PM Speciation Profiles for Heavy Duty Diesel Vehicle Exhaust for Years 2010 to 2050

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1 Introduction

The current in-use ARB PM speciation profiles (PM6XXX) for heavy-duty diesel truck (HDDT), school bus (SB), and transit bus (TB) emissions were developed in 2011 based on various vehicle test data and EMFAC2011 model results [1, 2].

There are several on-road heavy-duty diesel engine emission standards which have been promulgated since 1974. Each standard is associated with differences in engine technology and after-treatment strategies, which could result in changes in emission factors and emission speciation. In addition, the heavy-duty diesel fleet for each calendar year (CY) contains vehicles equipped with engines complaint to different standards due to the California Truck and Bus Regulation [3]. Therefore, in order to reflect the effects of engine standards and regulation implementation, the speciation profiles for ARB heavy-duty diesel categories are made for each specific CY [1].

During the development of the PM6XXX profiles in 2011, the most up to date test engines were four 2007-compliant diesel engines used in Phase I of the Advanced Collaborative Emission Study (ACES). Hence, when the CY specific composite profiles were made for 2010 and later years, the 2010-compliant and newer engines in the fleet were characterized by the profiles of the 2007-compliant engines due to the data limitation. In 2013, Phase II of ACES released its final report of regulated and unregulated emission species from three 2010-compliance engines [4]. Meanwhile, the California on-road mobile inventory model EMFAC2014 was published last year. The emissions of heavy-duty diesel vehicles (HDDV) that were used to generate the PM6XXX profiles became outdated. Thus, it is time to update the diesel PM profiles by using the new ACES II test data for the 2010 engine speciation and the new EMFAC2014 HDDV emissions for the fleet distribution. This memo focuses on the new PM profiles PM7XXX created for HDDT, SB and TB for years 2010 through 2050. The PM7XXX profiles will replace the existing PM6XXX profiles for the associated heavy-duty diesel idle and running exhaust categories.

2 Methodology

2.1 MY/AT Speciation Profile

To characterize the effect of engine technology and after-treatment strategy on emission composition, the vehicles are classified into G1 to G8 model year/after-treatment (MY/AT) groups according to their engine model year and after-treatment situation (Table 1) [1]. In this work, after-treatment mainly refers to diesel particulate filter (DPF) and other emission control techniques to reduce tailpipe emissions. As shown in Table 1, G8 is defined for the vehicles with 2010-compliant diesel engines. When the PM6XXX profiles were developed, G7 profiles were used for both G7 and G8 groups, as mentioned previously.

Table 1. The list of model year/after-treatment (MY/AT) groups

Engine Model Year (MY)	Exhaust After-Treatment (AT)	
	without	with
Pre-1994	G1	G2
1994-2002	G3	G4
2003-2006	G5	G6
2007-2009	/	G7
2010 and newer	/	G8

ACES II was performed by Southwest Research Institute (SwRI) in 2010. A comprehensive characterization of regulated and unregulated emission species were conducted for three 2011 model year heavy heavy-duty diesel engines in this study. The engines were supplied by Cummins, Detroit Diesel, and Volvo and they all met 2010 emission standards. Speciation samples were collected and analyzed for engines running over the 16-hour driving cycle using ultra-low sulfur diesel fuel (ULSD) [5].

The following steps were employed to create individual speciation profiles for the three test engines. The profile numbers are D20078, D20079 and D20080, respectively.

- Non-Carbon Organic Matter (NCOM) is calculated by subtracting organic carbon (OC) from organic matter (OM) which can be estimated from OC by multiplying the ratio of OM/OC. A default OM/OC ratio of 1.4 is applied for the diesel PM [6].
- A species group named ‘other’ is created to capture the mass of oxygen associated with the five geological elements (i.e., Al, Si, Ca, Fe, and Ti) using the following formula:

  $$0.89\times[Al]+1.14\times[Si]+0.40\times[Ca]+0.43\times[Fe]+0.67\times[Ti]$$

  where *[Al], [Si], [Ca], [Fe] and [Ti]* are weight fractions of these five elements, respectively [7].

