APPENDIX C

Heavy-Duty Diesel Vehicle PM Emissions Inventory and Estimated PM Emissions Benefits for Proposed Amendments to Heavy-Duty Vehicle Inspection Program and Periodic Smoke Inspection Program

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The Proposed Amendments to the Heavy-Duty Vehicle Inspection Program (HDVIP) and Periodic Smoke Inspection Program (PSIP) rulemaking are designed to reduce emissions of particulate matter (PM) from diesel powered heavy-duty vehicles (HDV) powered by diesel engines. Emission reductions would primarily result from heavy-duty diesel (HDD) trucks, which include heavy heavy-duty diesel trucks (HHDDT, >33,000 lbs. gross vehicle weight rating (GVWR)) and medium heavy-duty diesel trucks (MHDDT, 14,001-33,000 lbs. GVWR)[1]. This appendix discusses the activity and emissions test data associated with of HDD trucks, presents an updated PM emissions inventory, and provides an estimate of emissions benefits for the proposed regulation.

1. Heavy-Duty Vehicle PM Emissions Inventory - Baseline

1.1. Introduction

On-road mobile source emissions in California are currently calculated using the emission factors (EMFAC) 2017 model. For on-road motor vehicles, the base emission rate (ER) of a pollutant for a given model year is calculated by the following formula:

$$ER_{odo} = (ZMR + DR \times Odo) \times SCF \qquad (1)$$

where ZMR is the zero-mile emission rate, DR is the emissions deterioration rate, Odo is the average odometer of all vehicles in that model year at a given age, and SCF is the speed correction factor. More specifically, ZMR is the emission rate of the fleet when it is new and DR is the incremental rate of emission increase due to tampering, malmaintenance, and malfunctioning (TM&M) of engine and aftertreatment systems (such as selective catalytic reduction (SCR)) with mileage.

For a given calendar year, ERs of all individual model years at different ages can be calculated for different speeds using Eq. 1, and the calculated ERs are then combined

1 There are some PM emissions benefits from urban diesel buses (UDB), but they are likely very small compared to those from HDD trucks. PM emissions of UDB will not be discussed in the text, but they were included in the calculations of emissions inventory and emissions benefits when UDB and HDD trucks together are referred to as heavy-duty diesel vehicles.

with vehicle miles travelled (VMT) to obtain the emissions for the selected calendar year using the following equation:

$$Emissions = \sum_{Age} (ER_i \times VMT) \quad (2)$$

The ZMR, DR, and SCF in Eq. 1 are determined using emissions data obtained from testing randomly selected in-use vehicles on a chassis dynamometer over various test cycles, and VMT in Eq. 2 is derived from data and information on vehicle population, annual mileage accrual rates, and vehicle attrition rates.

While EMFAC2017 (CARB, 2017f) is the latest version of the EMFAC model, EMFAC2014 is still the current U.S. Environmental Protection Agency (U.S. EPA) approved version of the EMFAC model (CARB, 2015b). Over the last few years, new emissions test data for HDD trucks from several sources have become available, and staff has recently revised the emission rates of HHDDT and MHDDT based on these data. The revised emission rates were used to update the emissions inventory of diesel trucks in EMFAC 2017, which was released in December 2017, and the emissions inventory generated from this newly released model was used as the baseline for the calculations of emission benefits of the proposed regulatory amendments.

1.2. HDD Truck Emissions Testing Data

Emission rates of HDD trucks in EMFAC2017 were revised based on new emission test data. The new data were obtained mainly from two sources:

1) Data collected through a testing project conducted by the Truck and Engine Manufacturer's Association (EMA) in contract with the University of California, Riverside (UCR) (UCR, 2017). In this project, five late model trucks were tested on a chassis dynamometer over multiple test cycles (Table 1). As a collaborative testing effort, three of the five trucks were also tested in California Air Resources Board's (CARB) Metropolitan Transportation Authority (MTA) Heavy-Duty Emissions Testing Laboratory.

