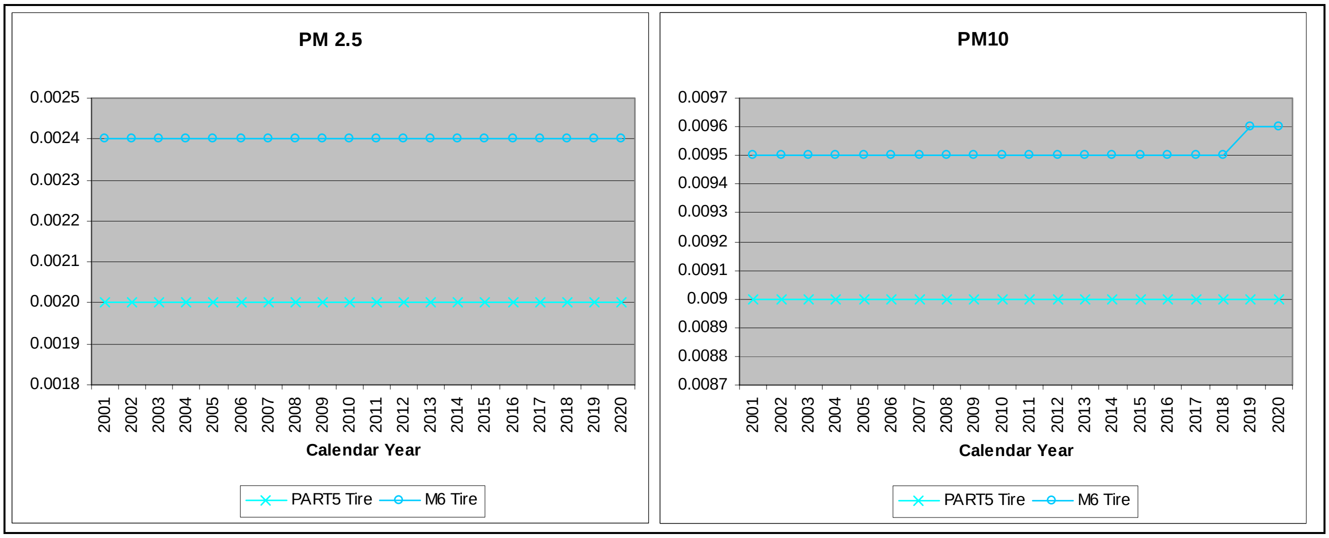


Figure 1 and Figure 2 show that M6.2 total exhaust emission factors, and SO_2 emission factors are slightly lower than PART5 results. The differences can be explained by M6.2 updates in input data such as vehicle registration and technology distributions, and the inclusion of recently adopted more stringent vehicle and fuel emissions standards. For example, base emission rates changes in M6.2 reflect that by 2007 and later, heavy-duty diesel vehicles will meet the 0.01 g/bhp-hr certification standard if low sulfur fuel is used (EPA's 2007 Heavy-duty Diesel Vehicle rule making effort). Also, for gasoline vehicles, M6.2 assumes compliance with 2004 Tier2 Light-duty Gasoline vehicles rulemaking and compliance with 2005 heavy-duty gasoline rulemaking if low sulfur fuel is used.

2. Tire Wear Emissions

Figure 3. PM tire wear emissions from M6and PART5 for all vehicle classes.

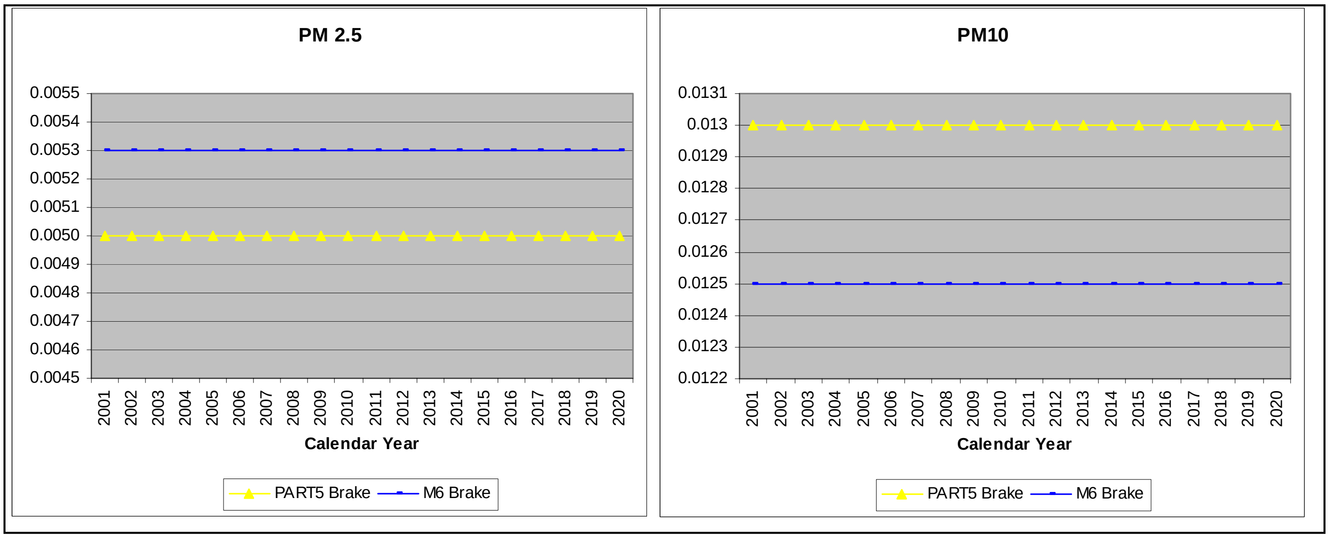


Tire wear emissions are a small fraction of the total PM emissions. Pierson and Brachaczek found that tire wear accounts for only 1 percent of total PM emissions. The tire wear emission factors calculations were not changed in M6.2 from PART5. They are calculated as a function of the fraction of particles less than or equal to the particle size cutoff, and the average number of wheels on each vehicle class. As noted in Figure 3 above, PART5 PM tire wear emissions factors are not sensitive to different calendar years. M6.2 shows slightly higher tire wear emission factors than PART5, and somewhat higher values in analyses years 2019 and 2020.

In PART5, the average number of wheels was: LDGV = 4, LDGT12 = 4, HDGV = 6, MC = 2, LDDV = 4, HDDV2B = 4, LHDDV = 6, MHDDV = 6, HHDDV = 18, Buses = 4.[3] In M6.2, the number of wheels on school buses was increased from four to six.[4] The slight differences between the two models outputs might be explained by these new assumptions on the number of tires, and the use of M6.2 new vehicle registration. Changes in vehicle registration are especially important in the heavier vehicle classes because they have more tires per vehicle.

3. Brake Wear Emission

Figure 4. PM brake wear emissions from M6.2and PART5 for all vehicle classes.

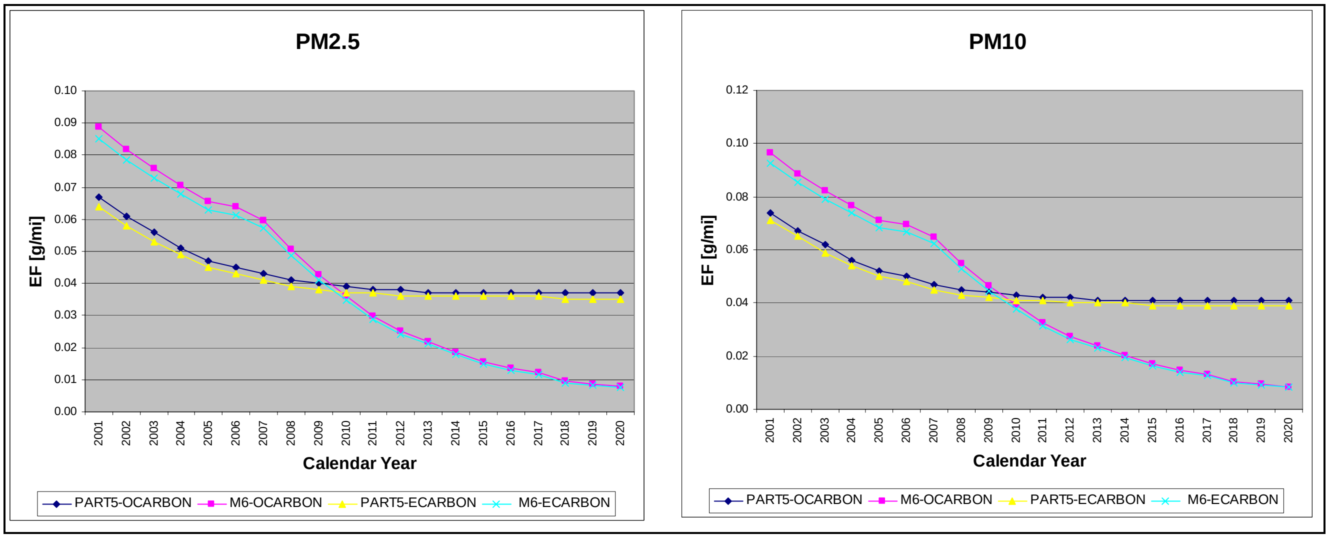


Like the M6.2 PM tire wear calculation, the brake-wear emission factors are also a function of the fraction of particles less than or equal to the particle size cutoff, and the average number of wheels per vehicle class. Emission factor calculations were not changed from PART5, and are assumed to be the same for all vehicle classes in the model.[4] As noted in the Figure 4, PM brake wear emission factors are not sensitive to different calendar years. The use of new registration data for M6.2 might explain the slight differences between PART5 and M6.2.

