Heavy Duty Diesel Vehicle Exhaust PM Speciation Profiles

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Acronyms and Abbreviations

16-hour Cycle	ACES Study 16-hour Driving Cycle
ARB	Air Resources Board
AT	After-treatment
CARB 5-Modes	California Air Resources Board 5-Modes Cycle
CAIRP	California Registered But Travel Interstate
CBD	Central Business District Cycle
CCRT	Catalyzed Continuously Regenerating Technology
CCS	Cold Start City Suburban Heavy Vehicle Route
CDPF	Catalyzed Diesel Particulate Filter
CLSF	Conventional Low Sulfur Fuel
CRT	Continuously Regenerating Technology
CSHVR	City Suburban Heavy Vehicle Route
CY	Calendar Year
DOC	diesel oxidation catalyst
DPF	Diesel Particulate Filter
DPX	A Trademark for Engelhard Diesel Particulate Filter
E	Engine
EC	Elemental Carbon
ECD	Emission Control Diesel
ECD-1	Emission Control Diesel-1
EGR/CGI	exhaust gas recirculation/clean gas induction
EICSOU	Emission Inventory Code--Source Category
EICSOU-764	Diesel Hot Stabilized Exhaust
EICSOU-765	Diesel Idle Exhaust
EICSUB	Emission Inventory Code Subcategory
EPF	Electric Diesel Particulate Filter
F-T	Laporte Fischer-Tropsch Diesel Fuel
FTP	Federal Test Procedure Heavy-Duty Transient Cycle
HCS	Hot Start City Suburban Heavy Vehicle Route
HDDT	Heavy-Duty Diesel Truck
HDDV	Heavy-Duty Diesel Vehicle
HW	Highway Cycle

LSD	Low Sulfur Diesel
MC	Manhattan Bus Cycle
MY	Model Year
NNOOS	From Non-Neighboring States (not registered in California)
NOOS	From Neighboring States (not registered in California)
OC	Organic Carbon
OM	Organic Matter
OOS	Out of State Vehicles (not registered in California)
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with Aerodynamic Diameter less than 2.5 µm
PM_{10}	Particulate Matter with Aerodynamic Diameter less than 10 µm
POAK	Drayage Trucks Serving Ports of Oakland Area
POLA	Drayage Trucks Serving Ports of LA/LB Area
PTO	Power Take Off
SB	School Bus
SWCV	Solid Waste Collection Vehicles
T6	Medium-Heavy-Duty Diesel Vehicle
T7	Heavy-Heavy-Duty Diesel Vehicle
TB	Transit Bus
TPM	Total Particulate Matter
UDDS	EPA Urban Dynamometer Driving Schedule
ULSD	Ultra Low Sulfur Diesel
V/E	Vehicle/Engine

1 Introduction

1.1 Background and Objective

For the purposes of emission inventory and air quality modeling, there is currently only one official ARB diesel exhaust PM speciation profile (PM 425—Diesel Vehicle Exhaust) for all diesel related emission categories and all emission inventory years [1]. This PM profile was created based on source tests conducted on diesel tractors more than 20 years ago under ARB research contract A6-175-32 [2].

In December 2008, ARB approved a new regulation known as the Truck and Bus Regulation to significantly reduce emissions from trucks and buses operating in California. On-road heavy-duty diesel fueled vehicles (HDDV) are subject to the regulation. The emission inventory for the heavy-duty diesel trucks (HDDT) has been updated to reflect the changes in fleet composition caused by the regulation. The existing diesel PM speciation profiles and profile assignments to emission inventory categories that reflect the regulation need to be updated correspondingly.

To facilitate representing the effect of the regulation in profile assignments, the medium-heavy-duty (T6) and heavy-heavy-duty (T7) vehicle inventory was split into eight population groups based on engine model year (MY) and regulation-related aftertreatment (AT) strategies. In this work, “aftertreatment techniques” refers to vehicles having a diesel particulate filter (DPF) installed. The eight Model Year/Aftertreatment (MY/AT) groups for which profiles are developed are listed in Table 1.

Table 1. Eight Model Year/Aftertreatment (MY/AT) Groups

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

Under the Truck and Bus Regulation, there are 1998, 2004, 2007 and 2010 on-road diesel engine emission standards, and each standard is associated with differences in emission control strategy and aftertreatment strategy. Since these differences yield differences in both emissions mass and composition, speciation profiles are developed for each of the eight MY/AT groups above. Additionally, the proportion of the fleet subject to each of these standards will change from year to year. As a result, in order to replace the currently assigned profile (PM425) for a certain calendar year (CY) with a single profile that reflects implementation of the Truck and Bus Regulation, a year-specific profile is created via a weighted average of these eight MY/AT group profiles. The weighting scheme is based upon the year-specific fleet composition for each of the groups. To illustrate this, a year-specific summary of MY/AT group distribution is provided in

Figure 1, which depicts the change of MY/AT combinations associated with the implementation of the Truck and Bus regulation over time.

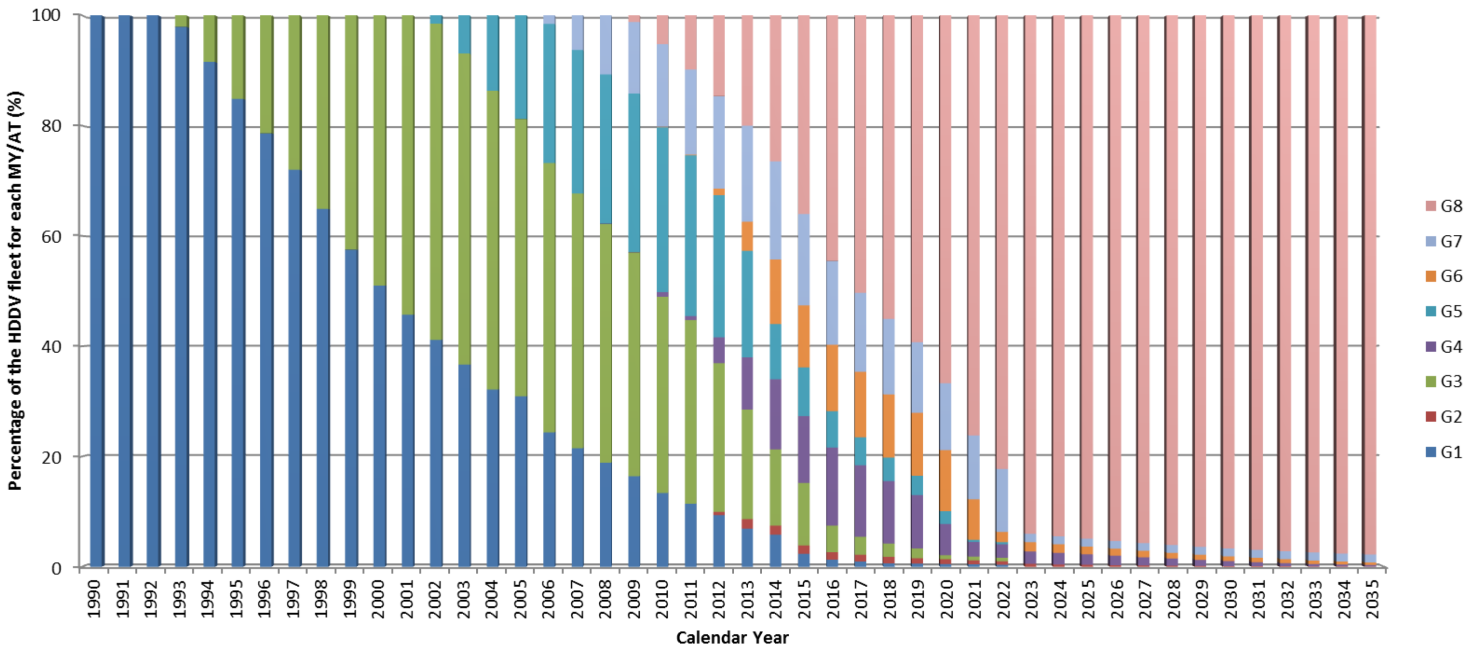

Figure 1. **MY/AT group distribution of the HDDT-T7 fleet based on daily population [3]**

1.2 Methodology

1.2.1 Development of Intermediate Profiles

A comprehensive review was conducted on recently published source testing studies involving diesel vehicle PM speciation. Over one hundred detailed profiles were developed based on the selected test data. These detailed, study-specific profiles were then grouped into the previously mentioned MY/AT groups for consideration in creating a MY/AT group-specific composite. Thus, the study-specific profiles are termed 'intermediate' profiles because they are only considered as inputs to creating the composite/average MY/AT group profiles but are not used directly. The source testing studies and profiles are summarized in Table 2. The following previously established steps were implemented during intermediate profile development [4]:

- Convert OC (organic carbon) to OM (organic matter) by multiplying by a factor of 1.4, which is traditionally used[5];
- Create a species group called 'others' to capture the mass associated with the five geological elements (i.e. Al, Si, Ca, Fe and Ti) by using the formula of $0.89 \times [Al] + 1.14 \times [Si] + 0.40 \times [Ca] + 0.43 \times [Fe] + 0.67 \times [Ti]$ where *[Al]*, *[Si]*, *[Ca]*, *[Fe]* and *[Ti]* are weight percentages of these five elements, respectively[4].
- Calculate the species of non-sulfate sulfur (non-SO_4 S), insoluble chlorine (insol-Cl), and insoluble potassium (insol-K) to avoid double-counting mass[4] if both sulfate and sulfur,

chloride and chlorine, and potassium ion and potassium exist in the same profile. Resulting negative values are set to zero;

- Calculate the weight percentage for each species.

The resulting, study-specific profiles are based on tests conducted under very specific vehicle configurations and specific test conditions. As mentioned above, they represent the intermediate profiles that are used in the composite averaging process for making the MY/AT composite profiles. The 100+ intermediate profiles are numbered starting with the letter 'D' (for diesel) and are referred to in Table 2, Table 7, Table 8, Table 9 and Table 10. Since they are intermediate profiles, they will not be added to the ARB speciation profile database.

1.2.2 Development of MY/AT profile

The current ARB emission inventory has two EICSOUs (Emission Inventory Code--Source Category) related to diesel vehicle exhaust: *Diesel Hot Stabilized Exhaust* (764) and *Diesel Idle Exhaust* (765). To get the emissions of the detailed species for modeling use, speciation profiles that match with these categories are needed. However, because the intermediate, 'D'-profiles are made based on very specific vehicle configurations and test conditions, they need to be composited to the profiles that represent general 'stabilized exhaust' and 'idle exhaust'. Section 2 (MY/AT Speciation Profiles) describes the approach used to composite the intermediate 'D'-profiles. These composite profiles are made for different MY/AT combinations, and they will be added to the ARB speciation profile database. The composited MY/AT profile numbers start with '4'. If the profile is appropriate for the MY/AT combination, it is numbered with four digits ('4XXX'); whereas, ***if the profile has limitations or conditions associated with its recommended use for a MY/AT combination, then t is numbered with five digits ('4XXXX')***. For example, Profile 4252 is for use with HDDT-G1-Idle; and Profile 42651 is *conditionally developed, with limitations* for application to SB-G4-Transient (DPX). The MY/AT profiles are shown in Table 5-Table 13.

1.2.3 Development of composite calendar year (CY) profiles

Due to the Truck and Bus Regulation, the HDDV fleet structure changes every calendar year (CY). In order to reflect such changes, the CY-specific profiles need to be created based upon year-specific fleet information. Section 1 provides the compositing methodology. These resulting CY-specific profiles are added to the ARB profile database, and their numbers start with '6' (Table 14).

1.3 Data Sources

Although source testing datasets for use in determining *emission factors* for PM mass and EC/OC from HDDV exhaust are relatively abundant, studies having sufficient test data for developing PM speciation profiles are limited, especially for newer vehicles and vehicles equipped with DPFs. As such, test results from the following ten studies were selected and used in this work. These studies and the intermediate profiles that are developed based on study-specific data are listed in Table 2:

Table 2. Selected Studies and Associated Intermediate* Profiles

No.	Name of Study	Intermediate* Profile No.
1	ARB Physiochemical and Toxicological Properties of Emissions from Heavy- and Light-Duty Vehicles [6]	D20053-D20055 D20057-D20070
2	CRC E55/59 Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics (Phases 1, 1.5 and 2) [7]	D20017-D20052
3	Speciation of Organic Compounds from the Exhausts of Trucks and Buses: Effect of Fuel and After-Treatment on Vehicle Emission Profiles [8, 9]	D20001-D20016
4	Advanced Collaborative Emissions Study (Phase I) [10]	D20071-D20074
5	Gasoline-Diesel PM Split Study [11]	D10001-D10010
6	Chemical composition of emissions from urban sources of fine organic aerosol [12]	D10011
7	Characterization of Heavy-Duty Diesel Vehicle Emissions [13]	D10012-D10016
8	Gaseous and Particulate Matter Emissions from Two In-Use Urban Transit Buses [14]	D10017-D10022
9	Evaluation of Factors That Affect Diesel Exhaust Toxicity [15]	D10023-D10028
10	Effects of a Catalyzed Particulate Filter on Emission from a Diesel Engine: Chemical Characterization Data and Particulate Emissions Measured with Thermal Optical and Gravimetric Methods [16]	D10029-D10032

**Intermediate profiles are used in the calculation of composite average profiles, they are not used directly.*

2 MY/AT Speciation Profiles

Over one hundred intermediate diesel PM speciation profiles were developed directly based on data from the ten studies mentioned earlier [6-16] (Table 2). The resulting intermediate profiles are stored in the database DieselPM.mdb (Appendix 2, available upon request). Various vehicle types, engine model years, aftertreatments, diesel fuels and test cycles are covered by these profiles (Table 3).