Table 1: Test Cycles for CARB and EMA-UCR Chassis Dynamometer Testing Projects

Test Cycle	Avg Speed (mph)	Duration (sec)	Length (mi)
UDDS	18.8	1060	5.54
Creep	1.8	253	0.12
Near Dock Drayage	6.6	3,046	5.59
Local Drayage	9.3	3,362	8.70
Transient	15.4	668	2.85
40-mph Cruise	39.9	2,083	23.1
50-mph Cruise	50.2	757	10.5
62-mph Cruise	62.0	1,385	23.2

2) Data collected through CARB's Truck and Bus Surveillance Program (TBSP). This program is designed to better understand the emission performance of in-use trucks and buses and provide representative test data for modeling emissions of diesel HDV fleets. In addition, data from this program are also used to support CARB in-use compliance programs. To date, 21 randomly selected HDD trucks have been tested on a chassis dynamometer over multiple test cycles.

The emissions test data from these two testing projects, along with some additional test data collected by CARB staff, were used to revise the emission rates and update the emissions inventory of HDD trucks.

1.3. Heavy Duty Truck PM Emissions Inventory Update

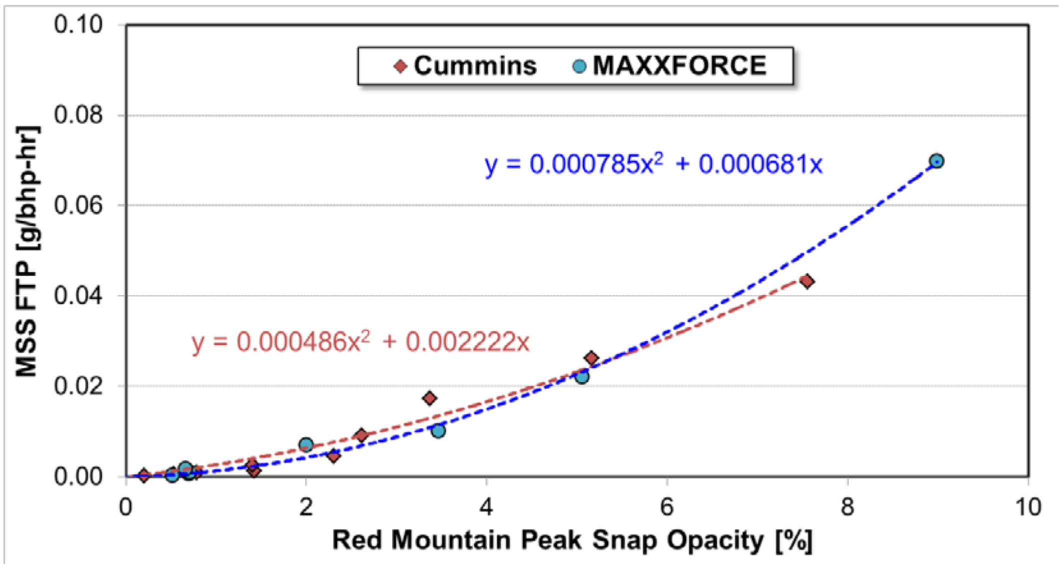
1.1.1 Revision of emission impact rate

As discussed earlier, the running exhaust emissions are a function of ZMR and DR (Eq.1). The underlying assumption in calculating emissions deterioration is that emissions from HDD trucks remain stable in the absence of TM&M. To assess the emission impact of TM&M, in EMFAC a methodology was developed that identifies a number of specific types of TM&M actions that cause an increase in emissions of the in-use HDV fleet over time. The emission impact rate (EIR) for a given TM&M action is the product of frequency of occurrence of that TM&M and the percent increase in emissions over the baseline level due to that action. The compounded EIR for all TM&M actions is then applied to in-use emissions test data to arrive at a ZMR and DR of a pollutant for a model year group.