4. Diesel Exhaust

Figures 1 to 4 illustrated composite emission factors for all vehicles classes combined. Diesel and gasoline particulate matter are very different in composition and physical behavior. Also, the models treat them with different level of detail. For gasoline exhausts, particulate emissions, organic, elemental and residual carbon, are all combined into one category for both PART5 and M6.2. For diesel exhaust, however, carbon particulates are classified in two categories: “organic carbon” (OCARBON) and “elemental & residual carbon” (ECARBON). To explore diesel carbon categories, a heavy-duty diesel vehicle class (HDDV2B) was used to compare both models' output for different calendar years. Using the same assumptions mentioned earlier, the results are presented in the following figures.

Figure 5. OCARBON and ECARBON emission factors for HDDV2B vehicle class by Calendar Year.



Note that the emission factors curve for OCARBON and ECARBON are different in Figure 5, although both models predict similar results. According to the M6.2 manual, other than name change, no other change was done from PART5's algorithm.

5. SO_2 Emissions for HDDV2B Vehicle Class

Figure 6. PM SO_2 emission factors from M6.2 and PART5 for HDDV2B vehicle class by calendar year.

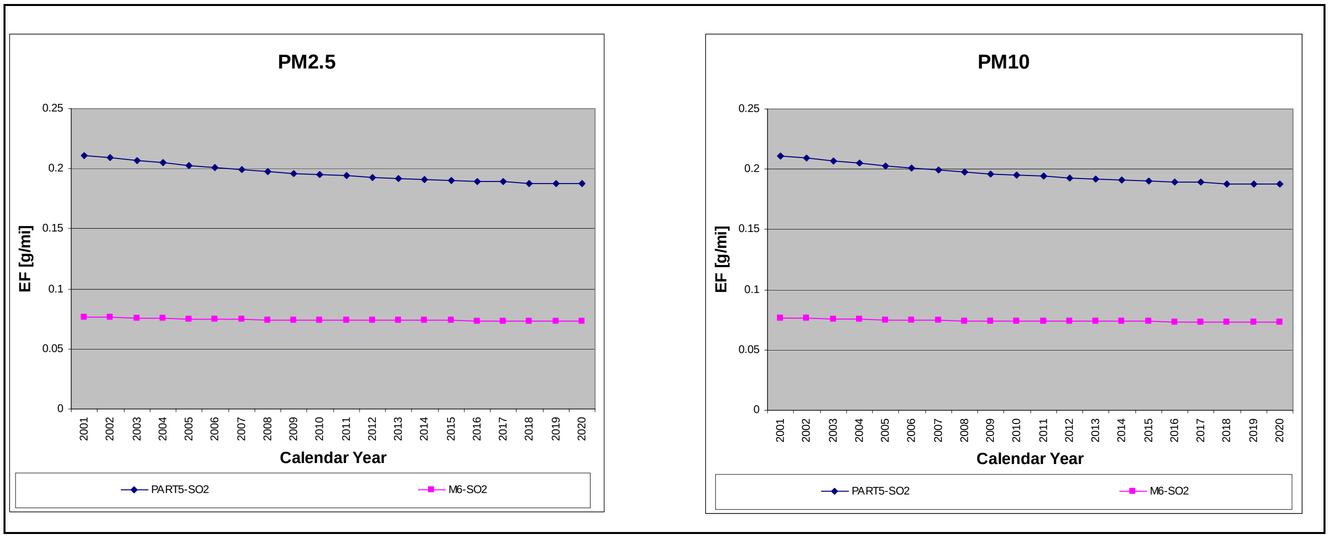


Figure 6 shows that M6.2 produces lower SO_2 emissions rates for HDDV2B vehicle class than those in PART5. The differences might be explained by M6.2 updates to reflect new fuel regulations.

6. Tire Wear Emissions for HDDV2B Vehicle Class

Figure 7. PM tire wear emissions from M6.2 and PART5 for HDDV2B vehicle class by calendar year.

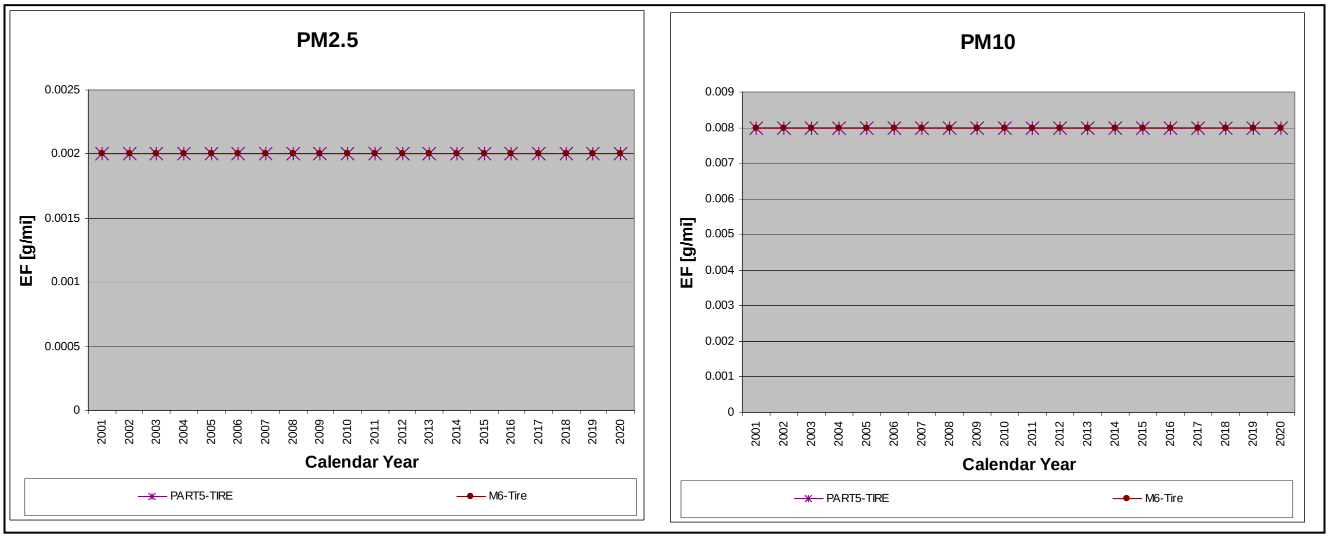


Figure 7 shows that for the HDDV2B vehicle class, there is no difference in the tire emissions between M6.2 and PART5 models. This result was expected because as mentioned earlier the average number of wheels for HDDV2B (4 wheels) did not change from PART5. As expected, the tire wear emissions rates are much higher for PM10 than PM2.5

Emissions Comparison by Speed

The next set of emissions comparison intended to examine whether vehicle speeds play a role in PM emissions rates in both the M6.2 and PART5 models. M6.2 output was compared to PART5 PM emissions results for various running speeds. Results are presented for exhaust, SO_2, tire and brake wear PM emissions. All the assumptions are the same as the previous analysis, except for the following:

1. Calendar year: For all speed scenarios, the calendar year used for modeling was 2004.
2. Speed: Vehicle speeds vary from 0 to 65 mph in 5 mph increments. PART5 allows a maximum speed of 55 mph. For speeds higher than 55 MPH, the model assumes constant emission factors.

Unlike the emission rates for VOC, NOx and CO that are highly sensitive to speed, speeds have a slight impact on PM emissions rates. Figures 9 to 12 show the results of emissions from M6.2 and PART5. Emission Factors for SO_2 (Figure 10), PM2.5 tire wear (Figure 11), and break wear (Figure 12), shows similar results from PART5 and M6.2. It was found that these emission factors have no speed effect. On the other hand, the "total exhaust" emission factors (Figure 10), shows that unlike PART5, M6.2 has some speed effect.

According to the “PART5 User Guide appendix”, minor speed effects in PART5 emission factors are caused by sulfate particulate. PART5 includes different direct sulfate values for speeds at or lower than 19.6, speeds at or above 34.8, and interpolated values for speed between 19.6 and 34.8.[3] These changes are not visible in PART5’s results, but they are notable in M6.2. According to EPA personnel, it might not be visible in PART5 because the sulfate and SO2 emission factor equations in the model have no sulfur balance, as M6.2 does.[5]

Figure 9. Total PM exhaust emissions from M6.2and PART5 for all vehicle classes.