Table 3. Coverage of the PM Speciation Profiles Developed Based on Selected Studies

Field	Contents
Test Type	Chassis dynamometer (HDDT, SB and TB), Engine dynamometer
Engine Model Year	from 1984 to 2007
Aftertreatment	Non-aftertreatment; Aftertreatment: trap, PM filter, oxidant catalyst, CRT, CCRT, V-SCRT, Z-SCRT, DPX, EPF, EGR/CGI + (DOC)CDPF
Diesel Fuel & Sulfur Content	Diesel 2, Jet A, CLSF, ECD, ECD-1, F-T, low aromatic diesel, pre-93 diesel, reformulated diesel; 5000 ppm (Pre-93 fuel); < 500 ppm (low sulfur diesel, LSD); < 15 ppm (ultralow sulfur diesel, ULSD)
Test Cycle	Idle, creep, cruise, HW, CBD, CCS, HCS, CSHVR, FTP, MC, transient, UDDS, CARB 5-modes, 16-hour (Appendix 1).

Composite averages of the intermediate profiles are based on the emissions inventory categorization. In the current ARB emission inventory, there are two EICSOUs related to diesel vehicle exhaust: *Diesel Hot Stabilized Exhaust* (764) and *Diesel Idle Exhaust* (765). To accommodate assigning profiles to these two EICSOU's, the 100+ intermediate profiles are composited into more generic profiles using the following three steps:

1. *Determine the <u>vehicle/engine type</u>* ***(V/E)*** *tested.* All of the intermediate speciation profiles are classified into four vehicle/engine (V/E) types: HDDT, school bus (SB), transit bus (TB) and engine (E). There are two types of dynamometers used in the source testing studies: chassis and engine. A chassis dynamometer provides resistance via one or two rollers that a vehicle's drive wheels sit on (i.e. where the entire vehicle is driven onto a platform and the drive wheels sit on one- or two drums which are connected to a dynamometer). So, chassis dynamometer testing takes the entire drive train, down to the wheels and tires, of a vehicle into account. Engine dynamometers are mounted directly to a bare engine for testing (i.e. a vehicle or drive train is not involved). The profiles for HDDT, SB and TB are developed based on chassis dynamometer tests, and the profiles for engines are made based on engine dynamometer tests.

2. *Determine the associated vehicle/engine - model year/aftertreatment* ***(V/E-MY/AT)*** *combinations.* The profiles in each V/E type are sorted based on their MY/AT information. For example, there are profiles for four *V/E-MY/AT* combinations for HDDT: HDDT-G1, HDDT-G3, HDDT-G4 and HDDT-G5.

3. *Determine the driving cycle used for source testing* ***(Cycle)****.* In each V/E-MY/AT group, there are intermediate profiles from source testing studies covering a variety of driving cycles (i.e., idle, cruise, CSHVR, UDDS, transient, and others). To take this into account, profiles of the same V/E-MY/AT are categorized into three generic driving cycles: idle, cruise and transient. A summary of how driving cycle test conditions are grouped into a 'generic cycle' for compositing the intermediate profiles is provided in Table 4. The composition of emissions during idling is different from other driving cycles. So, a generic 'idle' mode is used that includes the idle cycle along with the low speed creep test cycle and the idle/creep test cycle. In addition to the idle driving cycle, experts suggest having 'cruise' mode- and 'transient' mode driving cycles. This is because many of the physical and chemical transformations in the exhaust emissions are driven by temperature which is a strong function of driving cycle. The most critical differences in speciation come from cruise vs. transient operation. For the 'cruise' generic driving cycle group, intermediate profiles developed from tests conducted under the HW and cruise driving cycles are combined. For the 'transient' mode driving cycle group, intermediate profiles are combined from the FTP transient, HDDT transient, CBD, CSHVR (including CCS, HCS), UDDS, MC, CARB-5, and 16-hour driving cycle tests. For example, there are three composite V/E-MY/AT-Cycle profiles for HDDT-G1: HDDT-G1-idle, HDDT-G1-cruise, and HDDT-G1-transient. The fuel used is also taken into account in this step.

Table 4. Classification of driving cycles under which intermediate profile data are collected

Assigned Generic Driving Cycle for Compositing Profiles	As-Tested Driving Cycles
Idle	idle
	low speed creep
	idle/creep
Cruise	cruise
	HW cycle
Transient	FTP transient
	HDDT transient
	CBD
	CSHVR (including CCS, HCS)
	UDDS
	MC
	CARB-5modes
	16-hour

Based on the three steps described above and the available data, 28 composite V/E-MY/AT-Cycle speciation profiles (Table 5) are created.

Table 5. List of 28 Composite V/E-MY/AT-Cycle speciation profiles (number) developed in this work

V/E Type	Generic Cycle	MY/AT							
		G1	G2	G3	G4	G5	G6	G7	G8
HDDT	Idle	4252	/	4255	4258	4261	/	/	/
	Cruise	4253	/	4256	4259	4262	/	/	/
	Transient	4254 *42541(pre93)*	/	4257	4260	4263	/	/	/
SB	Idle	/	/	/	/	/	*42661(uncat*)*	/	/
	Cruise	/	/	/	/	/	*42671(uncat)*	/	/
	Transient	/	/	4264	*42651(DPX)*	/	*42681(uncat)*	/	/
TB	Idle	/	/	/	/	/	/	/	/
	Transient	4269	*42701(old tech)*	4271	*42721(CRT)* *42722(old tech)*	/	*42731(hybrid)*	/	/
E	Cruise	/	/	4275	4276	/	/	/	/
	Transient	4274	/	/	/	/	/	4277	/

*Note: uncat is uncatalyzed DPF.

The profile development for each individual V/E-MY/AT-Cycle group is discussed in the following sections: Section 2.1 (HDDT), Section 2.2 (SB), Section 2.3 (TB) and Section 2.4 (E). The complete detailed set of profiles is stored in database DieselPM.mdb (Appendix 2), which is available upon request.

*Please note that, for the purpose of quick reference and relative comparison, all figures and tables summarizing the profiles in this report are illustrated using a condensed set of the 5 species groups used for air quality modeling: organic compounds (**OM**), elemental carbon (**EC**), **sulfate**, **nitrate** and all **others**. The detailed species are actually carried in the profiles.*

Figure 2 and Table 6 provide an overview of the resulting V/E-MY/AT-Cycle composite profiles. Generally speaking, EC and OM dominate the PM emitted from non-DPF vehicles. As can be seen, by employing DPF aftertreatment, the EC fraction is greatly decreased (from around 0.5 or more to less than 0.2), and OM becomes the most abundant species. Also, sulfate and nitrate fractions are significantly higher in DPF-related profiles than in non-DPF profiles.

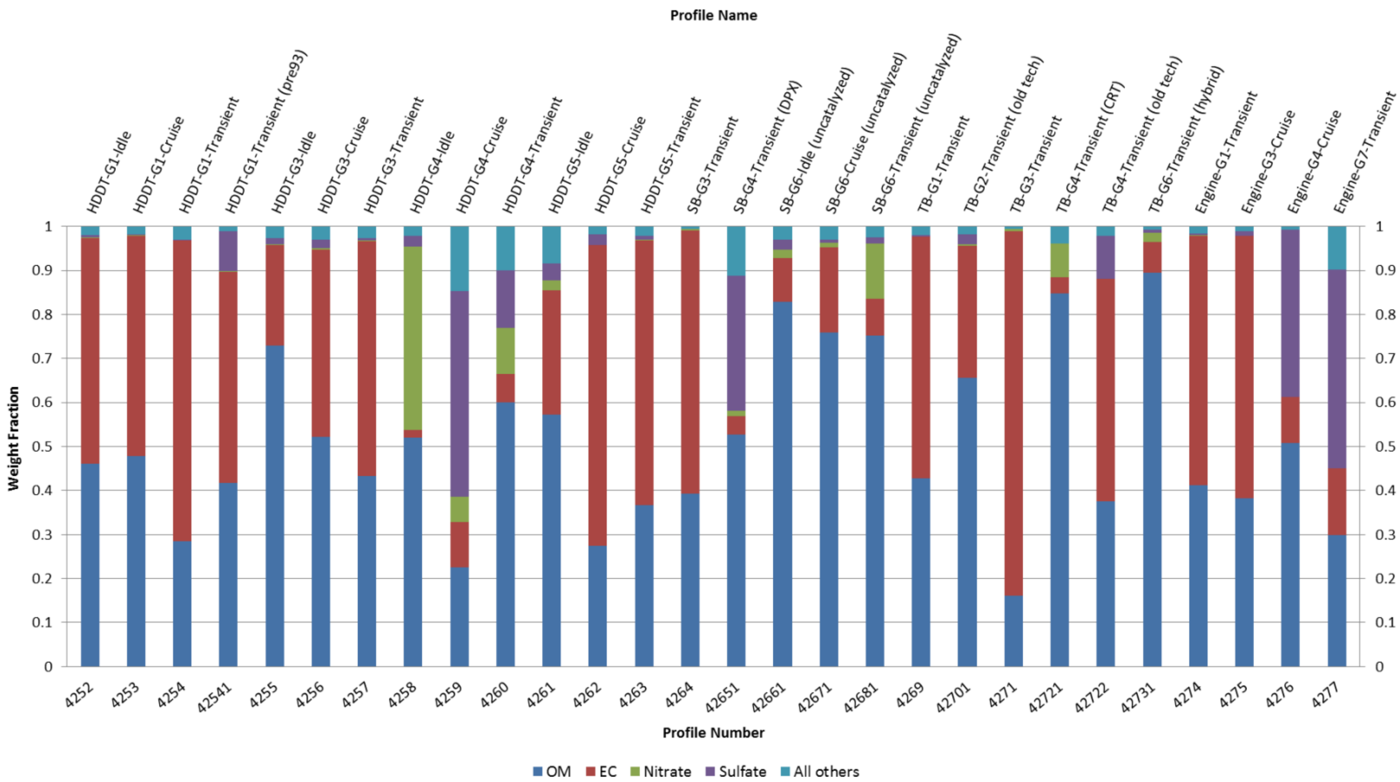

Figure 2. Summary of the 28 composite V/E-MY/AT-Cycle speciation profiles (Based on a condensed set of the 5 species used in air quality modeling. Detailed species are maintained in the actual profiles.)

Table 6. Composite V/E-MY/AT-Cycle profiles (summarized as five PM modeling species)

Profile No.	Profile Name	Weight Fraction of Modeling Species				
		OM	EC	Nitrate	Sulfate	All other species
4252	HDDT-G1-Idle	0.4612 *(±0.1559)*	0.5122 *(±0.1723)*	0.0026 *(±0.0041)*	0.0047 *(±0.0056)*	0.0192 *(±0.0194)*
4253	HDDT-G1-Cruise	0.4782 *(±0.0272)*	0.5011 *(±0.0324)*	0.0012 *(±0.0017)*	0.0026 *(±0.0025)*	0.0169 *(±0.0159)*
4254	HDDT-G1-Transient	0.2856 *(±0.1325)*	0.6824 *(±0.1337)*	0.0006 *(±0.0006)*	0.0023 *(±0.0035)*	0.0292 *(±0.0283)*
42541	HDDT-G1-Transient (pre93)	0.4174 *(±0.0504)*	0.4795 *(±0.0062)*	0.0012 *(±0.0010)*	0.0911 *(±0.0564)*	0.0108 *(±0.0051)*
4255	HDDT-G3-Idle	0.7302 *(±0.1643)*	0.2272 *(±0.1694)*	0.0026 *(±0.0036)*	0.0129 *(±0.0156)*	0.0271 *(±0.0187)*
4256	HDDT-G3-Cruise	0.5217 *(±0.0937)*	0.4262 *(±0.1030)*	0.0022 *(±0.0009)*	0.0195 *(±0.0143)*	0.0304 *(±0.0155)*
4257	HDDT-G3-Transient	0.4323 *(±0.0988)*	0.5340 *(±0.0996)*	0.0013 *(±0.0012)*	0.0055 *(±0.0055)*	0.0268 *(±0.0325)*
4258	HDDT-G4-Idle	0.5206 *(±0.2360)*	0.0167 *(±0.0187)*	0.4179 *(±0.2400)*	0.0242 *(±0.0420)*	0.0206 *(±0.0213)*
4259	HDDT-G4-Cruise	0.2245 *(±0.0827)*	0.1040 *(±0.0313)*	0.0569 *(±0.0676)*	0.4673 *(±0.1059)*	0.1472 *(±0.0171)*
4260	HDDT-G4-Transient	0.6012 *(±0.1476)*	0.0633 *(±0.0268)*	0.1042 *(±0.0834)*	0.1309 *(±0.1157)*	0.1004 *(±0.0546)*
4261	HDDT-G5-Idle	0.5732 *(±0.2268)*	0.2820 *(±0.2243)*	0.0215 *(±0.0220)*	0.0394 *(±0.0212)*	0.0838 *(±0.0032)*
4262	HDDT-G5-Cruise	0.2744 *(±0.0822)*	0.6827 *(±0.0676)*	0.0016 *(±0.0003)*	0.0240 *(±0.0119)*	0.0172 *(±0.0024)*
4263	HDDT-G5-Transient	0.3669 *(±0.1759)*	0.6022 *(±0.1838)*	0.0015 *(±0.0008)*	0.0090 *(±0.0011)*	0.0205 *(±0.0061)*
4264	SB-G3-Transient	0.3932 *(±0.0232)*	0.5973 *(±0.0213)*	0.0033 *(±0.0007)*	0.0005 *(±0.0010)*	0.0057 *(±0.0034)*
42651	SB-G4-Transient (DPX)	0.5267 *(±0.0985)*	0.0416 *(±0.0091)*	0.0129 *(±0.0142)*	0.3064 *(±0.0727)*	0.1124 *(±0.0420)*
42661	SB-G6-Idle (uncatalyzed)	0.8295	0.0990	0.0189	0.0223	0.0303
42671	SB-G6-Cruise (uncatalyzed)	0.7584	0.1940	0.0105	0.0068	0.0304
42681	SB-G6-Transient (uncatalyzed)	0.7515	0.0849	0.1243	0.0145	0.0248
4269	TB-G1-Transient	0.4272 *(±0.0306)*	0.5497 *(±0.0341)*	0.0000 *(±0.0000)*	0.0044 *(±0.0024)*	0.0187 *(±0.0011)*
42701	TB-G1-Transient (old tech)	0.6569 *(±0.2261)*	0.2991 *(±0.2266)*	0.0029 *(±0.0054)*	0.0236 *(±0.0319)*	0.0174 *(±0.0094)*
4271	TB-G3-Transient	0.1606 *(±0.0342)*	0.8293 *(±0.0333)*	0.0038 *(±0.0005)*	0.0007 *(±0.0010)*	0.0056 *(±0.0004)*
42721	TB-G4-Transient (CRT)	0.8476 *(±0.0229)*	0.0366 *(±0.0129)*	0.0765 *(±0.0210)*	0.0000 *(±0.0000)*	0.0393 *(±0.0110)*
42722	TB-G4-Transient (OC)	0.3759 *(±0.3422)*	0.5045 *(±0.2163)*	0.0006 *(±0.0004)*	0.0985 *(±0.1209)*	0.0204 *(±0.0054)*
42731	TB-G6-Transient (hybrid)	0.8945	0.0699	0.0214	0.0078	0.0065
4274	E-G1-Transient	0.4125 *(±0.0329)*	0.5668 *(±0.0346)*	0.0011 *(±0.0007)*	0.0032 *(±0.0019)*	0.0164 *(±0.0021)*
4275	E-G3-Cruise	0.3824 *(±0.1129)*	0.5963 *(±0.1054)*	0.0000 *(±0.0000)*	0.0106 *(±0.0113)*	0.0107 *(±0.0039)*
4276	E-G4-Cruise	0.5073 *(±0.4306)*	0.1051 *(±0.1076)*	0.0000 *(±0.0000)*	0.3804 *(±0.3330)*	0.0072 *(±0.0100)*
4277	E-G7-Transient	0.2985 *(±0.1339)*	0.1525 *(±0.0668)*	0.0000 *(±0.0000)*	0.4505 *(±0.0879)*	0.0984 *(±0.0537)*