Staff reviewed and revised the frequencies of diesel particulate filter (DPF) related TM&M based on the data collected in CARB's roadside testing campaigns. In order to use the roadside smoke test data to determine the DPF TM&M frequencies, opacity readings were related to PM emission levels using data from a study conducted by the

National Renewable Energy Laboratory (NREL) (NREL, 2016). (The NREL study is described further in Appendix B to this report.) In the study, the channel end caps in the DPFs of a 2008 MaxxForce and a 2011 Cummins engine were progressively milled off to simulate different levels of filter leaking, and for each simulated level of leaking the opacity and the PM emissions were measured. The results of the filter leaking simulation experiment are summarized in Figure 1. From the two curves, it can be estimated that the PM emission standard (0.01 g/bhp-hr) would be equivalent to a corrected opacity reading of 3.2 percent for the MaxxForce and 2.8 percent for the Cummins. Staff has assumed that the 3.2 percent and 2.8 percent opacity levels correspond to the PM emission standard for 2007-2009 model year (MY) engines and 2010+ MY engines, respectively.

Figure 1: Relationship between Federal Test Procedure (FTP) PM Emissions and Opacity Readings as Established in a NREL Study[2]

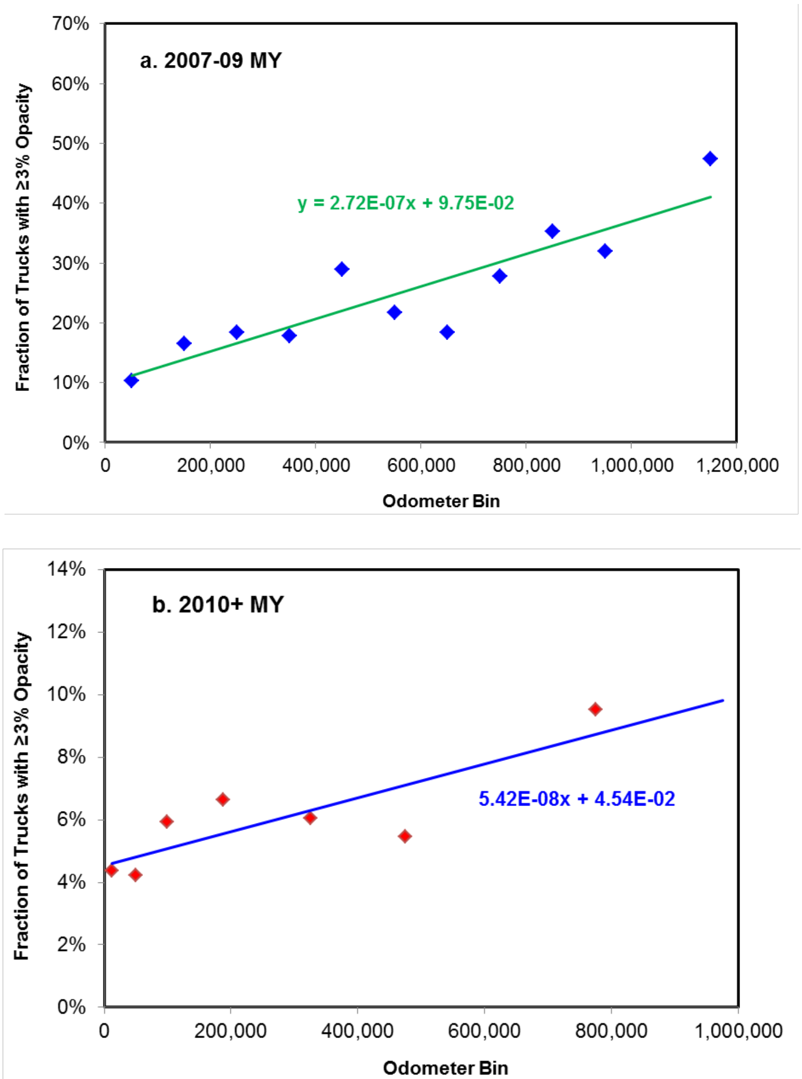


In analyzing the roadside smoke test data, a DPF was considered to be leaking if it has an opacity reading greater than 3.2 percent for a 2007-2009 MY engine and 2.8 percent for a 2010+ MY engine. Using these opacity limits, CARB staff analyzed the CARB roadside smoke test data to estimate the fractions of over-limit opacity readings as a function of odometers (Figure 2). For the 2007-09 MY, data points were grouped into odometer bins of 100,000 miles. However, for the 2010+ MY, due to the much fewer data points than the 2007-2009 MY group, larger bins were used for higher odometers;