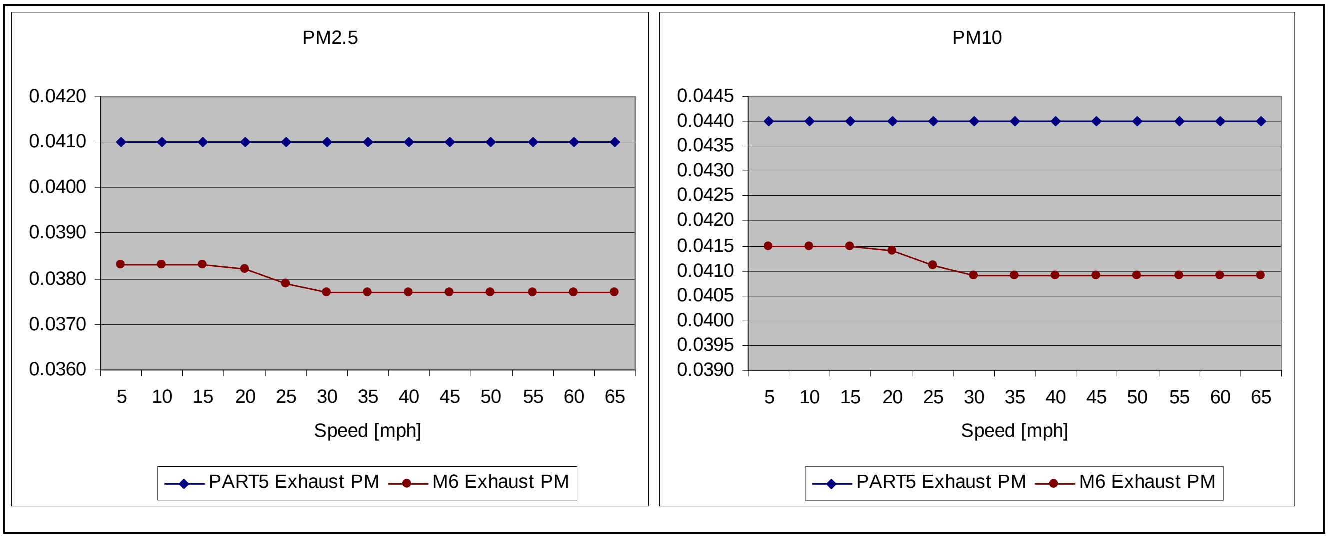


Figure 10. PM SO_2 emission factors from M6.2and PART5 for all vehicle classes.

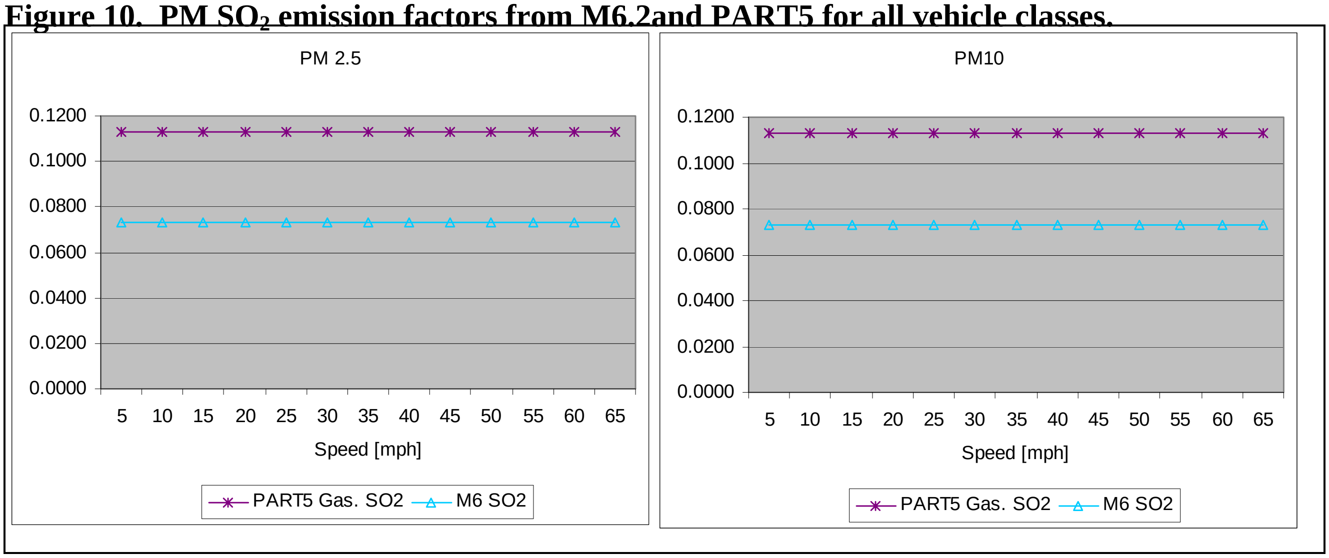


Figure 11. PM tire wear emission factors from M6.2 and PART5 for all vehicle classes.

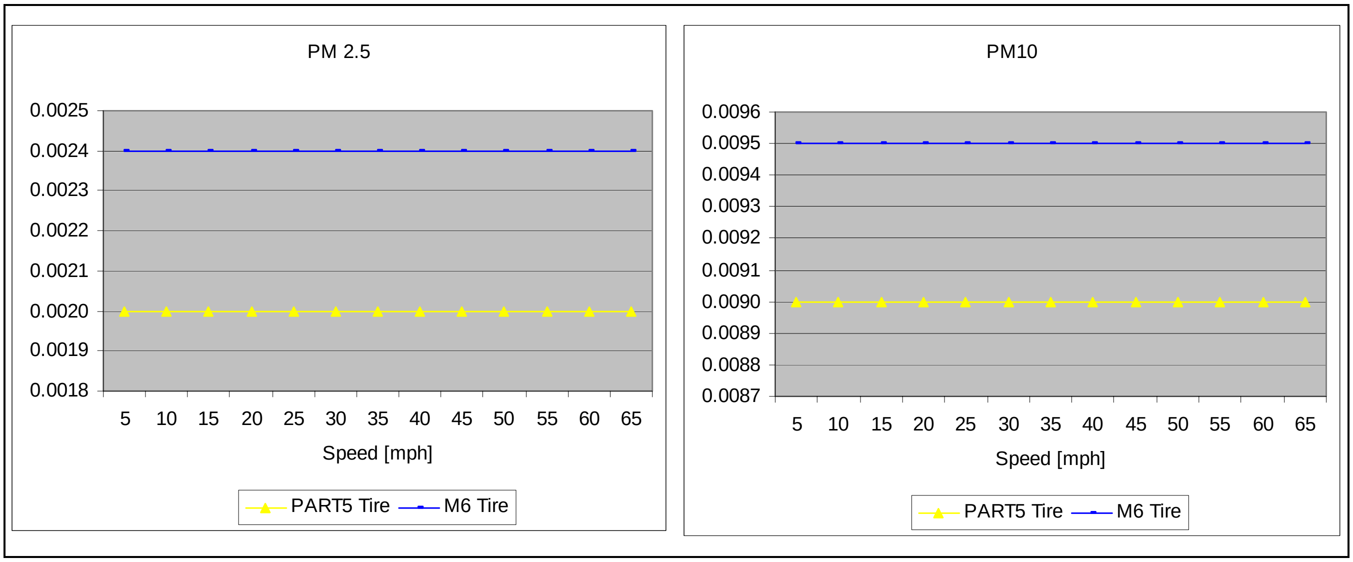
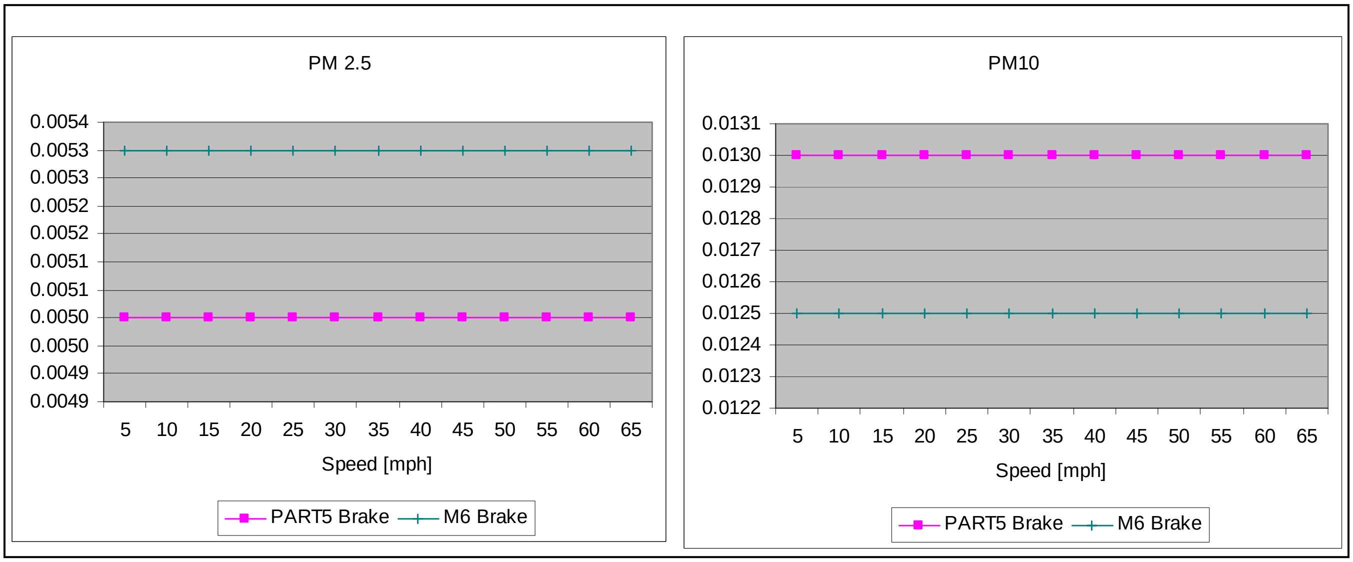