Note: standard deviations are listed in the paraphrases with average values.

2.1 Heavy Duty Diesel Truck (HDDT)

There are four V/E-MY/AT combinations out of seventy HDDT profiles: HDDT-G1, HDDT-G3, HDDT-G4 and HDDT-5. In each V/E-MY/AT, profiles are sorted into three driving cycles (i.e. idle, cruise, and transient) if data are available, and the speciation profiles for the same driving cycle are expected to be similar; however, this is not always true. The divergences may be caused by many other factors, such as, test fuel, test procedure, sample collection method, etc.

Table 7. Organization of HDDT profiles

V/E-MY/AT	Test Cycle	Intermediate Profile No.	Note	Sulfur in Test Fuel	New Profile No.
HDDT-G1	Idle	D10007	Average (*D10007 has relatively lower EC*)	<500ppm	4252
		D20027			
		D20028			
		D20050			
	Cruise	D10005	Average	<500ppm	4253
		D20030			
		D20052			
		D10011		<5000ppm	
	Transient	D10012	Average *(for pre93 fuel)*	<5000ppm	42541
		D10013			
		D10014			
		D10001	Average	<500ppm	4254
		D10003			
		D20029			
		D20031			
		D20051			
		D20036		<15ppm	
		D20037			
HDDT-G3	Idle	D10008	Average	<500ppm	4255
		D20017			
		D20018			
		D20022			
		D20023			
		D20032			
		D20044			
		D20047			
		D20066		<15ppm	
	Cruise	D10006	Average	<500ppm	4256
		D20020			
		D20025			
		D20046			
		D20049			
		D20053		<15ppm	
	Transient	D10002	Average	<500ppm	4257
		D10004			
		D20008			
		D20019			
		D20021			
		D20024			

V/E-MY/AT	Test Cycle	Intermediate Profile No.	Note	Sulfur in Test Fuel	New Profile No.
		D20026			
		D20033			
		D20034			
		D20035			
		D20045			
		D20048			
		D20010		<15ppm	
		D20054			
HDDT-G4	Idle	D20067	Average	<15ppm	4258
		D20068			
		D20069			
	Cruise	D20055	Average	<15ppm	4259
		D20057			
		D20059			
		D20061			
	Transient	D20009	Average	<15ppm	4260
		D20011			
		D20012			
		D20062			
		D20058			
		D20060			
HDDT-G5	Idle	D20038	Average	<500ppm	4261
		D20041			
	Cruise	D20040	Average	<500ppm	4262
		D20043			
	Transient	D20039	Average	<500ppm	4263
		D20042			

2.1.1 HDDT-G1

2.1.1.1 HDDT-G1-idle

There are four HDDT-G1-idle profiles. The sulfur content in the test fuels used to develop these profiles falls below 500ppm. The modeling-required species from these profiles are plotted in Figure 3. Intermediate profile D10007 is actually a composite profile based on many HDDT tests and it has much lower EC content (0.26) than OM (0.69). Intermediate profiles D20027, D20028 and D20050 are all based on individual vehicle source testing and they are comparable to each other. The EC content (0.55-0.65) is higher than OM (0.34-0.45) in these profiles. The composite Profile 4252 for HDDT-G1-idle is created by averaging the above four profiles.

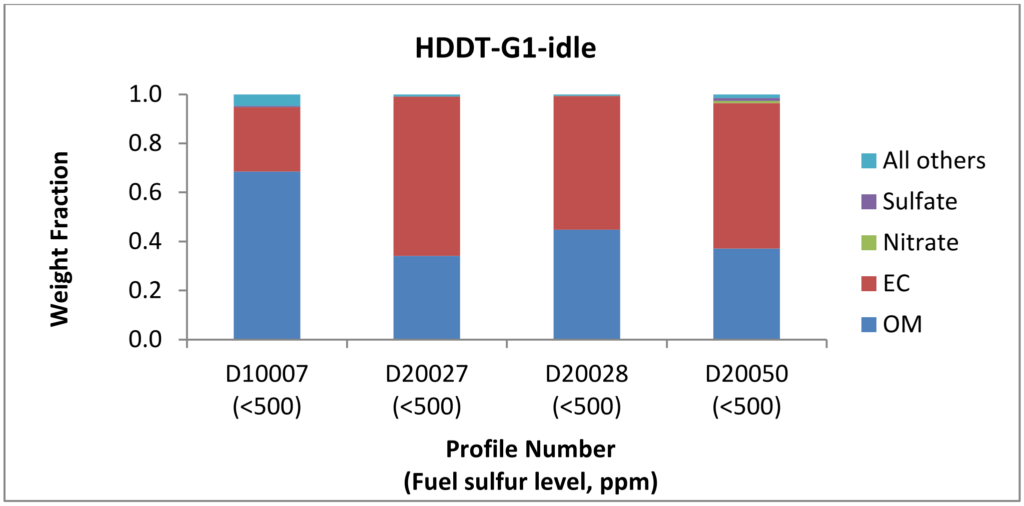

Figure 3. Intermediate Profiles Used for HDDT-G1-idle

2.1.1.2 HDDT-G1-cruise

The four HDDT-G1-cruise intermediate profiles, D10011, D1005, D20030 and D20052 have very similar composition although the test fuel for Profile D10011 contains much higher sulfur (<5000 ppm) than the ones for the other profiles (<500 ppm). In other words, no obvious impact of fuel is observed on the speciation. The average of the four profiles is calculated as new Profile 4253 for HDDT-G1-cruise (Figure 4)

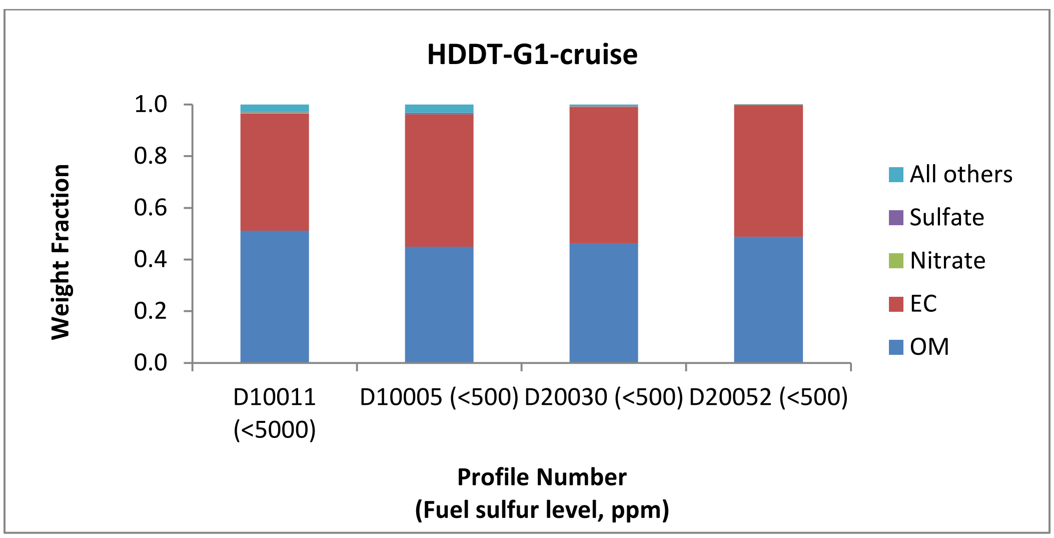

Figure 4. Intermediate Profiles Used for HDDT-G1-cruise

2.1.1.3 HDDT-G1-transient

There are ten intermediate profiles used to create the composite HDDT-G1-transient profile. The impact of diesel sulfur on speciation can be seen for this group in Figure 5. The sulfate fractions in intermediate Profiles D10012, D10013 and D10014 (0.13, 0.11 and 0.02, respectively) are much higher than in others (up to 0.008), and this is due to the much higher sulfur contents in the test fuel used for the former three profiles (less than 5000 ppm vs. less than 500 ppm and 15 ppm). It should be noted that Profiles D10012 to D10014 are composite profiles based on several individual truck and transit bus source tests; while others are based on single vehicle testing. Profiles D20036 and D20037 are the only two profiles based on tests with ULSD, and their OM content is much lower than other profiles (expect for Profile D20051). The difference in OM may be due to the impact of fuel, and it may also be caused by different transient driving cycles. Since the high sulfur fuel has been prohibited in the fleet since 1993, it is suggested to separate the high sulfur fuel profiles from the other profiles when the composite profiles are made. Therefore, the average of Profiles D10001, D10003, D20019, D20031, D20036, D20037 and D20051 is calculated as Profile 4254 for HDDT-G1-transient (LSD and ULSD), and the average of Profiles D10012, D10013 and D10014 is calculated to be Profile 42541 for HDDT-G1-transient for pre-93 fuel.

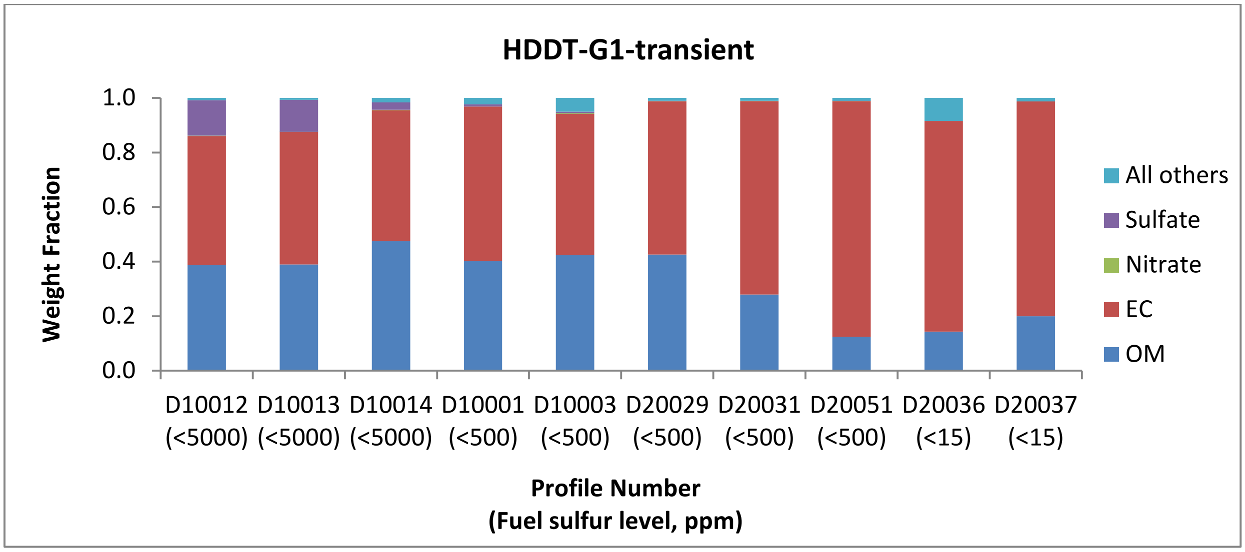

Figure 5. Intermediate Profiles Used for HDDT-G1-transient

2.1.2 HDDT-G3

2.1.2.1 HDDT-G3-idle

There are nine intermediate profiles used to create the composite profile for HDDT-G3-idle (Figure 6). Compared to HDDT-G1-idle, the intermediate profiles in this group have much higher OM and lower EC. The test cycles include idle/creep (Profile D20032), creep (Profiles D20018 and D20023), and idle (all other profiles). Profile D20066 is based on test using ULSD, and all other profiles are based on tests operating with LSD. Profile D10008 is a composite profile made based on several L/M/H-HDDT sources tests. Therefore, the composite Profile 4255 for HDDT-G3-idle is created by averaging intermediate profiles D10008, D20017, D20018, D20022, D20023, D20032, D20044, D20047, and D20066.