[2] The channel end caps in a DPF were progressively milled to simulate DPF leaking. MSS FTP refers to measurements using an AVL micro soot sensor connected to a dynamometer-constant volume sampler system. PM measurements by MSS are highly correlated with those based filters (R^2 >0.99).

in particular, the data points for all trucks with an odometer reading >500,000 miles were combined into a single bin because only a very small number of high mileage 2010+ MY trucks were captured in the three roadside studies.

Figure 2: Fraction of Trucks with Excessive Opacity Readings by Odometer Reading[3]



As shown in Figure 2, there is a positive correlation between the fraction of trucks with over-limit opacity readings and odometer, suggesting that the fraction of leaking DPFs can also be correlated with truck mileages. The fitted linear line based on 2007-2009 MY data gives a frequency of 38 percent at 1 million miles (Figure 2, a), which is

[3] Excessive opacity readings refer to a level at or greater than 3.2 percent for 2007-2009 MY engines and at or greater than 2.8 percent for 2010+ MY engines. The data were collected from CARB roadside smoke inspection campaigns conducted in 2011, 2014, and 2016.

essentially identical to the 37.6 percent frequency of the DPF Leaking category for the 2007-2009 MY group in EMFAC 2014 (Table 2). In contrast, the fitted 2010+ MY data yields a frequency of 10 percent (Figure 2, b), much lower than the 37.6 percent used in EMFAC2014 (Table 2)[4]. Based on the roadside smoke test data, staff has revised the frequency for the DPF leaking category to 38 percent for the 2007-2009 MY and 10 percent for the 2010+ MY, as shown in Table 2.

Table 2: Frequency of DPF Leaking for HDD Trucks

DPF Related TM&M	EMFAC2014			EMFAC2017		
	2007-09 MY	2010-12 MY	2013+ MY	2007-09 MY	2010-12 MY	2013+ MY
DPF Leaking	37.6%	37.6%	26.3%	38%	10%	6.7%
DPF Disabled	2%	2%	1.3%	0%	0%	0%

Historically, EMFAC assumes that a small percentage (~2 percent) of the fleet have a disabled filter due to tampering. However, in CARB's recent roadside smoke inspections of DPF-equipped HDD trucks, inspectors did not differentiate between tampered DPFs and leaky DPFs on the tested fleet. A disabled DPF would act as a completely damaged DPF in terms of its opacity reading and should be captured in the opacity database. Thus, since the roadside smoke inspection data can include vehicles with a disabled DPF and a leaky DPF, staff decided to eliminate "DPF disabled" as a separate DPF TM&M category, as shown in Table 2.

Staff also reviewed the emission increase rates for DPF related TM&M. In EMFAC 2014, it was assumed that, on average, a leaking DPF would result in a 600 percent increase in PM emissions relative to ZMR. This assumption was based on the projection that a HDV engine has an emission level near the 0.01 g/bhp-hr certification level and a leaking DPF would emit around 0.07 g/bhp-hr, which is 600 percent higher. However, for computer-controlled SCR-DPF combination systems, engine manufacturers have been able to certify their engines at PM emission levels almost 10 times lower than the standard, around 0.001 g/bhp-hr. Therefore, the emissions increase associated with a leaking DPF on these SCR-DPF combination systems will be much larger than a 600 percent increase above ZMR. Staff assessed OBD durability demonstration vehicle (DDV) data submitted by heavy-duty engine manufacturers as part of the HDD OBD requirements to update the PM emission increase rates for leaking DPFs. DDV reports simulate specific emission system malfunctions to test