- Calculate the species of non-sulfate sulfur, insoluble chlorine, and insoluble potassium to avoid double-counting mass if sulfate and sulfur, chloride and chlorine, and potassium ion and potassium exist in the same profile. Resulting negative values are set to zero [7];
- For mass balance, a species named 'unknown' is added to the profiles to make the total weight fractions of all species add up to 1.0.

The details of these individual profiles D20078, D20079 and D20080 are saved in the ARB internal diesel PM profile database '*DieselPM.mdb*'. The average of the three profiles was calculated to be the new MY/AT profile for G8 group, PM4278, which is also saved in the DieselPM.mdb database.

The PM standards for 2010 and 2007 engines are the same (0.01 g/bhp-hr), but the NOx standard for 2010 is more stringent than the 2007 standard (0.2 vs. 1.2 g/bhp-hr). To meet the 2010 NOx standards, a urea-based selective catalytic reduction (SCR) system was introduced to the exhaust downstream of the DPF for NOx reduction. An ammonia oxidation (AMOX) catalyst was also added downstream of the SCR to minimize ammonia slip [5]. With the addition of SCR and AMOX, the 16-hour cycle tests detected a much lower level of PM emissions from the 2010 engines and a very different PM composition compared to the PM emissions from the 2007 engines (Figure 1). For the 2010-compliant engines, the PM is dominated by OC followed by element carbon (EC) and nitrate, while sulfate is almost half of the 2007 engine PM followed by OC and EC. This is probably due to the lack of active DPF regeneration during the 2010 engine tests, whereas it did occur for the 2007 engines tested in the Phase I ACES study. The PM composition in the 2010 engines also showed some level of nitrate that was absent from the PM in 2007 engines. Nitrate is likely to be a derived product of the urea and SCR system interactions [4].

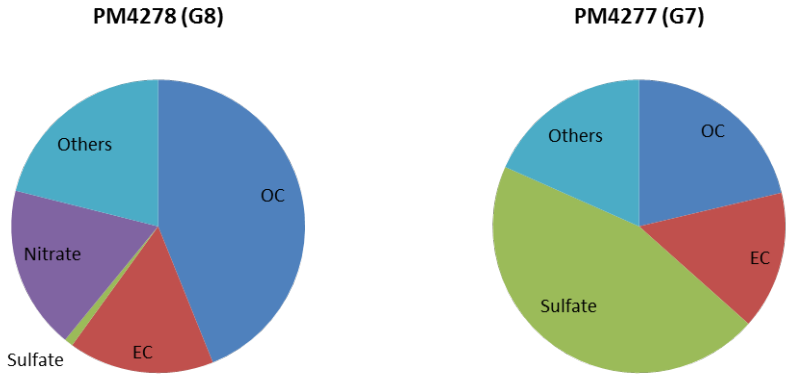


Figure 1. PM composition comparison: PM4278 (G8, 2010 engines) vs. PM4277 (G7, 2007 engines)

2.2 Fleet composition from EMFAC2014

The EMFAC model calculates emission inventories for motor vehicles operating on roads in California. The distribution of PM emissions from G1 to G8 groups that was used to develop the PM6XXX profiles was obtained from EMFAC2011. The newly released EMFAC2014 has been incorporated with updated emission factors for Class 8 diesel trucks that are certified to 2007 and 2010 engine standards. It also reflects the state and federal regulations and standards, including the ones adopted or amended after EMFAC2011 was released. One of the most important regulations is the California Truck and Bus Rule, which requires HDDVs to be retrofitted with DPFs or replaced with trucks having 2007 or 2010 engines; nearly all trucks and buses need to have 2010 engines or equivalent by January 2023 [3]. In general, EMFAC2014 predicts lower emissions for 2020 and later years compared to EMFAC2011[8]. The distribution of $PM_{2.5}$ emitted from G1 to G8 HDDV is plotted in Figure 2. It is shown that emissions from the G7 group are dramatically reduced from year 2023 and over 80% of the $PM_{2.5}$ emissions are contributed by G8 group after 2023. It also indicates that all G1 vehicles are retired from the fleet after year 2023. The emission distribution as illustrated in Figure 2 is used for the development of the new CY specific composite profiles PM7XXX.