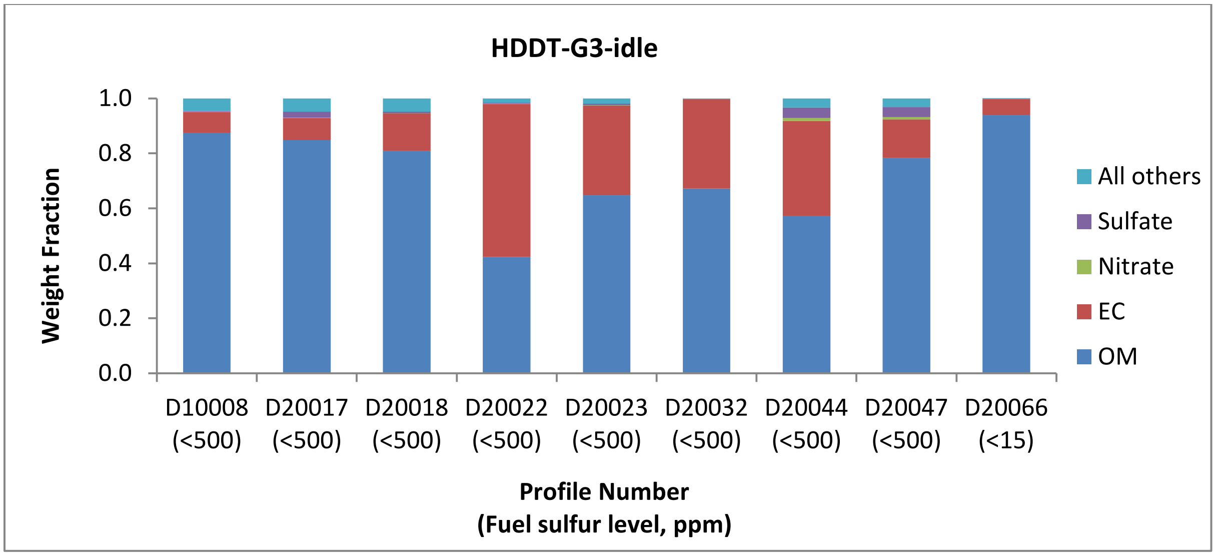

Figure 6. Intermediate Profiles Used for HDDT-G3-idle

2.1.2.2 HDDT-G3-cruise

There are six intermediate profiles used to create composite profile HDDT-G3-cruise (Figure 7). All profiles were tested using LSD except that Profile D20053 was for ULSD. Profiles D10006, D20020, D20025, D20046, D20049, and D20053 are averaged to create the composite Profile 4256 for HDDT-G3-cruise.

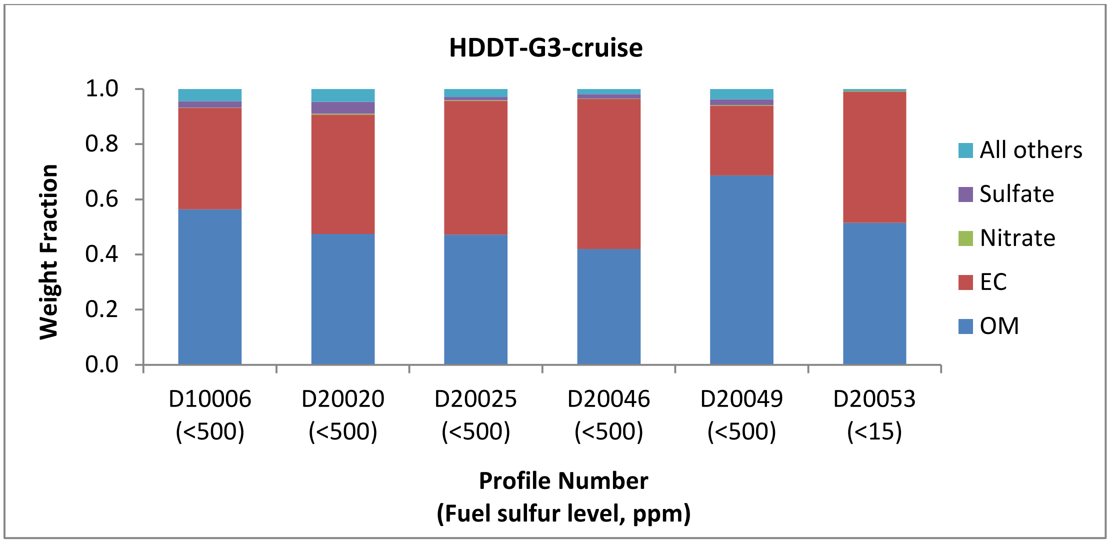

Figure 7. Intermediate Profiles Used for HDDT-G3-cruise

2.1.2.3 HDDT-G3-transient

There are fourteen intermediate profiles used to create composite profile HDDT-G3-transient (Figure 8). The test driving cycles include CSHVR (cold start and hot start), UDDS, 5modes, and transient. Intermediate profiles D20010 and D20054 were tested using fuels with less than 15 ppm sulfur (equivalent to ULSD), and all other profiles in this group were tested using LSD.

No significant fuel impacts are observed on the speciation from Figure 8. Intermediate profiles D10002, D10004, D20008, D20010, D20019, D20021, D20024, D20026, D20033, D20034, D20035, D20045, D20048, and D20054 are averaged to get the composite Profile 4257 for HDDT-G3-transient.

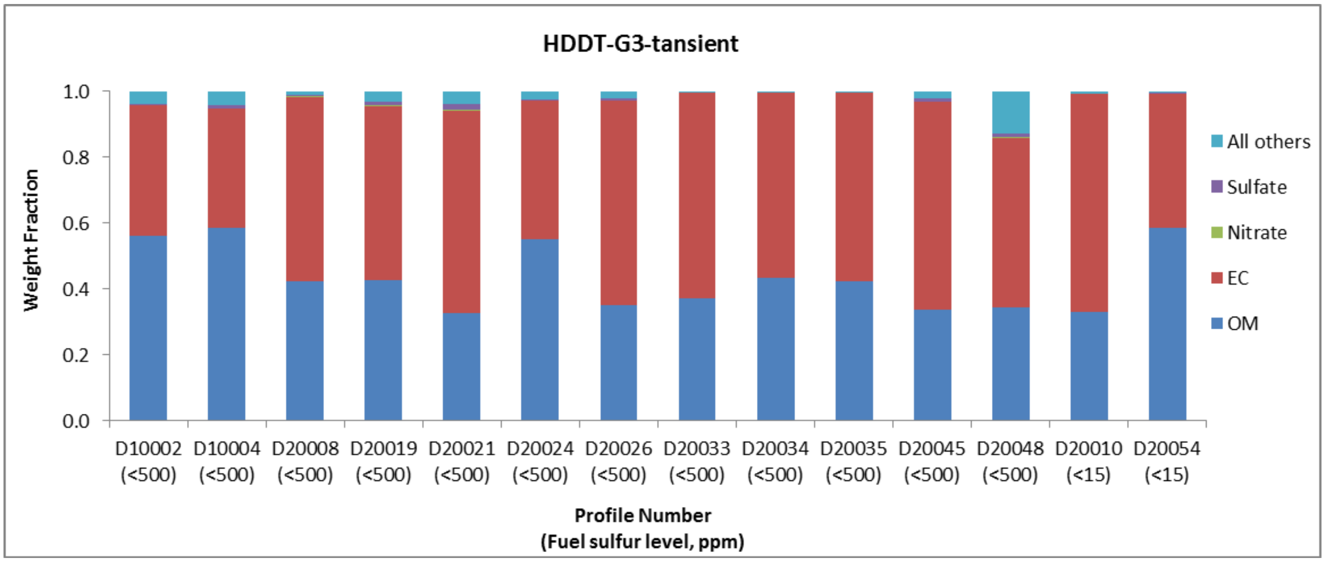

Figure 8. Intermediate Profiles Used for HDDT-G3-transient

2.1.3 HDDT-G4

2.1.3.1 HDDT-G4-idle

All three HDDT-G4-idle intermediate profiles are based on tests using ULSD. However, the intermediate profiles are quite different (Figure 9). This is mostly due to the different aftertreatment techniques (i.e. V-SCRT, Z-SCRT and DPX) utilized for the test vehicles. Although the profiles in this group differ a lot, they all have much lower EC content (< 0.04) and much higher nitrate content (0.17 – 0.65) compared to profiles in the non-DPF groups, such as HDDT-G1-idle (Figure 3) and HDDT-G3-idle (Figure 6), in which, OM and EC are dominant species and nitrate is extremely low. The greatly reduced EC fraction in PM profiles is caused by using a DPF. Since there is no information currently available for how the diesel fleet uses different aftertreatment techniques, these three profiles (D20067, D20068 and D20069) are averaged to create a composite Profile 4258 for HDDT-G4-idle. More specific profiles with different aftertreatment techniques should be added as more information on the fleet is available in the future.

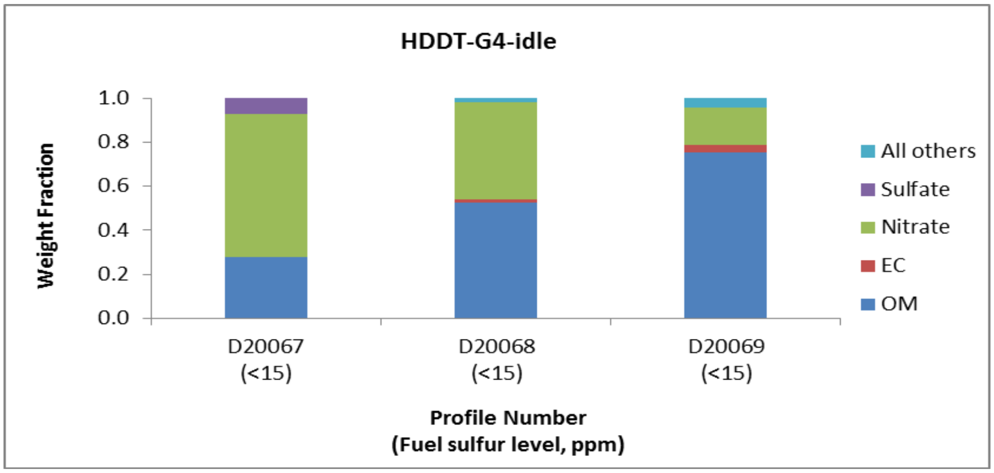

Figure 9. Intermediate Profiles Used for HDDT-G4-idle

2.1.3.2 HDDT-G4-cruise

The four HDDT-G4-cruise profiles are all based on tests using ULSD. Different aftertreatments applied to the test vehicles include CRT, V-SCRT, Z-SCRT, and DPX. It can be seen that sulfate is the dominant species over OM and EC in these profiles for trucks with DPF (Figure 10), and this is very different from what is observed from profiles for trucks without DPF (i.e. HDDT-G1-cruise and HDDT-G3-cruise), in which EC and OM are the most abundant species (Figure 4 and Figure 7). The greatly increased sulfate and reduced EC contents in the profiles for this group are caused by the application of catalyzed aftertreatment. Since there is no information currently available for how the diesel fleet uses different aftertreatment techniques, the average of these four profiles (D20055, D20057, D20059 and D20061) is used as the composite Profile 4259 for HDDT-G4-cruise. More specific profiles with different aftertreatment techniques should be added as more information on the fleet is available in the future.

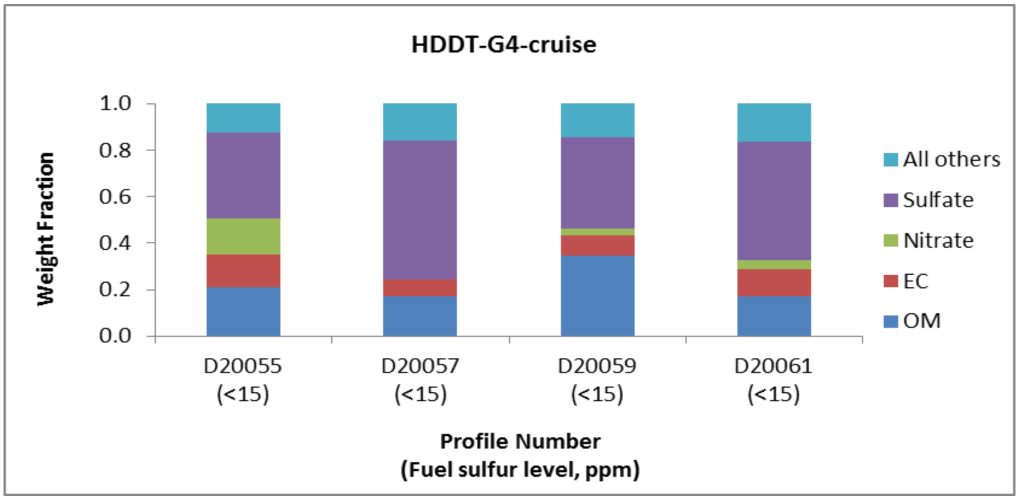

Figure 10. Intermediate Profiles Used for HDDT-G4-cruise

2.1.3.3 HDDT-G4-transient

There are six HDDT-G4-transient profiles. The fuel sulfur contents are all lower than 15ppm. The aftertreatment techniques include DPX, V-SCRT and Z-SCRT. OM is the most abundant species in these profiles (0.44 – 0.82) (Figure 11). The average of Profiles D20009, D20011, D20012, D20058, D20060 and D20062 is used as the composite Profile 4260 for HDDT-G4-transient.