Figure 12. PM brake wear emission factors from M6.2and PART5 for all vehicle classes.



M6.2 PM SENSITIVITY ANALYSIS

To better understand M6.2 particulate matter modeling function, a series of test runs were performed to examine the sensitivity of certain parameters on PM2.5 and PM10 emission rates. The selected parameters studied were vehicle activities (vehicle speed and vehicle miles traveled (VMT) on different roadway facilities), fuel physical properties (Reid Vapor Pressure (RVP), and sulfur content), and environmental conditions (minimum and maximum temperature) were tested. For the sensitivity analysis the following assumptions were kept constant for all model runs (except when the parameter was the one tested):

- Calendar year: 2005

- Diesel sulfur: 250 ppm
- Fuel RVP: 8.5 psi
- Min/max temperatures: 72.0 F and 98.0 F
- Min/max temperatures during gas sulfur runs are: 88.0 F and 100.0 F
- All other data are M6.2 defaults.

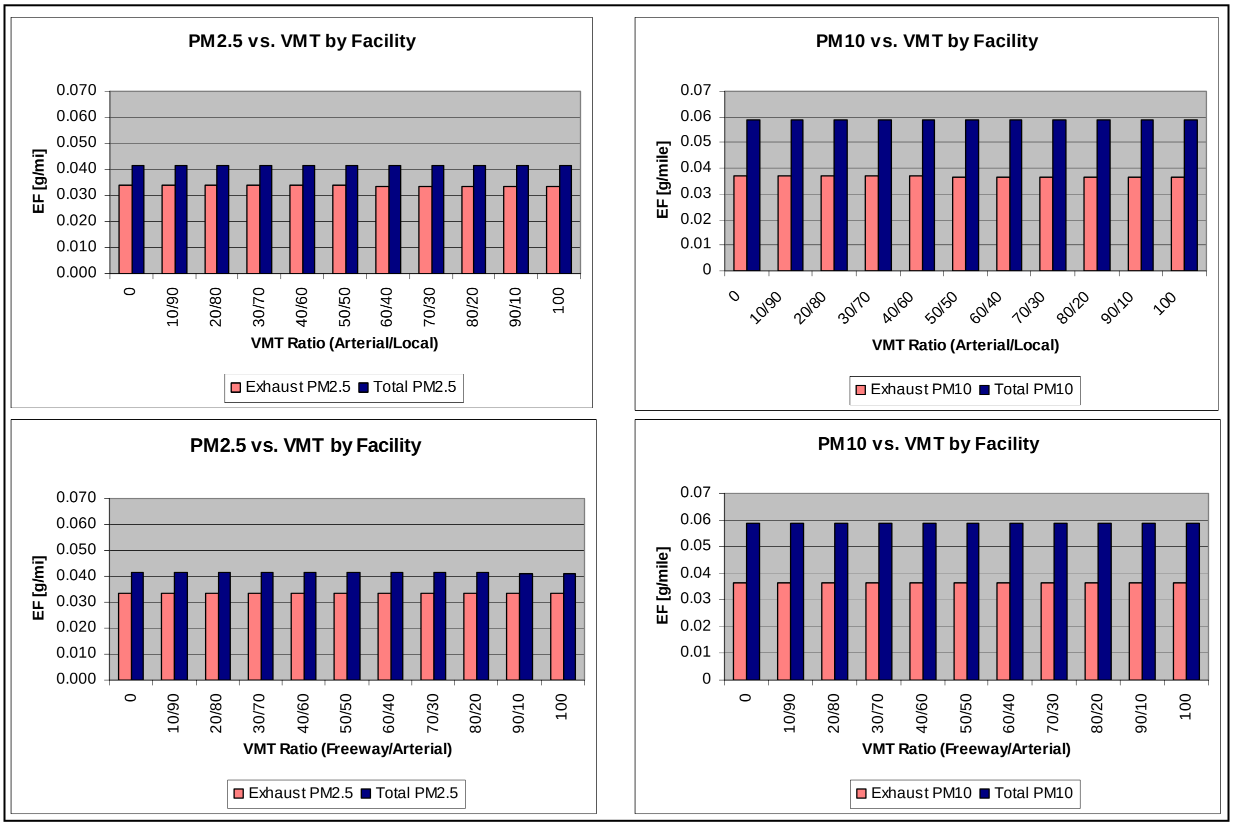
The selected parameters were studied individually, and their interdependencies were not analyzed.

Vehicles Miles Traveled by Facility

To evaluate the effects of roadway facility types on PM2.5 and PM10 emission factors, VMT distribution by facility was evaluated for arterials, locals and freeways. The command "VMT BY FACILITY" allows users to allocate VMT to various roadway or facility types by vehicle class.6 Figure 13 shows the PM emission rates changes against various VMT ratio between arterial and local/collectors, and the VMT ratio between freeways and arterials.

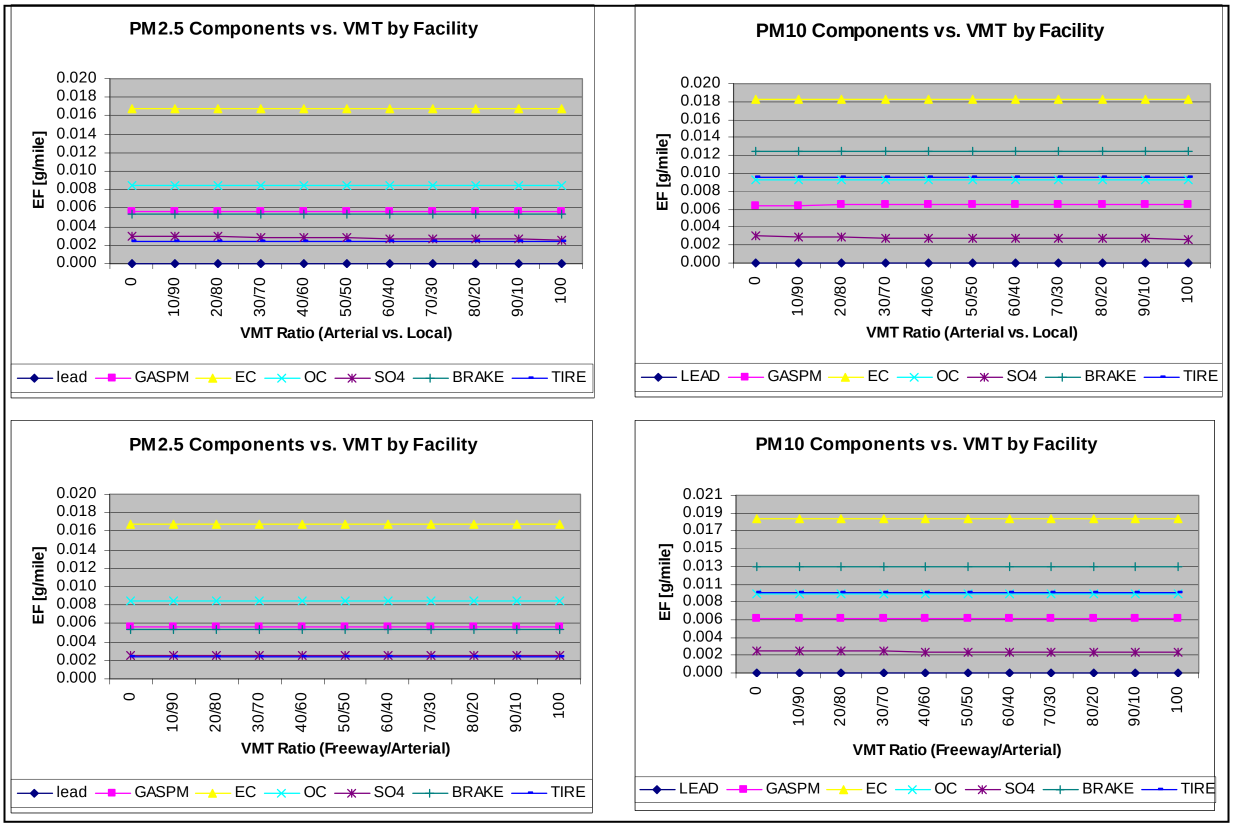
As shown in Figure 13, the changes in VMT ratio between arterials/locals or freeways/arterials result in negligible exhaust PM2.5 and PM10 changes. Also, it is noted that for exhaust PM2.5 the arterial/local and freeways/arterials graphs are identical.