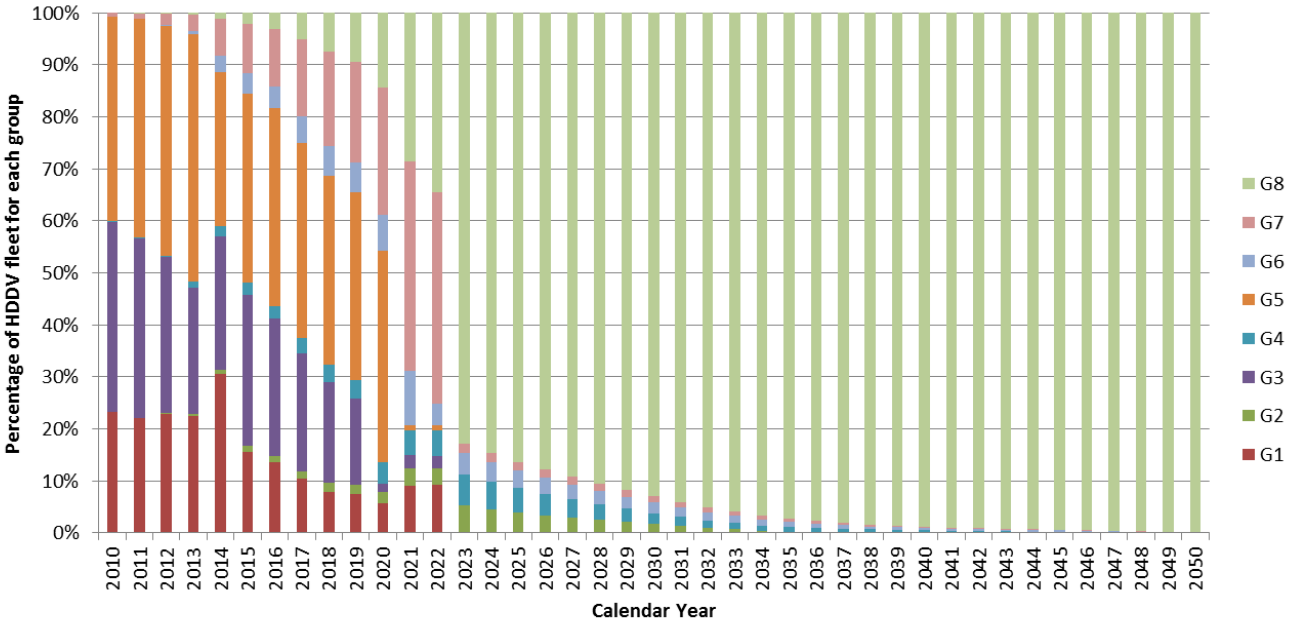


Figure 2. Distribution of $PM_{2.5}$ emissions for G1 to G8 HDDV

2.3 Calendar Year (CY) Specific Composite Profiles

To reflect the effects of engine standard and after-treatment technologies on PM speciation and regulation implementation, the following equation is used to calculate the CY specific composite profiles PM7XXX:

$$F_{Y_k}^{S_j} = \sum_{i=1-8} (F_{G_i}^{S_j} \times P_{G_i}^{Y_k}) \qquad \text{(Equation 1)}$$

where,

$F_{Y_k}^{S_j}$: weight fraction of Species *j* in the CY profile for Year *k.* For example, F_{2020}^{EC} represents the weight fraction of *EC* in the *2020* composite profile;

$F_{G_i}^{S_j}$: weight fraction of Species *j* in the MY/AT profile for Group *Gi (i=1, 2, 3, 4, 5, 6, 7, and 8).* For example, F_{G8}^{EC} represents the weight fraction of *EC* in the MY/AT profile for *G8*, i.e., PM4278. All the MY/AT profiles are available in the DieselPM.mdb database;

$P_{G_i}^{Y_k}$: fraction of Group *Gi* over the whole fleet including G1 to G8 groups for Year *k*, weighted by PM mass. For example, P_{G8}^{2020} represents the weight fraction of PM emitted from G8 over the PM emissions from all G1 to G8 groups. These values are calculated from EMFAC2014.