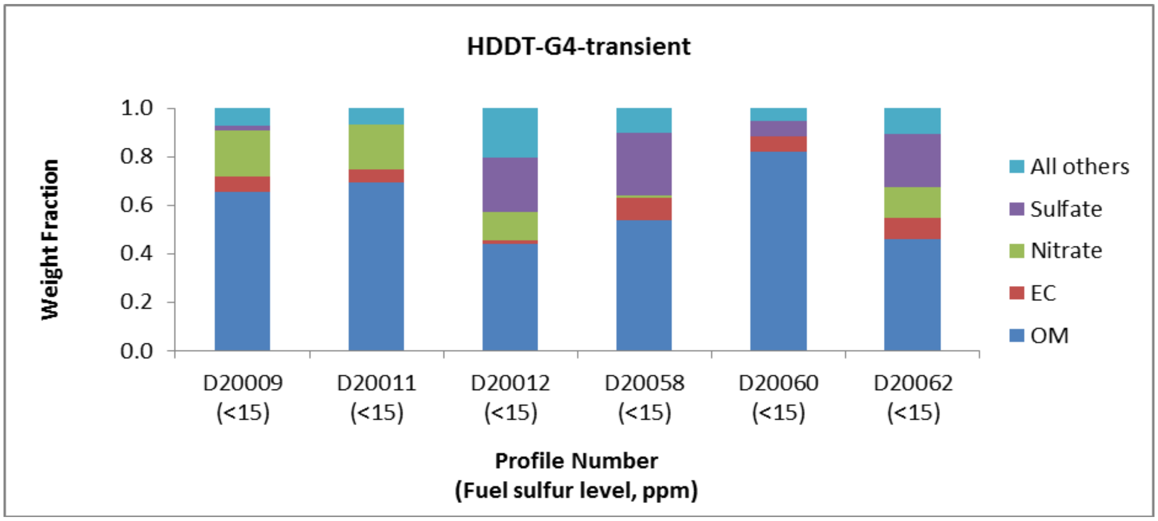

Figure 11. Intermediate Profiles Used for HDDT-G4-transient

2.1.4 HDDT-G5

2.1.4.1 HDDT-G5-idle

There are two HDDT-G5-idle profiles and low-sulfur diesel fuel (LSD) was used in both tests. OM and EC are dominant species in these profiles (Figure 12). The composite Profile 4261 for HDDT-G5-idle is created by averaging these two profiles (D20038 and D20041).

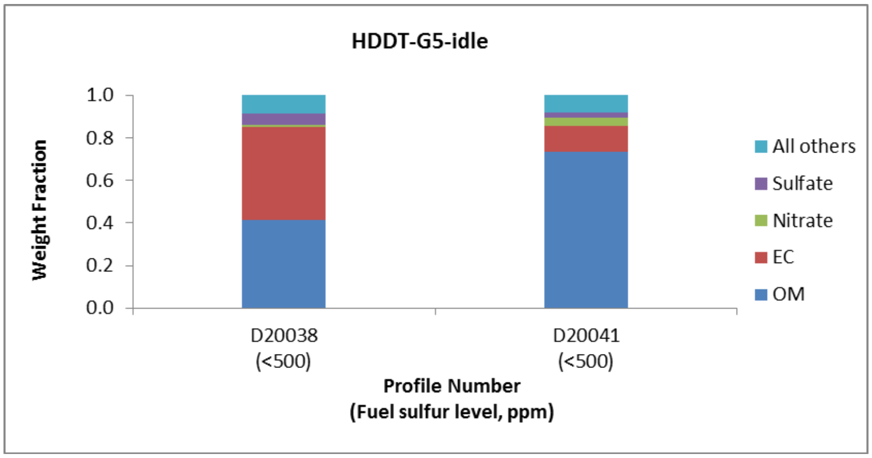

Figure 12. Intermediate Profiles Used for HDDT-G5-idle

2.1.4.2 HDDT-G5-cruise

There are two HDDT-G5-cruise profiles and LSD was used in both tests. EC and OM are dominant species in the profiles (Figure 13). The average of these two profiles (D20040 and D20043) is used to create the composite Profile 4262 for HDDT-G5-cruise.

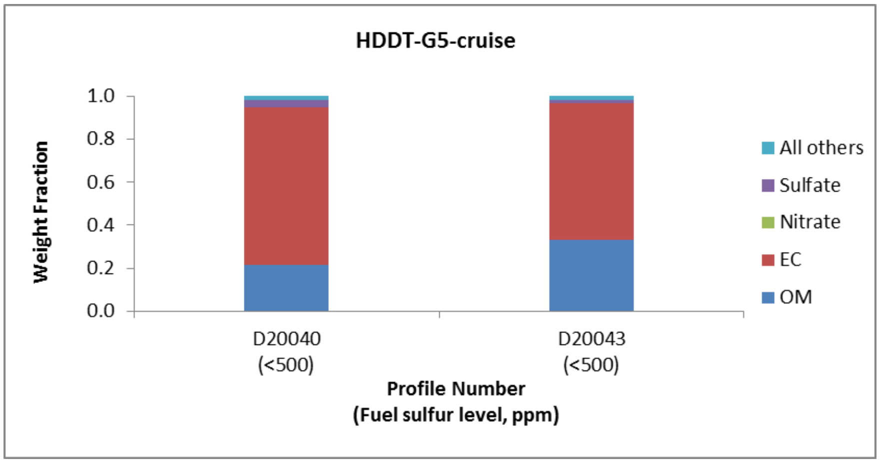

Figure 13. Intermediate Profiles Used for HDDT-G5-cruise

2.1.4.3 HDDT-G5-transient

There are two HDDT-5-transient profiles and LSD was used in both tests. EC and OM are dominant species in the profiles (Figure 14). The average of these two profiles (D20039 and D20042) is used to create the composite Profile 4263 for HDDT-G5-transient.

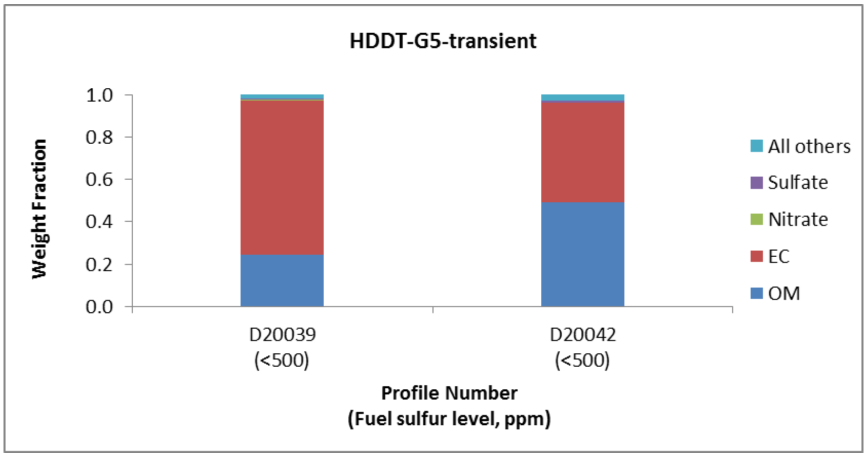

Figure 14. Intermediate Profiles Used for HDDT-G5-transient

2.2 School Bus (SB)

Ten intermediate profiles are made based on school bus chassis dynamometer tests, covering SB-G3, SB-G4, and SB-G6. Table 8 summarizes how these profiles are grouped into generic test cycles (i.e. idle, cruise, and transient). The speciation profiles in the same V/E-MY/AF-Cycle group are assumed to be similar; however, this is not always true due to factors mentioned earlier. The details for each V/E-MY/AF-Cycle are discussed in the following sections.

Table 8. Organization of Intermediate SB Profiles

V/E-MY/AF	Test Cycle	Intermediate Profile No.	Note	Sulfur in Test Fuel	New Profile No.
SB-G3	Transient	D20001	Average	<500ppm	4264
		D20002		<15ppm	
		D20004			
		D20006			
SB-G4	Transient	D20003	Average	<15ppm	42651
		D20005			
		D20007			
SB-G6	Idle	D20070	*(Uncatalyzed)*	<15ppm	42661
	Cruise	D20063	*(Uncatalyzed)*	<15ppm	42671
	Transient	D20064	*(Uncatalyzed)*	<15ppm	42681

2.2.1 SB-G3 (-transient)

All four available intermediate SB-G3 profiles were developed based on transient operation. Different diesel fuels (sulfur contents varied from 1 to 114.5 ppm) were used in the source testing, but no impacts on PM composition are observed (Figure 15). Hence, the average of these four intermediate profiles (D20001, D20002, D20004 and D20006) is used to get the composite Profile 4264 for SB-G3-transient.

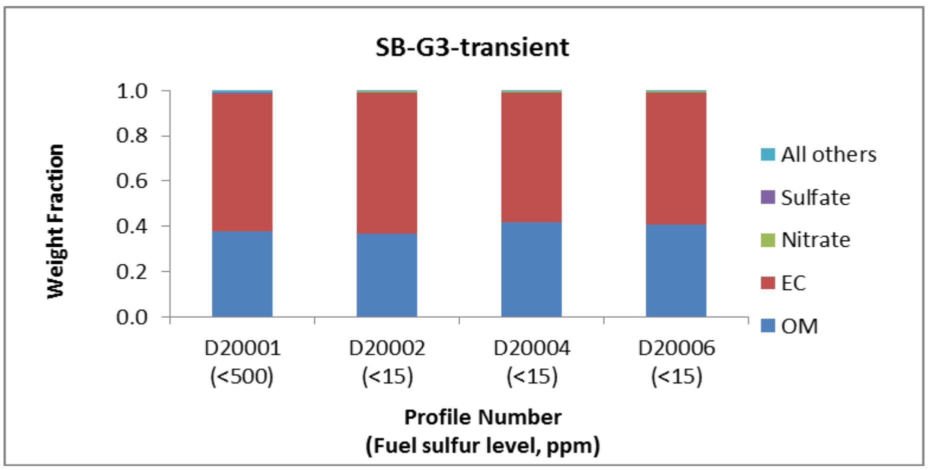

Figure 15. Intermediate Profiles Used for SB-G3-transient

2.2.2 SB-G4 (-transient)

All of the available SB-G4 intermediate profiles were developed based on transient operation and with the same aftertreatment—DPX. The sulfur content of the test diesel fuels are all less than 15 ppm. Compared to the profiles for SB without any DPF (i.e. SB-G3-transient, Figure 15), the PM emitted from DPF applied SB has much higher sulfate (0.25 – 0.39 vs. up to 0.002) and much lower EC (0.05 vs. 0.60). The average of the three profiles (D20003, D20005 and D20007) (Figure 16) is used to get the composite Profile 42651 for SB-G4-transient (DPX).

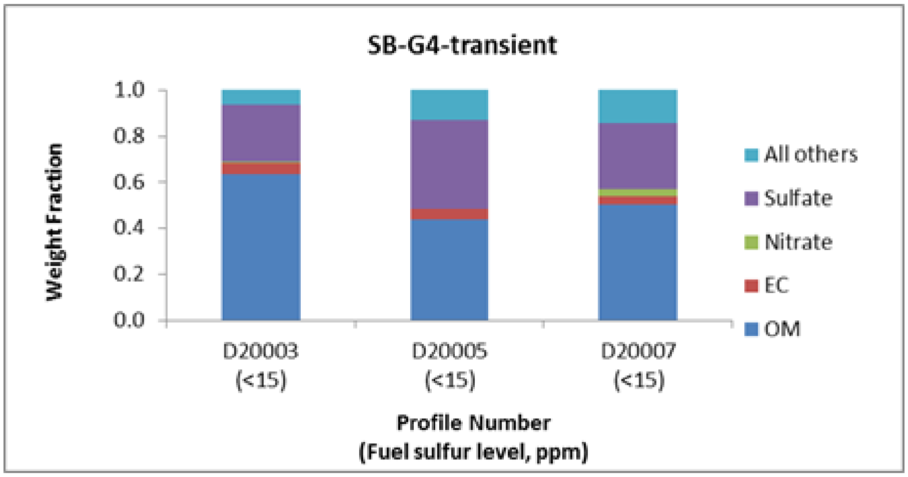

Figure 16. Intermediate Profiles Used for SB-G4-transient

2.2.3 SB-G6

There are three intermediate SB-G6 profiles, and they were tested on idle, cruise and transient cycles, respectively. All three tests were performed on the same school bus equipped with an <u>*uncatalyzed*</u> DPF. It is known that almost all DPFs are heavily catalyzed, and the only uncatalyzed filters are being used in retrofits and for captive fleets, such as school buses and refuse trucks. The PM composition of exhaust from uncatalyzed DPF must be different than the ones from the regular catalyzed DPF; ***therefore, the profiles developed for SB-G6 in this work are only good for <u>uncatalyzed</u> DPF-equipped vehicles and the use of these profiles should be cautioned to avoid biases or errors.***

2.2.3.1 SB-G6-idle (uncatalyzed)

Since only one intermediate profile is available, Profile D20070 (Figure 19), it is renumbered as <u>Profile 42661</u> for SB-G6-idle (uncatalyzed).

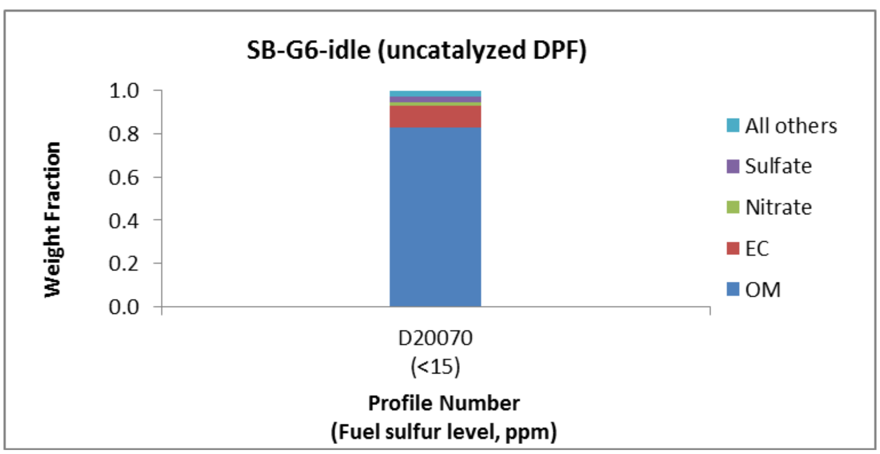

Figure 17. Intermediate Profiles Used for SB-G6-idle (uncatalyzed)

2.2.3.2 SB-G6-cruise (uncatalyzed)

Since only one intermediate profile is available, Profile D20063 (Figure 18), it is renumbered as Profile 42671 for SB-G6-cruise (uncatalyzed).