4 One reason for such a discrepancy is that EMFAC is assuming a PM certification level at the standard (0.01 g / bhp-hr), but the actual certification levels of HDD engines have been several times lower. As a result, it takes a significant performance degradation in DPFs to register an opacity reading over the limit equivalent to the PM standard. See text for the discussion on PM emission increase rate revision.

when the malfunction indicator light (MIL) illuminates. For example, some of the malfunctions that DDV reports simulate include oxides of nitrogen (NOx) sensor failures, exhaust gas recirculation (EGR) failures, SCR failures, and DPF failures. Staff analyzed the DDV test data related to PM filter performance to estimate PM emission increases on modern diesel HDVs. To simulate a DPF issue, manufacturers typically degrade the DPF on a test vehicle by milling holes into the filter core, increasing PM emissions to the level where the MIL would illuminate. Staff assessed the PM emissions from baseline tests and from compromised filter tests in the DDV reports and then applied a sales weight to the PM emission data to account for engine sales volumes. Based on the weighted average PM emissions from the DDV data, the emission rate for leaky DPFs is about 0.051 g/bhp-hr, which represents about a 5,200 percent increase in PM emissions above the certified level of about 0.001 g/bhp-hr. Assuming that this relative increase in PM emissions would apply similarly to the ZMR and DR rates, staff revised the emission increase rate for 2010+ MY diesel engines with leaky filters to 5,200 percent (Table 3). Staff left the EMFAC2014 leaky DPF emission increase rate unchanged for 2007-2009 MY diesel engines as they do not possess SCR-DPF combination systems.

Table 3: PM Emission Increases over ZMR emission levels for DPF Leaking for HDD Trucks

DPF Related MM	EMFAC2014		EMFAC2017	
	2007-09 MY	2010+ MY	2007-09 MY	2010+ MY
DPF Leaking	600%	600%	600%	5,200%

Based on the revised frequencies and emission increases for the DPF related TM&M, staff revised the EIRs for the 2013+ MY HDD trucks. Table 4 shows a comparison between the EIRs in EMFAC2014 and the revised EIR for EMFAC2017. Results in the table show that the combined effect of lower frequency and higher emissions increase rate for DPF leaking TM&M category yielded an overall increase in the EIR for 2010-2012 MY and 2013+ MY HDD trucks.

Table 4: PM Emissions Impact Rates for 2010+ MY HDD Trucks

Model Year Group	EMFAC2014			EMFAC2017		
	2007-09 MY	2010-12 MY	2013+ MY	2007-09 MY	2010-12 MY	2013+ MY
EIR	288%	288%	193%	268%	528%	339%

1.1.2 Revision of PM Zero-Mile Rate and Deterioration Rate

As discussed earlier, emissions test data of late model HHDDTs from two recent chassis dynamometer testing projects were used to update the ZMR and DR of PM emissions (see Eqs. 1 and 2 discussed in Section 1). To do this, an average emission rate (ER_{avg}) and an average odometer reading (Odo_{avg}) were first calculated using emission data collected over the continuous urban dynamometer driving schedule (UDDS) cycle for all test vehicles. Using the ER_{avg} and Odo_{avg}, the ZMR and DR can be derived using the flowing relationships:

$$ZMR = ER_{avg} \;/\; \left(1 + EIR \times Odo_{avg}\right) \qquad (3)$$

$$DR = \left(ER_{avg} - ZMR\right) \;/\; Odo_{avg} \qquad (4)$$

Table 5 shows the revised PM ZMR and DR for HHDDT and their ZMR and DR in EMFAC2014.