The ARB HDDV categories include 30 EICSUBs (emission inventory code—subcategories). In order to match the EICSUBs with the profile-related driving cycles, the EICSUBs are classified into cruise-type groups and transient-type groups (Appendix 1) based on assumed EICSUB-related driving characteristics [1]. The cruise-type group includes the long-haul trucks that travel mostly on the highway; and the transient-type group includes the vehicles that are typically driven locally, such as, utility trucks, public trucks, and solid waste collection vehicles. All the buses including SB and TB are classified into the transient-type group. In addition, there are two source categories, idle exhaust and hot stabilized exhausts, associated with each EICSUB in our inventory. Therefore, the following seven composite profiles are created for HDDV for each year to meet our needs: HDDT-idle (PM7XX1), HDDT-cruise (PM7XX2), HDDT-transient (PM7XX3), SB-idle (PM7XX4), SB-transient (PM7XX5), TB-idle (PM7XX6), and TB-transient (PM7XX7). The two digits in the middle of each profile number are used to indicate the specific CY. For example, PM7<u>10</u>1 is the HDDT-idle profile for 20<u>10</u>, and PM7<u>20</u>2 is the HDDT-cruise profile for 20<u>20</u>. The MY/AT profiles used in Equation 1 to calculate CY profiles for different vehicle types and driving cycles are summarized in Table 2.

Table 2. Mapping of MY/AT profiles used to develop CY profiles

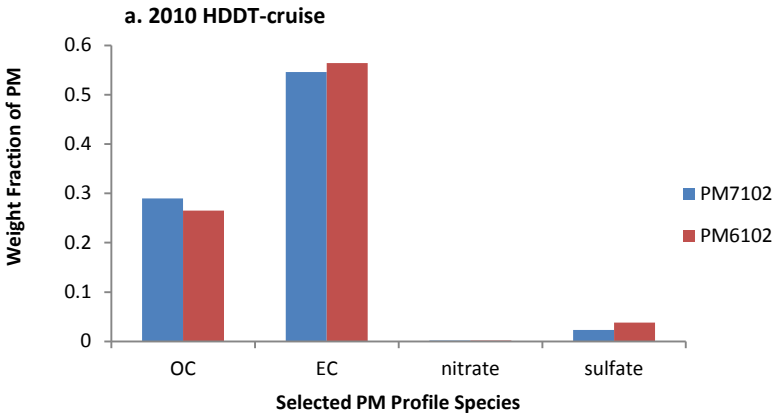
Vehicle Type	Cycle	MY/AT							
		G1	G2	G3	G4	G5	G6	G7	G8
HDDT	Idle	4252	4258	4255	4258	4271	4258	4277	4278
	Cruise	4253	4259	4256	4259	4262	4259	4277	4278
	Transient	4254	4260	4257	4260	4263	4260	4277	4278
SB	Idle	4252	4258	4255	4258	4271	4258	4277	4278

	Transient	4254	4260	4264	4260	4263	4260	4277	4278
TB	Idle	4252	4258	4255	4258	4271	4258	4277	4278
	Transient	4269	4260	4271	4260	4263	4260	4277	4278

3 Results and Discussion

With all the information available, including the fleet composition, the MY/AT profiles, and the mapping of the MY/AT profiles (Table 2), the CY profiles for HDDT, SB, and TB are then calculated for each year from 2010 to 2050. The profile numbers and names are assigned in Appendix 2. The details of these CY profiles PM7XXX are stored in the database DieselPM.mdb.

Because the new profiles are generated using the most up-to-date emission model data and the latest engine test data, they should be more representative of the real world situation than the current profiles. In this memo, the HDDT-cruise profiles for years 2010, 2020 and 2030 are selected for comparisons between the new profiles PM7XXX and the existing profiles PM6XXX. Figure 3a shows that the two 2010 profiles, PM7102 vs. PM6102, are very close. Since 2010 is the first year that G8 vehicles started to enter the fleet, their extreme low emissions didn't have much impact on the composite PM speciation. As for year 2020, Figure 2 indicates that about 15% of the PM emissions are from G8 vehicles. The new profile and the current profile exhibit big differences in EC and sulfate fractions (Figure 3b). PM7202 has over 40% EC but PM6202 has less than 20% EC; instead, PM7202 has a much less sulfate content than PM6202. For year 2030, over 90% of the fleet PM emissions are contributed from G8 vehicles, thus the G8 profile dominates the new composite profile PM7302. Since the G7 profile was used for G8 vehicles to make PM6302, the changes from PM6302 to PM7302 are roughly the differences between G7 and G8 profiles (Figure 3c). The replacement of PM6302 with PM7302 will result in about 100% increase in OC and nearly 100% decrease in sulfate. There will also be an addition of nitrate if the new profile is used.