Figure 13. PM versus VMT by facility.



Exhaust PM is constituted by diesel organic carbon (OCARBON), diesel elemental carbon (ECARBON), GASPM (or gasoline PM, which is the sum of the organic and elemental carbon portion, and any residual carbon portion of gasoline vehicles exhaust particle), sulfate and lead.[4] Figure 14, illustrates the PM2.5 and PM10 exhaust and total PM emission constituents versus VMT by facility. These figures show the negligible change in exhaust and total PM emissions against the various VMT ratios by facility. For both PM2.5 and PM10, the slight variation shown in exhaust PM is caused by changes in SO_4. As speed increases, SO_4 slowly decreases. As stated in the M6.2 manual, no changes were made from PART5 in the definition of most of the constituents (with the exception of SO_4), or in the values of the related parameters in their associated calculation.[4] Because PART5 cannot model effects of roadway facility types, it was expected that the M6.2 calculation of these PM components would also be fairly insensitive to changes in VMT by facility.

Figure 14. PM components versus VMT by facility.


PM2.5 Components vs. VMT by Facility

PM10 Components vs. VMT by Facility

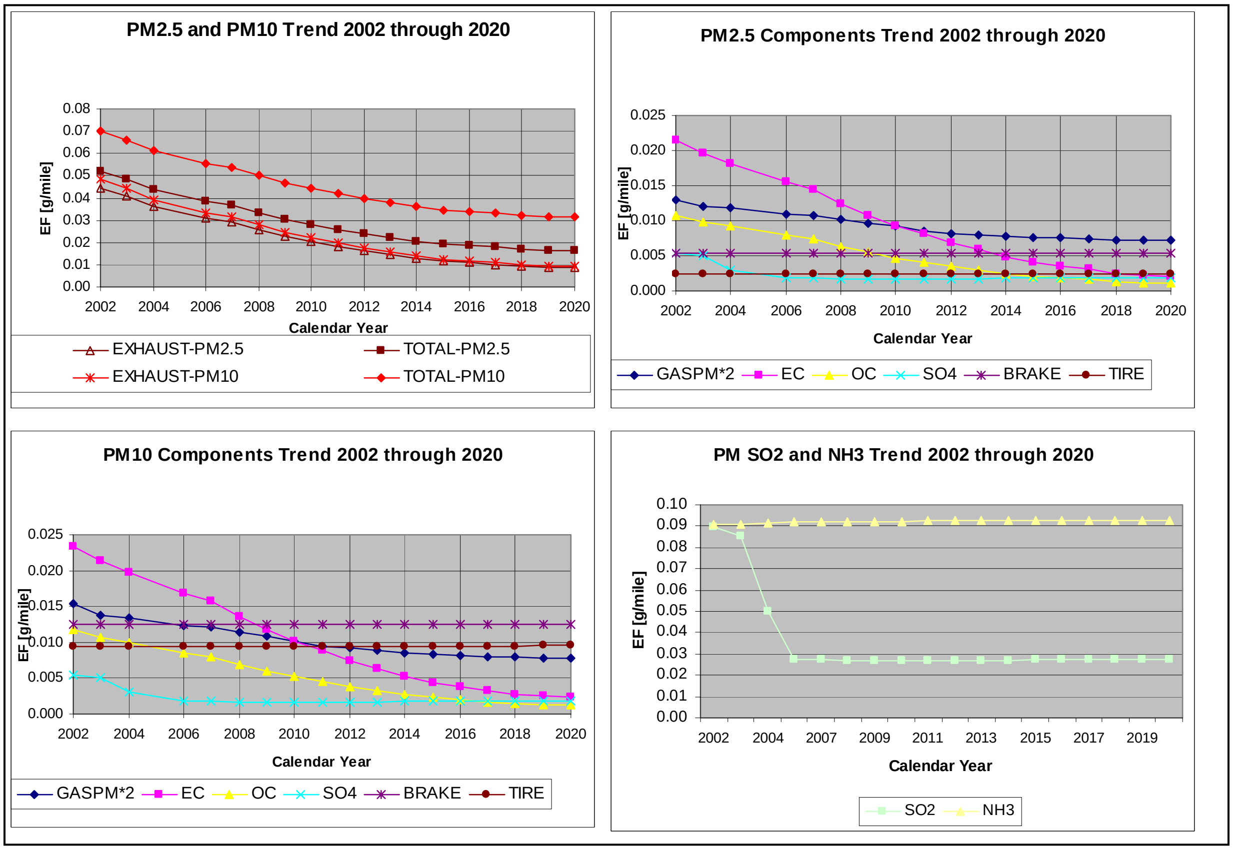
PM2.5 Components vs. VMT by Facility

PM10 Components vs. VMT by Facility

Trend Analysis

The PM2.5 and PM10 emission factors predicted by M6.2 for calendar years 2002 through 2020, are shown in Figure 15. The downward trends of all the PM components emissions are due to the influence of tighter standards on vehicle emissions and fuel programs. As expected, tire and brake wear emission factors were higher for PM10 than PM2.5, but they are held constant for all calendar years.

Figure 15. Trends by calendar year.



PM2.5 and PM10 Trend 2002 through 2020

PM2.5 Components Trend 2002 through 2020

PM10 Components Trend 2002 through 2020

PM SO2 and NH3 Trend 2002 through 2020

Roadway Facility Speed

The AVERAGE SPEED command was used to test roadway speeds for freeways (assigning 100% of the VMT to a freeway mainline), and for arterials (assigning 100% of the VMT to an arterial mainline). As shown in Figures 16 and 17, speed changes have minor effects on the emission rates for PM2.5 and PM10. Again, for both PM2.5 and PM10, the slight variation shown in exhaust PM is caused by changes in SO_4. These results concur with the ones found when different VMT ratios by facility were examined: as speed increases, SO_4 slowly decreases.

Figure 16. PM2.5 roadway facility speed effects.