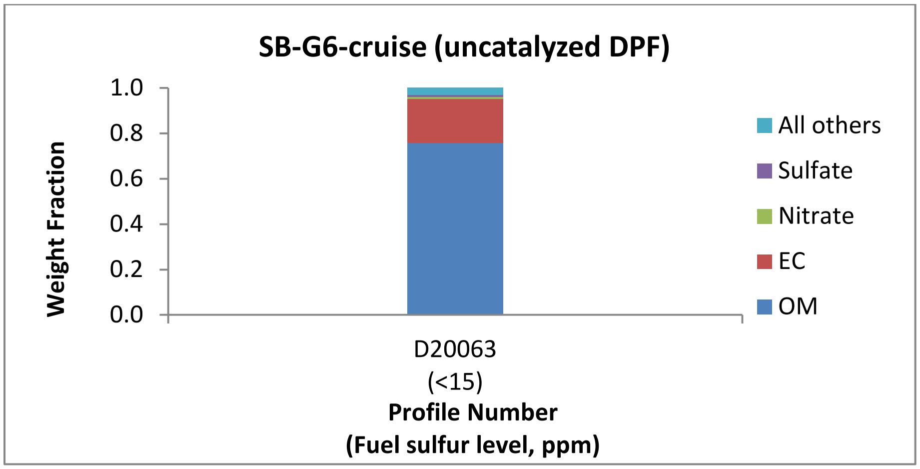

Figure 18. Intermediate Profiles Used for SB-G6-cruise (uncatalyzed)

2.2.3.3 SB-G6-transient (uncatalyzed)

Since only one intermediate profile is available, Profile D20064 (Figure 19), it is renumbered as Profile 42681 for SB-G6-transient (uncatalyzed).

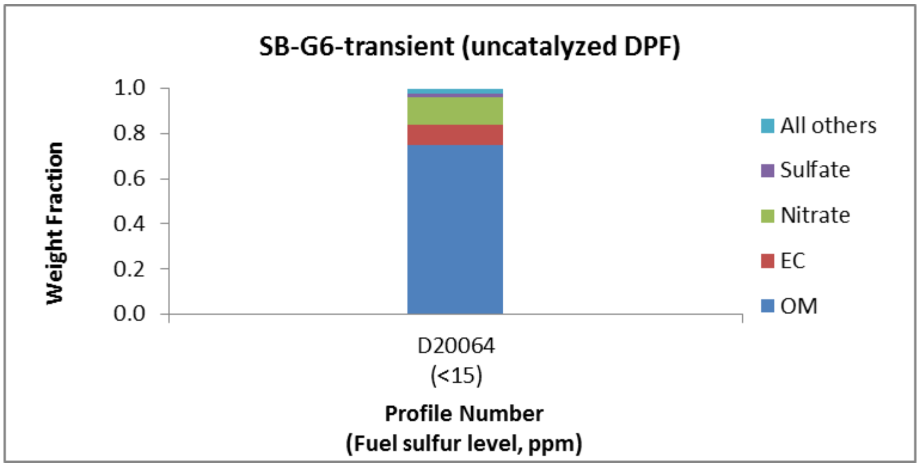

Figure 19. Intermediate Profiles Used for SB-G6-transient (uncatalyzed)

2.3 Transit Bus (TB)

All of the available intermediate TB profiles in this work are based on testing under the transient cycle, which represents the real-world operating conditions of transit buses. These profiles cover G1, G2, G3, G4 and G6 five MY/AT groups (Table 9).

Table 9. Organization of Intermediate TB Profiles

V/E-MY/AT	Test Cycle	Intermediate Profile No.	Note		Sulfur in Test Fuel	New Profile No.
TB-G1	Transient	D10009	Average		<500ppm	4269
		D10010				
TB-G2	Transient	D10015	*(trap)*	Average *(old tech)*	<5000ppm	42701
		D10016				
		D10017	*(muffler)*		<500ppm	
		D10018				
		D10019	*(oxidation catalyst)*			
		D10020				
TB-G3	Transient	D20013	Average		<500ppm	4271
		D20015			<15ppm	
TB-G4	Transient	D20014	Average *(CRT)*		<15ppm	42721
		D20016				
		D10021	*Average (oxidation catalyst)*		<500ppm	42722
		D10022				
TB-G6	Transient	D20065	*(Hybrid+CCRT)*		<15ppm	42731

2.3.1 TB-G1 (-transient)

There are two intermediate TB-G1 profiles, and the fuel sulfur contents are in the same range (< 500 ppm). The average of intermediate Profiles D10009 and D10010 is used to create composite Profile 4269 for TB-G1-transient (Figure 20).

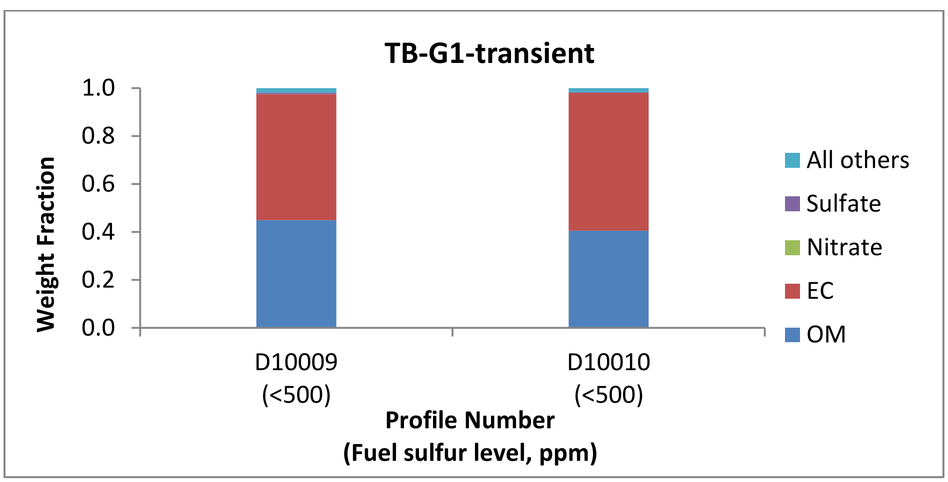

Figure 20. Intermediate Profiles Used for TB-G1-transient

2.3.2 TB-G2 (-transient)

There are six intermediate TB-G2 profiles. Profiles D10015 and D10016 are composite profiles made for transit buses (TB) equipped with particle traps, and the sulfur concentrations of the test diesel are less than 5000 ppm [13]. The EC fraction in D10015 is about 10 times higher than in D10016. Profiles D10017 and D10018 are developed based on tests for TBs equipped with a muffler [14]. Profiles D10019 and D10020 are developed based on tests for TBs equipped with an oxidation catalyst (OC) [14]. The sulfur content in the test fuel for these four profiles is less than 500 ppm. *Big variations exist in these profiles and this may be caused by the different aftertreatments used for the TBs in the source testing*. It should be noted that the three aftertreatments (i.e. particle trap, muffler and OC) are not the up-to-date retrofit techniques like the DPF, so the average of the six profiles in this V/E-MY/AT (D10015, D10016, D10017, D10018, D10019 and D10020) is used to get a composite profile for old aftertreatment techniques only. ***This composite TB-G2-transient Profile 42701 is not appropriate to be employed for TBs equipped with relatively new aftertreatment techniques***.

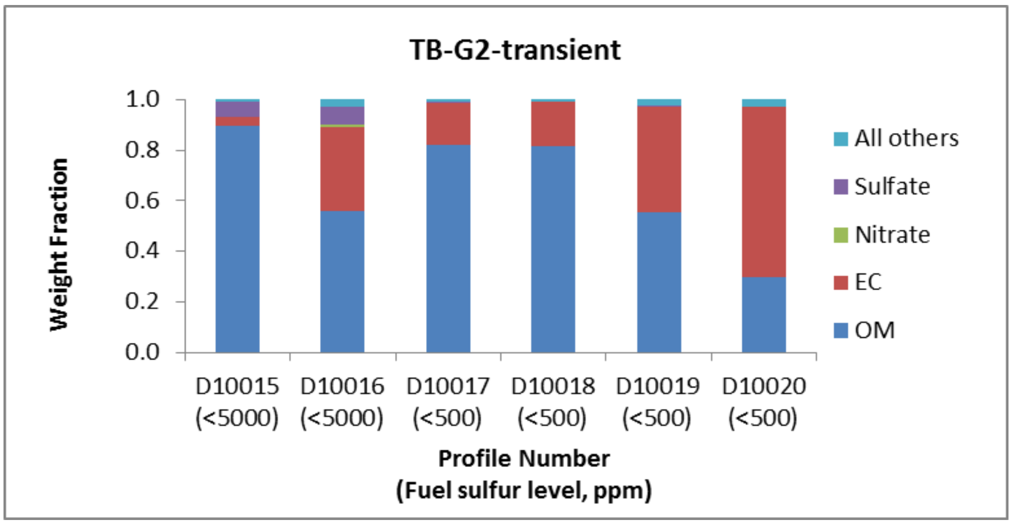

Figure 21. Intermediate Profiles Used for TB-G2-transient

2.3.3 TB-G3 (-transient)

The two TB-G3 profiles D20013 and D20015 are based on tests for TBs without any DPF. EC dominates over OM in both profiles (Figure 22). The average of these two profiles is used to get composite Profile 4271 for TB-G3. Theoretically, the newer engines generally emit less EC in the PM than the old engines; however, the EC fractions of TB-G3 profiles are much higher than those of TB-G1 profiles (0.83 vs. 0.55) (Figure 20).

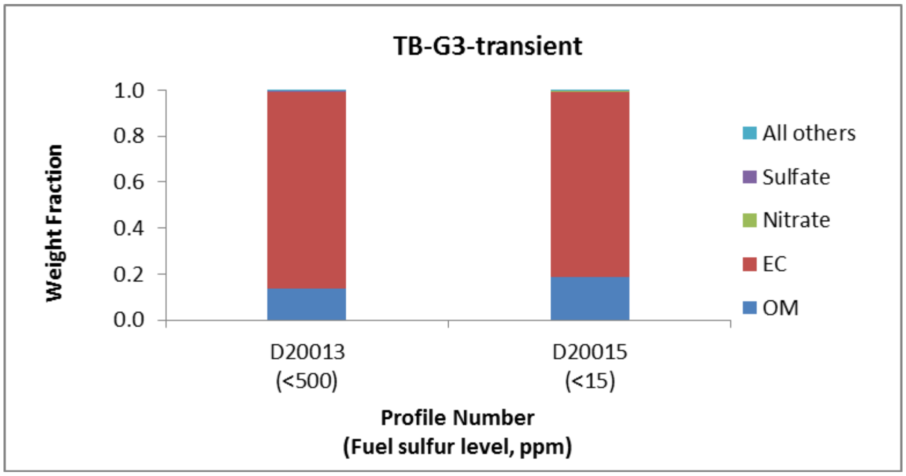

Figure 22. Intermediate Profiles Used for TB-G3-transient

2.3.4 TB-G4 (-transient)

The four intermediate TB-G4 profiles cover two aftertreatement techniques. Intermediate profiles D20014 and D20016 are for TBs equipped with a CRT filter while Profiles D10021 and D10022 are for TBs equipped with an OC [14]. Similar to HDDT-G4 and SB-G4 profiles, Profiles D20014 and D20016 have very low EC fractions (0.03-0.05) and abundant OM (0.83-0.86) because the particulate EC can be significantly removed by the filters. However, Profiles D10021 and D10022 show very high EC fractions (0.35 and 0.66), which is different from what is observed in Profiles D10021 and D10022 Figure 23. This is probably because the close-coupled oxidation catalyst system is not as efficient as the up-to-date DPFs in removing EC. Therefore, the average of Profiles 20014 and D20016 is used to get the composite TB-G4-transient Profile 42721 for CRT only; and the average of Profiles 10021 and D10022 is used to get a composite TB-G4-transient Profile 42722 for the OC system.

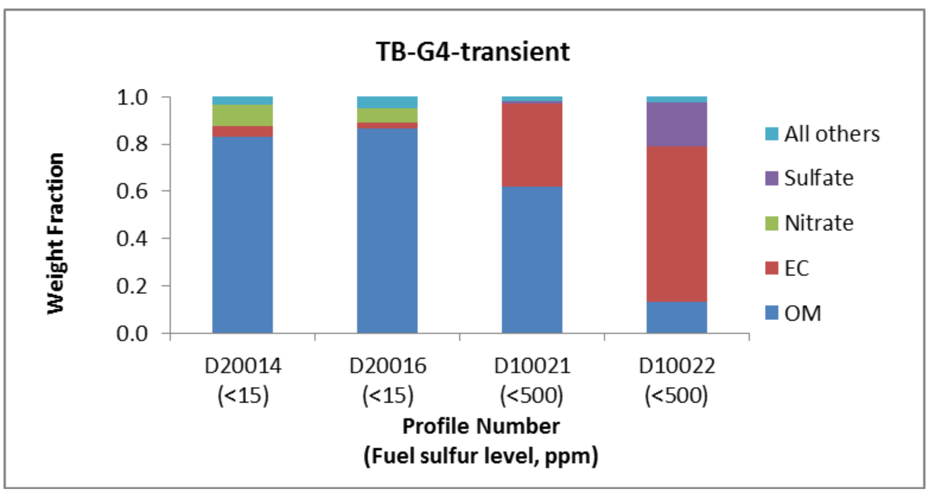

Figure 23. Intermediate Profiles Used for TB-G4-transient

2.3.5 TB-G6 (-transient)

There is only one intermediate TB-G6 profile. The associated test vehicle is a hybrid TB, and CCRT was applied. ***It should be noted that this profile is only good for hybrid TB equipped with CCRT (Figure 24) and it should be used very careful to avoid biases or errors***. The single intermediate profile is renumbered as Profile 42731 for TB-G6-transient (hybrid).