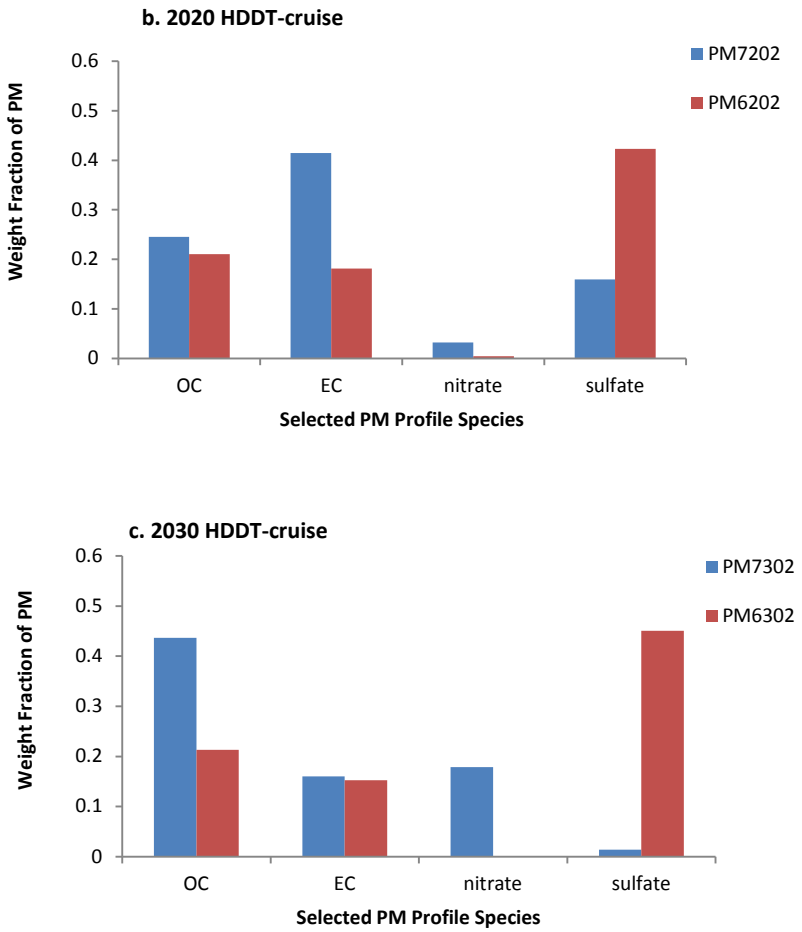


Figure 3. Major model species in new and current profiles for years 2010, 2020 and 2030

References:

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3. *California Code of Regulations, Regulation to Reduce Emissions of Diesel Particulate Matter, Oxides of Nitrogen and Other Criteria Pollutants from In-Use Heavy-Duty Diesel-Fueled Vehicles. Section 2025*, in *Title 13*: Sacramento, CA.
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6. Reff, A., et al., *Emissions Inventory of PM2.5 Trace Elements across the United States.* Environmental Science & Technology, 2009. **43**(15): p. 5790-5796.
7. Allen, P., *Developing PM Species Profiles for Emission Inventory*, 2008.
8. *EMFAC2014 Technical Documentation*, 2015, California Air Resources Board.