Table 5: PM ZMR and DR for HHDDT in EMFAC2014 and EMFAC2017

Engine Model Year	EMFAC2014		EMFAC2017	
	ZMR (mg/mi)	DR (mg/mi/10K mi)	ZMR (mg/mi)	DR (mg/mi/10K mi)
2007-2009	27.9	0.80	28.5	0.77
2010-2012	4.5	0.13	2.2	0.13
2013+	4.5	0.10	2.2	0.08

Emission rates for MHDDT of pre-2006 MYs were based on test data from the Coordinating Research Council E-55/59 project. Only a few late model MHDDT have been tested and thus there are not sufficient test data available to develop MHDDT's specific emission rates. As a result, the emission rates for MHDDT of 2007+ MY were derived by applying the ratio of 2003-2006 MY HHDDT to 2003-2006 MY MHDDT emission rates to 2007+ MY HHDDT as:

$$ER_{2007+\;MY\;MHDDT} = \frac{ER_{2007+\;MY\;HHDDT}}{ER_{2003-06\;MY\;HHDDT}} \times ER_{2003-06\;MY\;MHDDT} \qquad (5)$$

With the scaled MHDDT ER_{avg} and the EIR derived earlier, the PM ZMR and DR for the 2010-12 and 2012+ MY MHDDT were then calculated, as shown in Table 6.

Table 6: PM ZMR and DR for MHDDT in EMFAC2014 and EMFAC2017

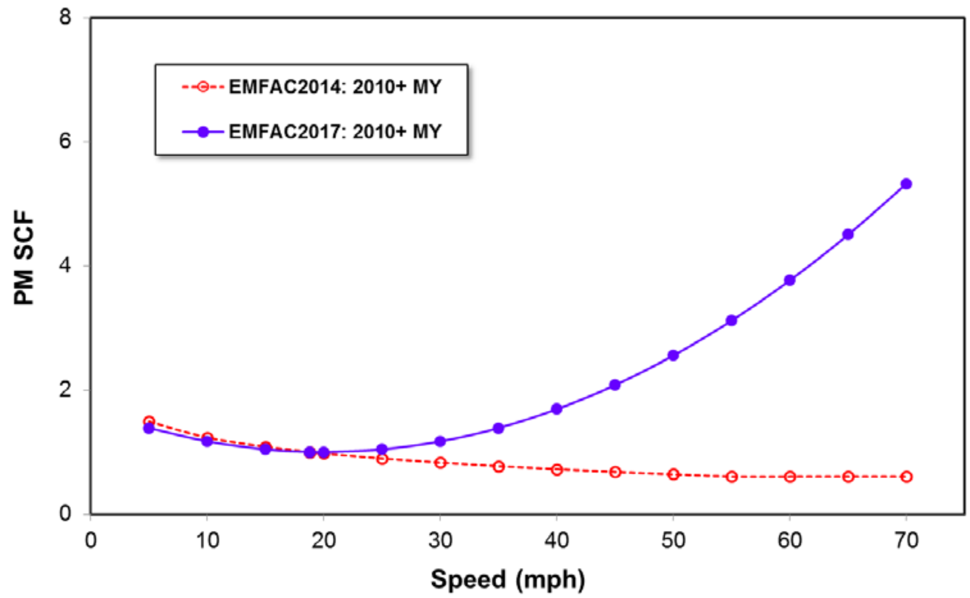
Engine Model Year	EMFAC2014		EMFAC2017	
	ZMR (mg/mi)	DR (mg/mi/10K mi)	ZMR (mg/mi)	DR (mg/mi/10K mi)
2007-2009	17.3	0.99	17.6	0.95
2010-2012	2.8	0.16	1.4	0.16
2013+	2.8	0.11	1.4	0.10

1.1.3 Updated PM Speed Correction Factor

As discussed earlier, EMFAC utilizes UDDS averaged emissions for specific MY groups to derive the ZMR and DR, over which an SCF is applied to arrive at running exhaust rates at different speeds per Eq. 1. An SCF for a pollutant is developed from pollutant-specific average ER's measured over several test cycles with different average speeds, and then normalized to the UDDS cycle.