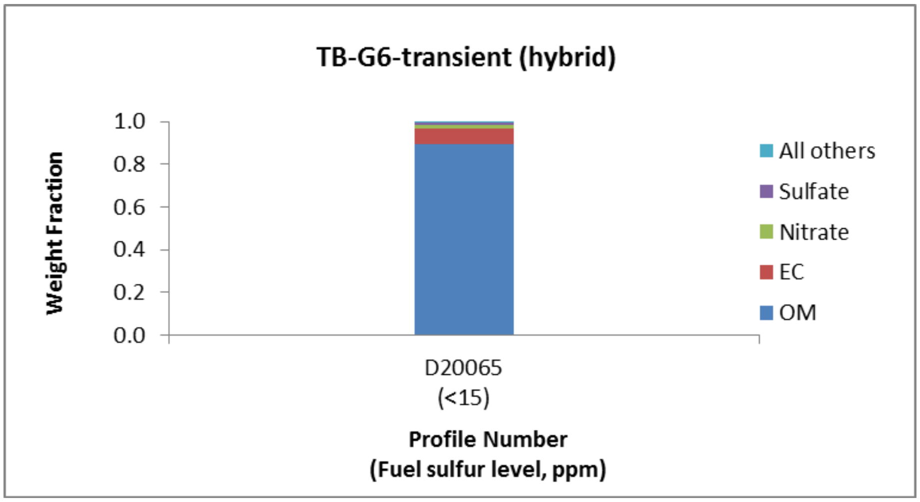

Figure 24. Intermediate Profiles Used for TB-G6-transient (hybrid)

2.4 Engine (E)

As discussed previously, engine dynamometer testing is different from chassis dynamometer testing. Under engine dynamometer testing, the engine is removed from the vehicle and mounted directly to the dynomometer for testing. As such, the speciation profiles measured from these two types of dynamometer tests are expected to be different. All the profiles discussed in Sections 2.1 (HDDT), 2.2 (SB) and 2.3 (TB) are based on chassis dynamometer tests, but the profiles in this section are all based on engine dynamometer tests [10] [15] [16]. Table 10 provides a summary of the intermediate profiles associated with the studies based on engine dynamometer testing.

Table 10. Organization of Engine Exhaust Profiles

V/E-MY/AT	Test Cycle	Intermediate Profile No.	Note	Sulfur in Test Fuel	New Profile No.
E-G1	Transient	D10025	Average	<500ppm	4274
		D10026			
		D10027			
		D10028			
		D10023		<15ppm	
		D10024			
E-G3	Cruise	D10029	Average	<500ppm	4275
		D10031			
E-G4	Cruise	D10030	Average	<500ppm	4276
		D10032			
E-G7	Transient	D20071	Average	<15ppm	4277
		D20072			
		D20073			
		D20074			

2.4.1 E-G1-transient

The six intermediate E-G1-transient profiles were obtained from the same study [15]. The test engine was operated on both cold-start and hot-start FTP cycles with three kinds of diesel fuel (0.1-350 ppm sulfur), and the profiles are very close to each other. No significant effects of cold/hot start and diesel fuel were observed from these profiles (Figure 25). Therefore, the average of the six profiles (D10023-D10028) is used to get the composite Profile 4274 for E-G1-transient.

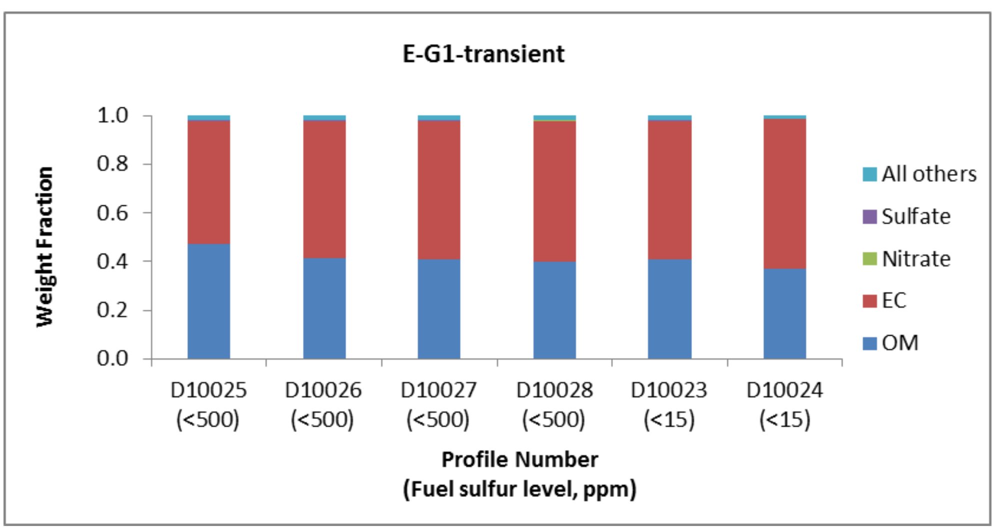

Figure 25. Intermediate Profiles Used for E-G1-transient

2.4.2 E-G3-cruise

Two intermediate E-G3-cruise profiles (Figure 26) are developed based on source characterizations performed at two steady-state operating conditions (Mode 9 and Mode 11) with 375 ppm sulfur fuel [16]. The composite profile, Profile 4275, for E-G3-cruise is made by averaging these two intermediate profiles (D10029 and D10031).

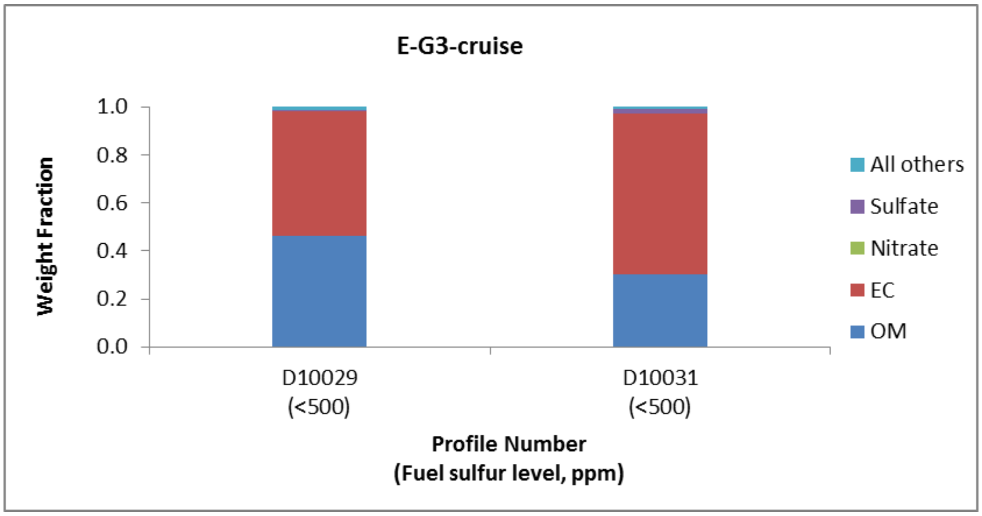

Figure 26. Intermediate Profiles Used for E-G3-transient

2.4.3 E-G4-cruise

Two intermediate E-G4-cruise profiles were developed based on tests performed at two steady-state operating conditions (Mode 9 and Mode 11) with 375 ppm sulfur fuel [16]. PM filters were used for the test engines. It can be seen from Figure 27 that the two intermediate profiles, D10030 and D10032, are quite different. The slight difference between Mode 9 and Mode 11 is not expected to cause such a divergence. However, because there is not enough information to choose one profile over the other, an average of the two profiles is used for the composite E-G4-cruise Profile 4276.

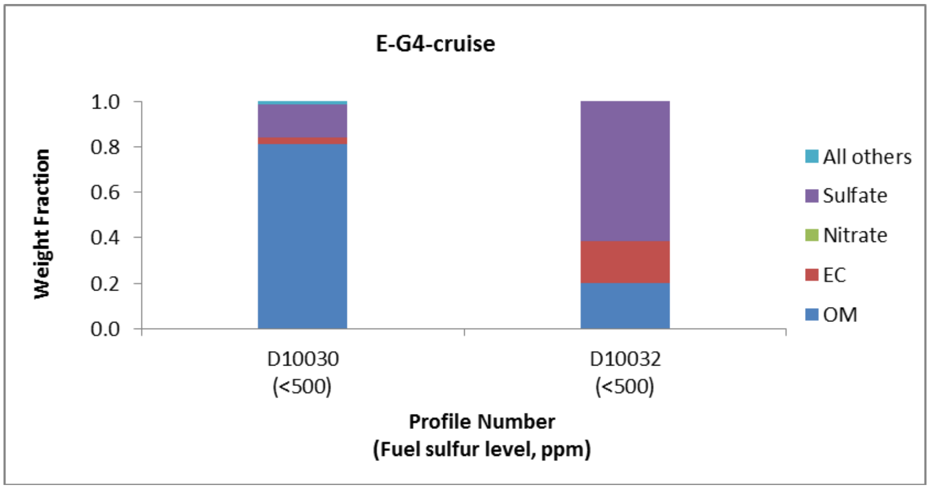

Figure 27. Intermediate Profiles Used for E-G4-transient

2.4.4 E-G7-transient

The four intermediate E-G7-transient profiles are all from the ACES study [7]. Four 2007 engines were tested over the 16-hour driving cycle using ultra-low sulfur diesel fuel (ULSD). Sulfate and OM fractions are greater than EC in these profiles (Figure 28). In addition, sulfate and OM are the most abundant species compared to EC, which is contradictory to the profiles for non-DPF vehicles or engines. The average of Profiles D20071 to D20074 is used to get the composite Profile 4277 for E-G7-transient.

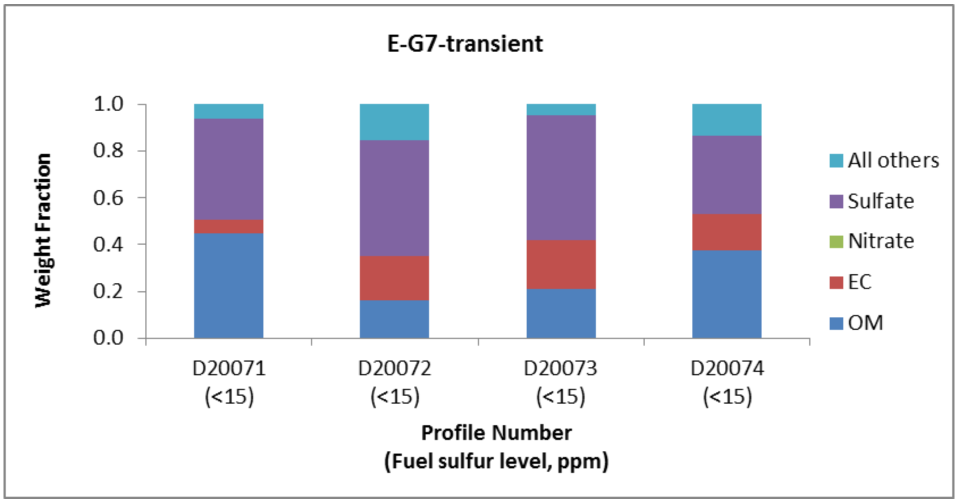

Figure 28. Intermediate Profiles Used for E-G7-transient

3 Calendar Year (CY) Specific Composite Profiles

As shown in Figure 1, the HDDV fleet composition (i.e., relative contribution of the eight MY/AT groups G1-G8 in Table 1) changes every calendar year due to the truck and bus rule. To reflect this year-to-year difference, the year-specific fleet composition and MY/AT composite profiles discussed in the prior section are used to calculate weighted-average, calendar-year (CY)-specific diesel PM speciation profiles. For each specific CY, profiles of MY/AT groups with a larger CY-specific fleet composition fraction contribute more to the weighted-average CY profile and profiles of groups with a smaller fleet composition fraction contribute less. The formula for the weighted average calculation is:

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

where,

$F_{Y_k}^{S_j}$: Weight fraction of Species *j* in the CY profile for Year *k* fleet;

$F_{G_i}^{S_j}$: Weight fraction of Species *j* in the MY/AT profile for Group *i (i=G1, G2, G3, G4, G5, G6, G7 and G8).* Detailed profiles are contained in DieselPM.mdb (Appendix 2); and

$P_{G_i}^{Y_k}$: CY fleet composition fraction of Group *i* vehicles in the fleet of Year *k*, weighted by $PM_{2.5}$ mass.

The two parameters, $P_{G_i}^{Y_k}$ (i.e. fleet composition) and $F_{Y_k}^{S_j}$ (i.e. MY/AT profile), needed for calculating composite, CY-specific profiles are discussed in Sections 3.1 and 3.2.

3.1 Fleet composition

Based on the truck and bus rule, the HDDV categories have been updated with 30 new 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' (Table 11. Newly updated HDDV EICSUB categories) based on assumed EICSUB-related driving characteristics. The cruise style group includes the long-haul trucks that travel mostly on the highway; and the transient style group includes the vehicles that are typically driven locally, such as, utility trucks, public trucks, and solid waste collection vehicles. All the buses are classified into the transient style group. Using this driving cycle scheme, the statewide annual average fleet composition weighted by $PM_{2.5}$ mass can be calculated for HDDT-cruise, HDDT-transient, SB-transient, and TB-transient from EMFAC2011[3] running exhaust emissions for each calendar year. The fleet of HDDT-transient, with the $PM_{2.5}$ mass contribution from eight MY/AT groups (i.e., G1-G8), is tabulated in Table 12 as an example. Similarly, the fleet compositions of HDDT-idle, SB-idle and TB-idle can be obtained from EMFAC2011[3] idle exhaust emissions.