Appendix 1. 2011 HDDV EICSUB categories

EICSUB Name	Note	Characteristic Driving Cycle	Vehicle Type
Motor Coach	Motor coach	Cruise	HDDT
PTO	Power take off		
T6 Ag	T6 Agricultural		
T6 CAIRP heavy	T6 CA registered but travel interstate, heavy		
T6 CAIRP small	T6 CA registered but travel interstate, small		
T6 instate construction heavy	T6 instate construction industry, heavy		
T6 instate construction small	T6 instate construction industry, small		
T6 instate heavy	T6 instate, heavy		
T6 instate small	T6 instate, small		
T6 OOS heavy	T6 Out of state vehicles (not registered in CA), heavy		
T6 OOS small	T6 Out of state vehicles (not registered in CA), heavy		
T7 Ag	T7 Agricultural		
T7 CAIRP	T7 CA registered but travel interstate		
T7 CAIRP construction	T7 CA registered but travel interstate, construction industry		
T7 NNOOS	T7 From non-neighboring states (not registered in CA)		
T7 NOOS	T7 From neighboring states (not registered in CA)		
T7 other port	T7 Drayage trucks serving other ports		
T7 POAK	T7 Drayage trucks serving ports of Oakland area		
T7 POLA	T7 Drayage trucks serving ports of LA/LB area		
T7 tractor	T7 Truck tractor		
T7 tractor construction	T7 Truck tractor, construction industry		
T6 public	T6, State and local government agencies	Transient	
T6 utility	T6, Privately owned utility company		
T7 public	T7 State and local government agencies		
T7 Single	T7 Single unit or straight trucks		
T7 single construction	T7 Single unit construction industry		
T7 SWCV	T7 Solid waste collection vehicles		
T7 utility	T7 Privately owned utility company		
SBUS	School bus	Transient	SB
All Other Buses	All other buses	Transient	TB

Appendix 2. List of CY profile numbers and names for HDDT, SB and TB

Calendar Year	Heavy Heavy-Duty Diesel Truck			School Bus		Transit Bus	
	idle	cruise	transient	idle	transient	idle	transient
2010	7101	7102	7103	7104	7105	7106	7107
2011	7111	7112	7113	7114	7115	7116	7117
2012	7121	7122	7123	7124	7125	7126	7127
2013	7131	7132	7133	7134	7135	7136	7137
2014	7141	7142	7143	7144	7145	7146	7147
2015	7151	7152	7153	7154	7155	7156	7157
2016	7161	7162	7163	7164	7165	7166	7167
2017	7171	7172	7173	7174	7175	7176	7177
2018	7181	7182	7183	7184	7185	7186	7187
2019	7191	7192	7193	7194	7195	7196	7197
2020	7201	7202	7203	7204	7205	7206	7207
2021	7211	7212	7213	7214	7215	7216	7217
2022	7221	7222	7223	7224	7225	7226	7227
2023	7231	7232	7233	7234	7235	7236	7237
2024	7241	7242	7243	7244	7245	7246	7247
2025	7251	7252	7253	7254	7255	7256	7257
2026	7261	7262	7263	7264	7265	7266	7267
2027	7271	7272	7273	7274	7275	7276	7277
2028	7281	7282	7283	7284	7285	7286	7287
2029	7291	7292	7293	7294	7295	7296	7297
2030	7301	7302	7303	7304	7305	7306	7307
2031	7311	7312	7313	7314	7315	7316	7317
2032	7321	7322	7323	7324	7325	7326	7327
2033	7331	7332	7333	7334	7335	7336	7337
2034	7341	7342	7343	7344	7345	7346	7347
2035	7351	7352	7353	7354	7355	7356	7357
2036	7361	7362	7363	7364	7365	7366	7367
2037	7371	7372	7373	7374	7375	7376	7377
2038	7381	7382	7383	7384	7385	7386	7387
2039	7391	7392	7393	7394	7395	7396	7397
2040	7401	7402	7403	7404	7405	7406	7407
2041	7411	7412	7413	7414	7415	7416	7417
2042	7421	7422	7423	7424	7425	7426	7427
2043	7431	7432	7433	7434	7435	7436	7437
2044	7441	7442	7443	7444	7445	7446	7447
2045	7451	7452	7453	7454	7455	7456	7457
2046	7461	7462	7463	7464	7465	7466	7467
2047	7471	7472	7474	7474	7475	7476	7477
2048	7481	7482	7483	7484	7485	7486	7487
2049	7491	7492	7493	7494	7495	7496	7497
2050	7501	7502	7503	7504	7505	7506	7507