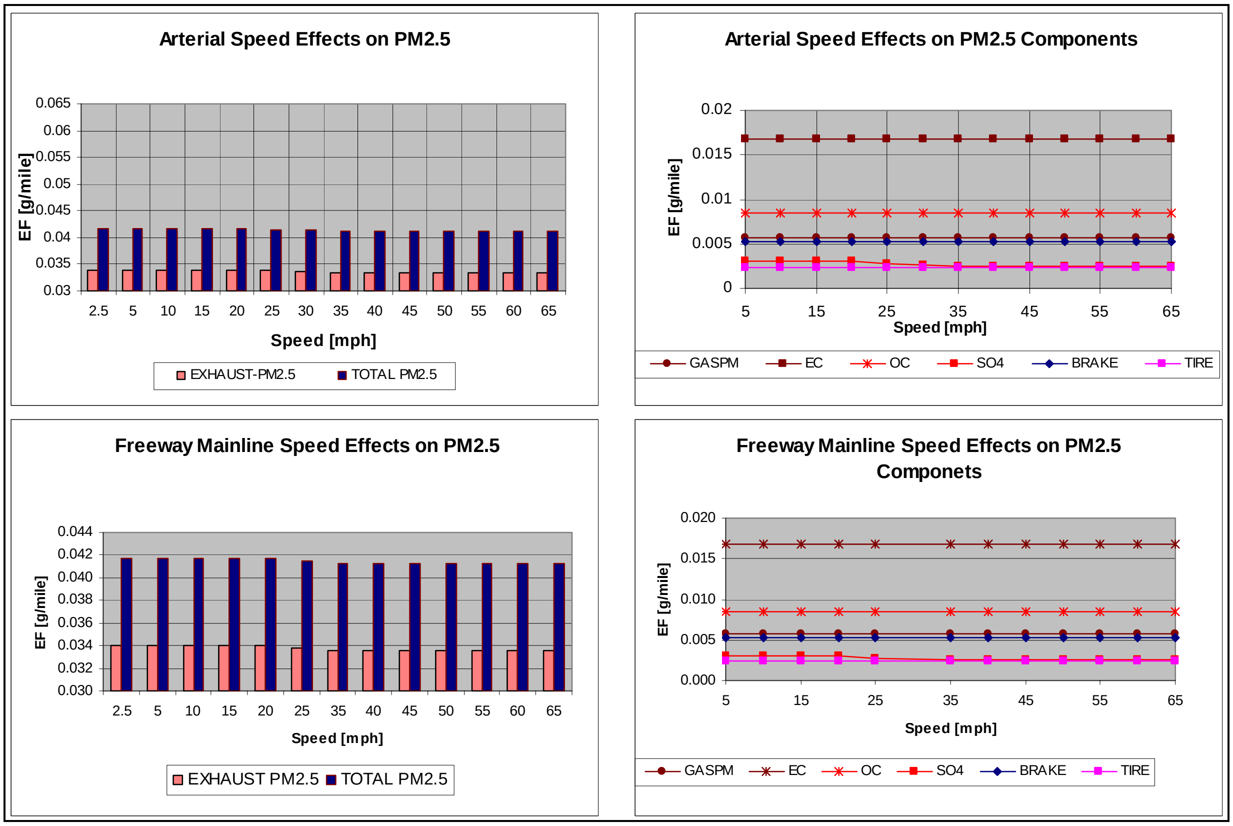
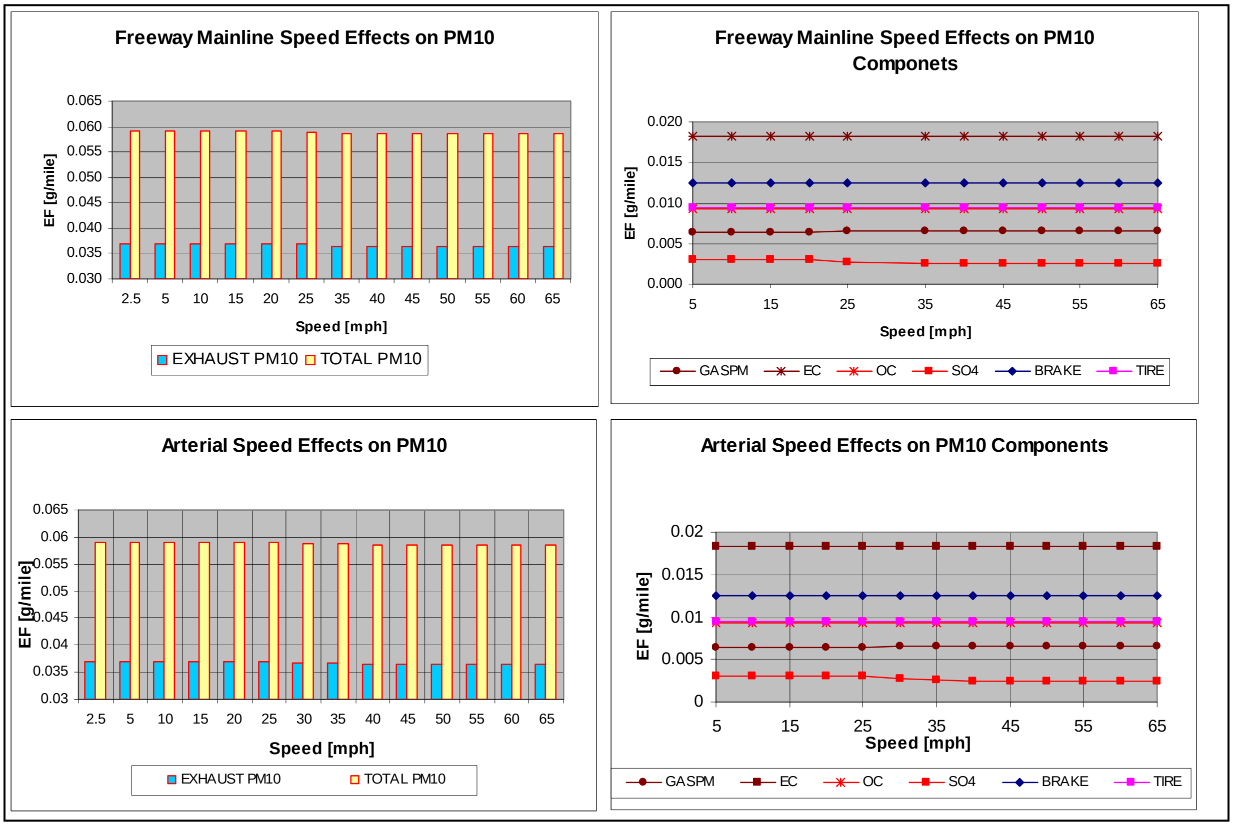


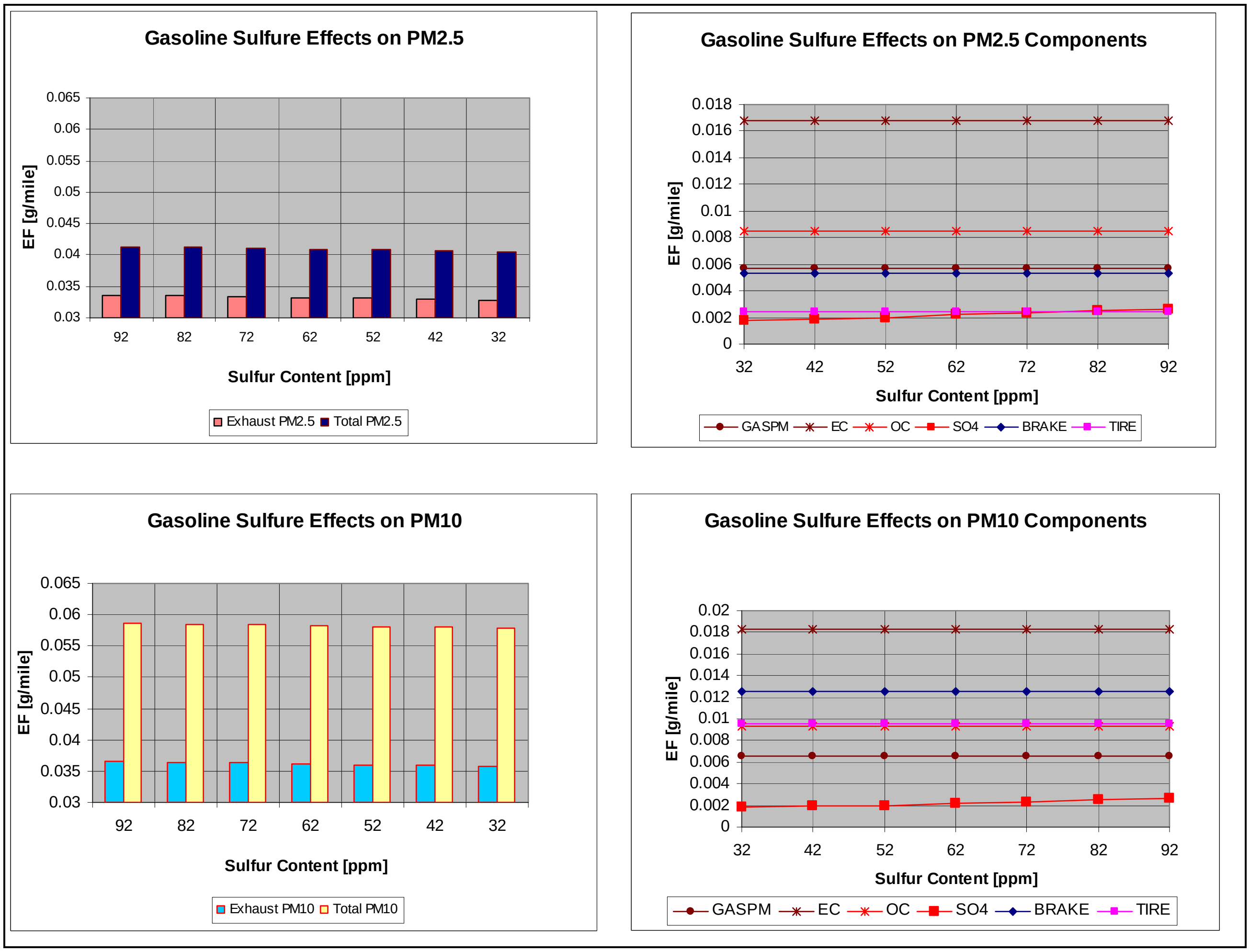
Figure 17. PM10 roadway facility speed effects.



Fuel Sulfur Content

As anticipated, fuel sulfur content had more effect on emission factors for diesel-fueled vehicles (Figure 19) than on gasoline-fueled vehicles (Figure 18). Like PART5, M6.2 assumes that all the sulfur in the fuel is exhausted either as sulfate, or as SO_2. Once SO_4 is calculated, the remaining sulfur in the fuel is considered to be SO_2. Consequently, the only components affected by changes in sulfur content are SO_2 and SO_4.