PM SCF of HHDDTs was revised based on the test data from the EMA/UCR truck testing project and the CARB TBSP. In both testing projects, each test vehicle was run over the UDDS and several other test cycles (Table 1) on a chassis dynamometer and the PM in the exhaust was collected on a filter. The PM emission rates derived from all test vehicles were averaged for the individual test cycles and then normalized to the PM emission rate of the UDDS cycle to obtain the PM SCF. Figure 3 shows the revised HHDDT PM SCF curve and the curve used in EMFAC2014.

Figure 3: HHDDT PM speed correction factor curves for EMFAC2014 and EMFAC2017



The notable increase in SCF at the high speed end is mainly due to the high PM emission rates measured in some test runs over the High Speed Cruise cycle. As is the case with the ZMR and DR of MHDDT, no sufficient test data is available to develop an SCF curve for MHDDT, and therefore the SCF of HHDDT was used for MHDDT.

1.1.4 Updated PM emissions inventory of Diesel HDVs

The revised ZMRs, DRs, and SCF for PM, as described above, were coded into the EMFAC2017 model to obtain a baseline PM emissions inventory of diesel HDV (including HDD trucks and diesel buses). Table 7 gives the baseline statewide PM2.5 exhaust emissions inventories for selected calendar years.

Table 7: PM2.5 Emissions Inventory for Years 2019-2025 (in tons/day)

Calendar Year	EMFAC2017
2019	6.068
2020	4.933
2021	4.145
2022	2.367
2023	1.388
2024	1.418
2025	1.435

2. PM2.5 Emissions Benefits from Proposed Regulation

The proposed amendments to the HDVIP and PSIP regulation would require diesel powered trucks and buses that are found to exceed i) the 20-40 percent opacity limit for non-DPF vehicles to repair their engines and ii) 5 percent opacity limit for DPF-equipped engines to either repair or replace their DPFs in order to reduce the opacity below the respective limits. The PM emissions benefits are the result of such repairs or replacement.

In quantifying this reduction in PM emissions, it was assumed that once an engine is repaired or a DPF is repaired or replaced, the PM emissions would be reduced to the level when the truck or bus was new. In EMFAC, this is equivalent to a PM emissions level at the zero mile or ZMR when DR is zero. It was further assumed that, once all repaired diesel HDVs are back in service again, the emissions deterioration process would restart due to TM&M, similar to what their original equipment manufacturer OEM engines had experienced.

To calculate the PM2.5 emissions benefits, a baseline PM inventory is first calculated, and the baseline is then adjusted by applying a set of modified emission rates to produce a regulation PM inventory, i.e., a PM inventory with the assumption that the regulatory amendments are in place. To adjust the emission rates, staff estimated the fraction of diesel HDV that would likely be repaired due to the proposed amendments. Staff estimated the percentage of HDVs operating above the proposed opacity limits using data from the CARB's roadside testing campaigns. Staff then used the estimated repair rates to project the fraction of vehicles that would get repaired. The baseline emission rates were then adjusted accordingly by the fraction of diesel HDVs expected to get repairs to the ZMR to simulate the emissions decrease. Refer to Appendix D for a more detailed discussion on how staff estimated the number of vehicles that would likely be repaired as a result of the proposed amendments. This lowered the average PM emission rate of the diesel HDV fleet and, with the fleet activities remaining the same, resulted in a decrease in the PM emissions inventory. The PM emission benefit was then obtained by subtracting the regulation PM inventory from the baseline PM inventory.

Staff calculated the PM2.5 emission benefits for several selected calendar years starting 2019, the first year when the proposed regulation would be implemented. Table 8 gives the statewide PM2.5 emissions benefits estimated for the years 2019-2025.

Table 8: Statewide PM2.5 Emission Benefits (in tons/day)

Calendar Year	EMFAC2017	With Regulation	Emissions Benefit
2019	6.068	5.519	0.549
2020	4.933	4.319	0.613
2021	4.145	3.569	0.576
2022	2.367	1.928	0.439
2023	1.388	1.072	0.316
2024	1.418	1.076	0.342
2025	1.435	1.072	0.363