Figure 18. Gasoline sulfur effects.



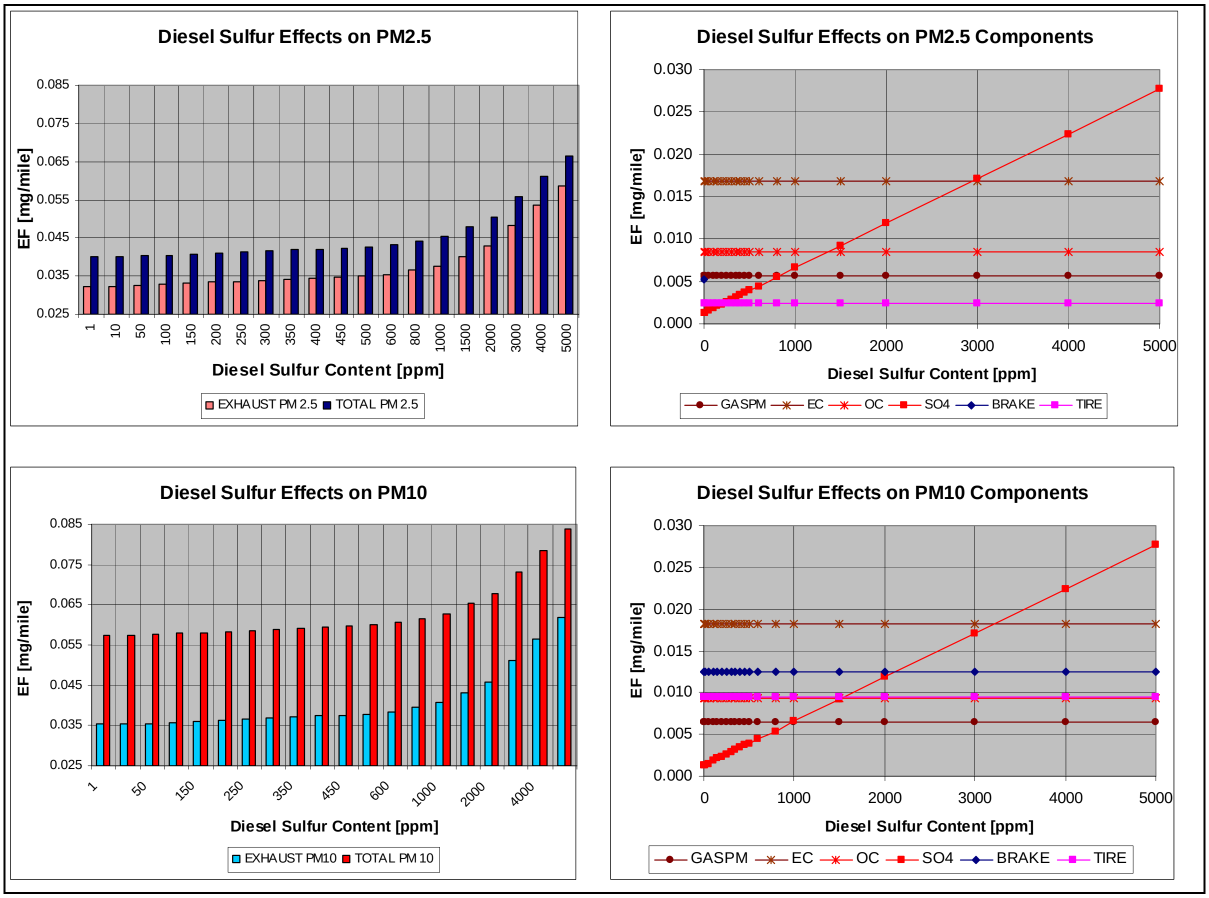
Gasoline Sulfure Effects on PM2.5

Gasoline Sulfure Effects on PM2.5 Components

Gasoline Sulfure Effects on PM10

Gasoline Sulfure Effects on PM10 Components

Figure 19. Diesel sulfur effects.

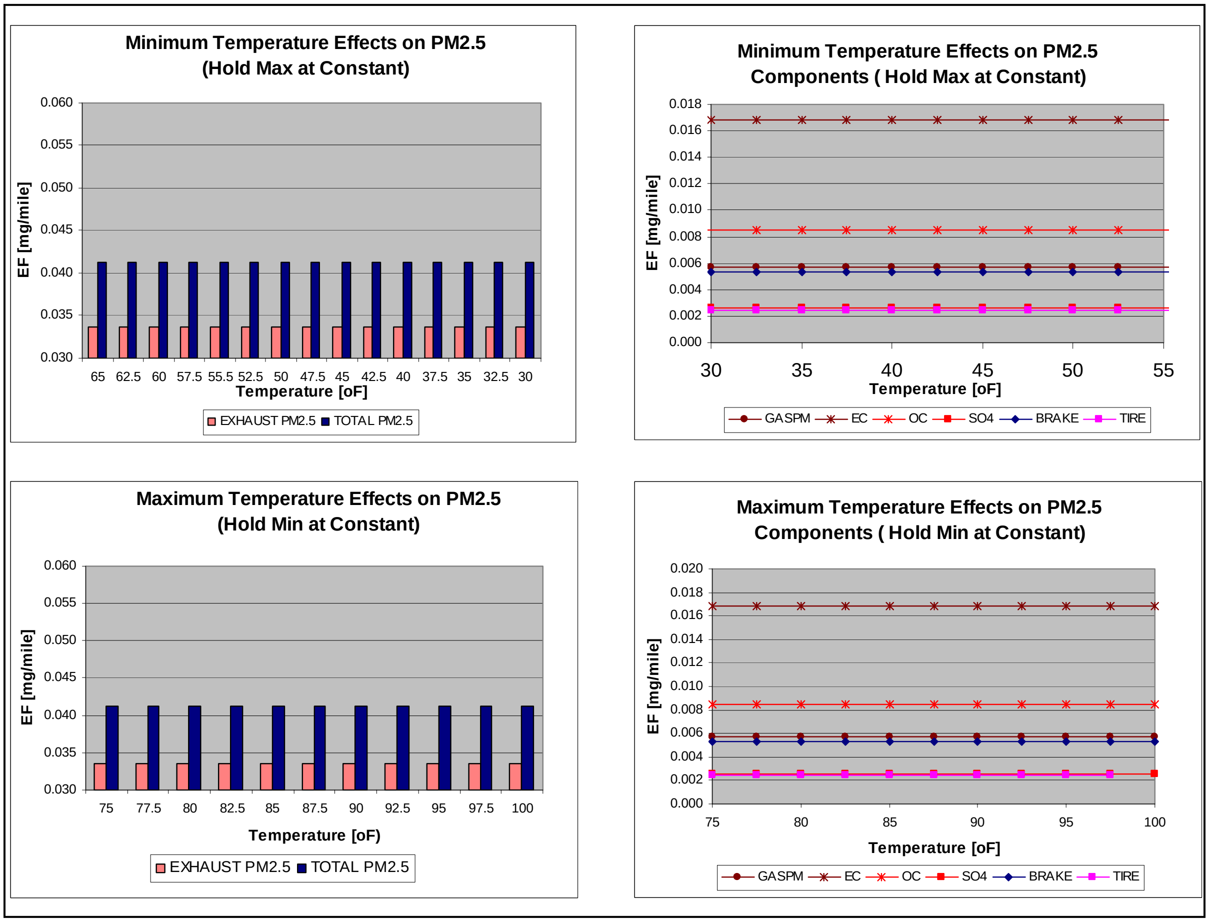


Parameters with no Sensitivity

<u>Minimum and Maximum Temperature</u>

As shown in Figures 20 and Figure 21, changes in minimum and maximum temperature do not have any effect on PM2.5 and PM10 emission factors. Neither PART5 nor EMFAC2000 model temperature effects.

Figure 20. Minimum and maximum temperature effects on PM2.5.

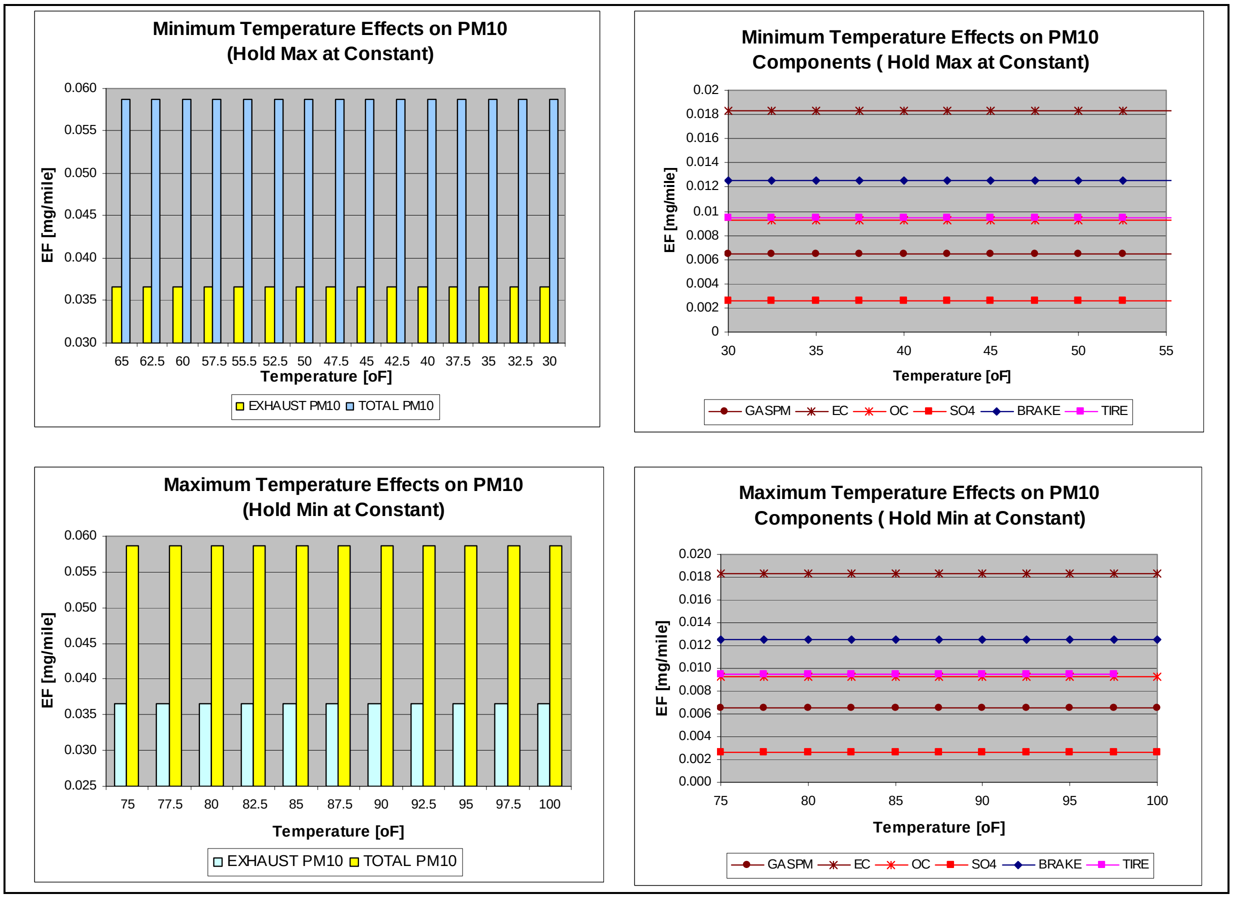

Minimum Temperature Effects on PM2.5 (Hold Max at Constant)

Minimum Temperature Effects on PM2.5 Components (Hold Max at Constant)

Maximum Temperature Effects on PM2.5 (Hold Min at Constant)

Maximum Temperature Effects on PM2.5 Components (Hold Min at Constant)

Figure 21. Minimum and maximum temperature effects on PM 10.


Minimum Temperature Effects on PM10 (Hold Max at Constant)

Minimum Temperature Effects on PM10 Components (Hold Max at Constant)

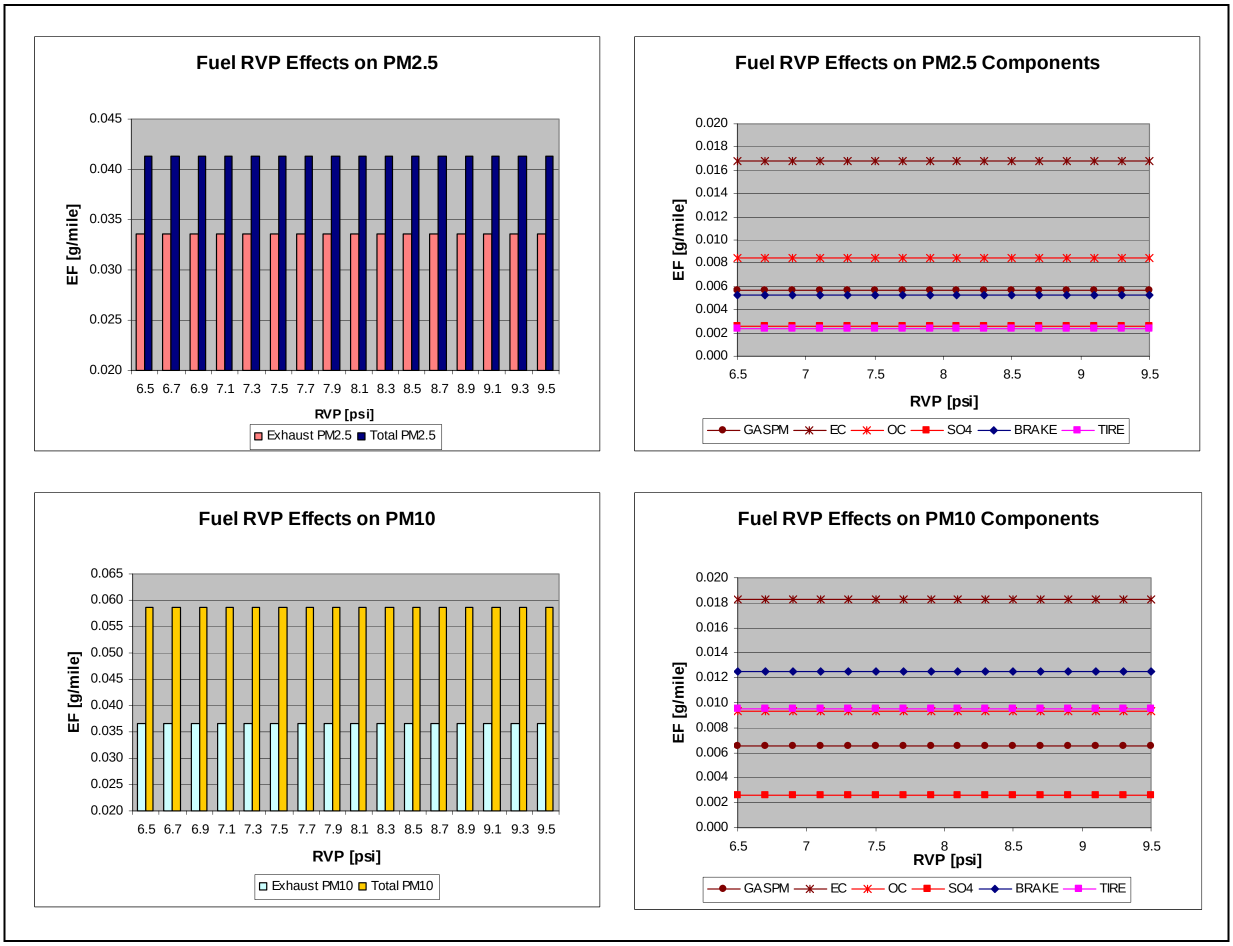
Maximum Temperature Effects on PM10 (Hold Min at Constant)

Maximum Temperature Effects on PM10 Components (Hold Min at Constant)

Fuel Volatility

Volatility is the property of a liquid fuel that defines its evaporation characteristics. EPA limits gasoline volatility during the summer months in order to reduce evaporative emissions that contribute to smog (June 1 to September 15 at retail stations). As shown in Figure 22, fuel RVP changes do not have any effect on PM2.5 and PM10 emission factors.

Figure 22. Fuel volatility effects on PM10.



CONCLUSIONS

Results from the M6.2 and PART5 models were compared. Exhaust emissions factors tend to be lower using M6.2 than predicted by PART5, while tire wear and brake wear emission factors tend to be higher. M6.2's PM emission factors benefit from the use of newer data (vehicle registration, diesel fractions, fuel economy, and mileage accumulation rates), the inclusion of recent rulemaking (including fuel sulfur level reductions), and its capability to account for the sulfur level of fuels (gasoline and diesel). These explain most of the differences between the two models. Therefore it was shown that M6.2 shares most of PART5's deficiencies and shortcomings.

The sensitivity analysis of the M6.2 PM module indicated that PM2.5 emission factors results are consistent with PM10 emission factors. It was found that emission factors tend to decrease for both PM2.5 and PM10 in later calendar years. The difference is apparently related to future model years updates reflecting more stringent vehicle emissions and fuel standards. Effects of both roadway facility types and speed on emissions rates were negligible. When testing fuel parameters, it was found that RVP and gasoline sulfur content also had negligible effects in PM emission factors. On the other hand, PM emission factors are highly sensitive to diesel sulfur content. Parameters tested that showed no effect on PM2.5 and PM10 emissions are minimum and maximum temperature, and fuel RVP.

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