Table 11. Newly updated 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		

EICSUB Name	Note	Characteristic Driving Cycle	Vehicle Type
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

Table 12. Fleet Composition of HHDT-transient weighted by $PM_{2.5}$ mass [3]

Calendar Year	G1	G2	G3	G4	G5	G6	G7	G8
	pre-1994 w/o DPF	pre-1994 w/ DPF	1994~2002 w/o DPF	1994~2002 w/ DPF	2003~2006 w/o DPF	2003~2006 w/ DPF	2007~2009	2010 & newer
1990	1	0	0	0	0	0	0	0
1991	1	0	0	0	0	0	0	0
1992	1	0	0	0	0	0	0	0
1993	0.9982	0	0.0018	0	0	0	0	0
1994	0.9807	0	0.0193	0	0	0	0	0
1995	0.9586	0	0.0414	0	0	0	0	0
1996	0.9371	0	0.0629	0	0	0	0	0
1997	0.9132	0	0.0868	0	0	0	0	0
1998	0.8831	0	0.1169	0	0	0	0	0
1999	0.8470	0	0.1530	0	0	0	0	0
2000	0.8062	0	0.1938	0	0	0	0	0
2001	0.7798	0	0.2202	0	0	0	0	0
2002	0.7510	0	0.2458	0	0.0031	0	0	0
2003	0.7128	0	0.2534	0	0.0338	0	0	0
2004	0.6603	0	0.2575	0	0.0821	0	0	0
2005	0.6549	0	0.2374	0	0.1076	0	0	0
2006	0.5311	0	0.2687	0	0.1997	0	0.0004	0
2007	0.4975	0	0.2842	0	0.2140	0	0.0044	0
2008	0.4611	0.0001	0.3034	0.0001	0.2263	0	0.0090	0
2009	0.4221	0.0001	0.3249	0.0001	0.2397	0	0.0127	0.0004
2010	0.3786	0.0001	0.3500	0.0001	0.2528	0	0.0142	0.0041
2011	0.3411	0.0001	0.3724	0.0001	0.2612	0	0.0154	0.0097
2012	0.2751	0.0156	0.3600	0.0177	0.2841	0.0064	0.0208	0.0204
2013	0.2132	0.0325	0.3456	0.0412	0.2780	0.0222	0.0284	0.0388
2014	0.2476	0.0418	0.3037	0.0813	0.1373	0.0732	0.0406	0.0744
2015	0.1021	0.0470	0.3164	0.1015	0.1568	0.1013	0.0487	0.1263
2016	0.0453	0.0688	0.0705	0.1928	0.0713	0.2061	0.0775	0.2679
2017	0.0351	0.0686	0.0137	0.1977	0.0095	0.2451	0.0891	0.3412

Calendar Year	G1	G2	G3	G4	G5	G6	G7	G8
	pre-1994 w/o DPF	pre-1994 w/ DPF	1994~2002 w/o DPF	1994~2002 w/ DPF	2003~2006 w/o DPF	2003~2006 w/ DPF	2007~2009	2010 & newer
2018	0	0.0692	0	0.1807	0	0.2532	0.1006	0.3963
2019	0	0.0611	0	0.1508	0	0.2490	0.1041	0.4350
2020	0	0.0545	0	0.0898	0	0.2397	0.1062	0.5098
2021	0	0.0493	0	0.0424	0	0.1685	0.1083	0.6314
2022	0	0.0442	0	0.0397	0	0.0471	0.1118	0.7572
2023	0	0.0388	0	0.0366	0	0.0431	0.0231	0.8584
2024	0	0.0326	0	0.0333	0	0.0393	0.0212	0.8736
2025	0	0.0264	0	0.0302	0	0.0364	0.0189	0.8881
2026	0	0.0213	0	0.0277	0	0.0328	0.0170	0.9012
2027	0	0.0169	0	0.0254	0	0.0296	0.0156	0.9125
2028	0	0.0135	0	0.0235	0	0.0263	0.0146	0.9222
2029	0	0.0112	0	0.0215	0	0.0233	0.0134	0.9305
2030	0	0.0086	0	0.0198	0	0.0212	0.0118	0.9385
2031	0	0.0079	0	0.0178	0	0.0187	0.0106	0.9450
2032	0	0.0077	0	0.0154	0	0.0164	0.0096	0.9509
2033	0	0.0067	0	0.0130	0	0.0148	0.0088	0.9567
2034	0	0.0053	0	0.0105	0	0.0143	0.0076	0.9623
2035	0	0.0019	0	0.0083	0	0.0139	0.0068	0.9691

3.2 MY/AT profiles

To make the CY profiles, G1-G8 MY/AT profiles are needed for all driving cycles, including HDDT-idle, HDDT-cruise, HDDT-transient, SB-idle, SB-transient, TB-idle, and TB-transient. However, the V/E-MY/AT-Cycle profiles developed in this work based on source testing data are limited and they only cover parts of the above combinations (Table 5). The following assumptions are made to fill in the blanks and meet the needs for CY profile development (Table 13):

- DPF profiles are significantly different than non-DPF profiles, so for the missing DPF V/E-MY/AT-Cycle profiles, available DPF profiles should be chosen rather than non-DPF profiles:
  - HDDT-G4-idle profile (4258) is used for HDDT-G2/G6-idle;
  - HDDT-G4-cruise profile (4259) is used for HDDT-G2/G6-cruise;
  - HDDT-G4-transient profile (4260) is used for HDDT-G2/G6-transient;
  - E-G7-transient profile (4277) is used for HDDT-G7/G8-idle/cruise/transient.
- The available HDDT profiles are used for corresponding missing SB profiles:
  - HDDT-G1/G2/G3/G4/G5/G6/G7/G8-idle profiles are used for SB-G1/G2/G3/G4/G5/G6/G7/G8-idle, respectively;
  - HDDT-G1/G2/G4/G5/G6/G7/G8-transient profiles are used for SB-G1/G2/G4/G5/G6/G7/G8-transient, respectively.
- The available HDDT profiles are used for corresponding missing TB profiles:
  - HDDT-G1/G2/G3/G4/G5/G6/G7/G8-idle profiles are used for TB-G1/G2/G3/G4/G5/G6/G7/G8-idle, respectively;

- HDDT-G2/G4/G5/G6/G7/G8-transient profiles are used for TB-G2/G4/G5/G6/G7/G8-transient, respectively.

Table 13. Mapping of V/E-MY/AT-Cycle speciation profiles used to develop CY profiles

V/E	Cycle	MY/AT							
		G1	G2	G3	G4	G5	G6	G7	G8
HDDT	Idle	4252	4258	4255	4258	4261	4258	4277	4277
	Cruise	4253	4259	4256	4259	4262	4259	4277	4277
	Transient	4254	4260	4257	4260	4263	4260	4277	4277
SB	Idle	4252	4258	4255	4258	4261	4258	4277	4277
	Transient	4254	4260	4264	4260	4263	4260	4277	4277
TB	Idle	4252	4258	4255	4258	4261	4258	4277	4277
	Transient	4269	4260	4271	4260	4263	4260	4277	4277

3.3 CY profile numbers and names

With all the information needed, including the fleet composition (Appendix 2), the mapping of MY/AT profiles (Table 13) and the profile speciation (Appendix 2), the CY profiles for HDDV are developed for each calendar year from 1990 to 2035 (Table 14). The details of these CY profiles are stored in the database DieselPM.mdb (Appendix 2).

Table 14. List of CY Profile numbers and names for HDDV

Calendar Year	HDDT			SB		TB	
	idle	cruise	transient	idle	transient	idle	transient
1990	6901	6902	6903	6904	6905	6906	6907
1991	6911	6912	6913	6914	6915	6916	6917
1992	6921	6922	6923	6924	6925	6926	6927
1993	6931	6932	6933	6934	6935	6936	6937
1994	6941	6942	6943	6944	6945	6946	6947
1995	6951	6952	6953	6954	6955	6956	6957
1996	6961	6962	6963	6964	6965	6966	6967
1997	6971	6972	6973	6974	6975	6976	6977
1998	6981	6982	6983	6984	6985	6986	6987
1999	6991	6992	6993	6994	6995	6996	6997
2000	6001	6002	6003	6004	6005	6006	6007
2001	6011	6012	6013	6014	6015	6016	6017
2002	6021	6022	6023	6024	6025	6026	6027
2003	6031	6032	6033	6034	6035	6036	6037
2004	6041	6042	6043	6044	6045	6046	6047
2005	6051	6052	6053	6054	6055	6056	6057
2006	6061	6062	6063	6064	6065	6066	6067
2007	6071	6072	6073	6074	6075	6076	6077
2008	6081	6082	6083	6084	6085	6086	6087
2009	6091	6092	6093	6094	6095	6096	6097
2010	6101	6102	6103	6104	6105	6106	6107

Calendar Year	HDDT			SB		TB	
	idle	cruise	transient	idle	transient	idle	transient
2011	6111	6112	6113	6114	6115	6116	6117
2012	6121	6122	6123	6124	6125	6126	6127
2013	6131	6132	6133	6134	6135	6136	6137
2014	6141	6142	6143	6144	6145	6146	6147
2015	6151	6152	6153	6154	6155	6156	6157
2016	6161	6162	6163	6164	6165	6166	6167
2017	6171	6172	6173	6174	6175	6176	6177
2018	6181	6182	6183	6184	6185	6186	6187
2019	6191	6192	6193	6194	6195	6196	6197
2020	6201	6202	6203	6204	6205	6206	6207
2021	6211	6212	6213	6214	6215	6216	6217
2022	6221	6222	6223	6224	6225	6226	6227
2023	6231	6232	6233	6234	6235	6236	6237
2024	6241	6242	6243	6244	6245	6246	6247
2025	6251	6252	6253	6254	6255	6256	6257
2026	6261	6262	6263	6264	6265	6266	6267
2027	6271	6272	6273	6274	6275	6276	6277
2028	6281	6282	6283	6284	6285	6286	6287
2029	6291	6292	6293	6294	6295	6296	6297
2030	6301	6302	6303	6304	6305	6306	6307
2031	6311	6312	6313	6314	6315	6316	6317
2032	6321	6322	6323	6324	6325	6326	6327
2033	6331	6332	6333	6334	6335	6336	6337
2034	6341	6342	6343	6344	6345	6346	6347
2035	6351	6352	6353	6354	6355	6356	6357

3.4 Size fraction profiles

A complete ARB PM profile includes two parts, the weight fraction of chemical species and the particle size fraction. The chemical speciation profiles have been discussed in the prior sections, and size fraction profiles are covered in this section.

In the current ARB Profile PM425, 100% of the total particulate matter (TPM) emitted by diesel vehicles is PM_{10} and 92% is $PM_{2.5}$. As new source testing data become available, this size fraction profile needs to be updated too. CRC E-24-2 Study [17] reported the average composite MOUDI (Micro-Orifice Uniform-Deposit Impactor) size distributions for 19 diesel vehicles (model year from 1977 to 1993): 99.4% of the TPM is PM_{10} and 95.1% is $PM_{2.5}$. These composite averages were obtained by determining the percentage of mass on each MOUDI stage for each vehicle and then averaging these percentages. The results were generally consistent from vehicle to vehicle [17]. The ratios of $PM_{2.5}$ to PM_{10} measured in the CARB Toxicological Study [18] for more recent vehicles (model year 1998 to 2007), with and without DPF, are in agreement with the above result. Therefore, the average composite size distributions are used for all of the updated diesel vehicle profiles presented in this report to replace the existing size profile (Table 15).

Table 15. Size fractions for all diesel vehicles profiles

Size Fraction Profile	PM_{10}/TPM (%)	$PM_{2.5}$/TPM (%)
newly developed (for all new profiles)	99.4	95.1
existing (for PM425)	*100*	*92*

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Appendix 1. Test Driving Cycles

The driving cycles that the test vehicles/engines were subjected to during the source testing are summarized as follows. The test vehicle speeds over the duration of the driving cycles are shown in the referenced figures.

- Idle—the vehicle is operated at a zero speed (Figure A1).
- Creep—a slow speed driving mode (Figure A2).
- Cruise— the vehicle is operated at a constant speed in cruise cycles (Figure A3).
- HW—the Highway cycle is also known as the Freeway cycle, which is based on the operation of the tractor's travels on 4-lane restricted highways (Figure A4).
- UDDS—the EPA Urban Dynamometer Driving Schedule (UDDS) has been developed for chassis dynamometer testing of heavy-duty vehicles [*CFR 40, 86, App.I*]. It is sometimes referred to as "cycle D" (Figure A5).
- CARB 5Modes—this schedule is developed for heavy-heavy-duty diesel trucks (HHDDTs, gross vehicle weight > 33,001 lbs) by the CARB staff. The test cycle consists of five speed-time modes, including an idle mode, a slow speed 'creep' mode (cycle average speed = 1.8 mph), a transient mode (cycle average speed = 15 mph), a 40-mph cruise mode, and a 50-mph cruise mode (Figure A6).
- CSHVR—the City Suburban Heavy Vehicle Route (CSHVR) is a chassis dynamometer test for heavy-duty vehicles developed by the West Virginia University (Figure A7).
- HCS and CCS—in one of the studies, vehicles were tested on hot start CSHVR (HCS) and cold start CSHVR (CCS) separately.
- FTP Transient—the Federal Test Procedure (FTP) heavy-duty transient cycle is currently used for emission testing of heavy-duty on-road engines in the USA *[CFR Title 40, Part 86.1333]*. The transient test was developed to take into account the variety of heavy-duty truck and buses in American cities, including traffic in and around the cities on roads and expressways. The FTP transient test is based on the UDDS chassis dynamometer driving cycle. The cycle includes "motoring" segments and, therefore, requires a DC or AC electric dynamometer capable of both absorbing and supplying power (Figure A8).
- HHDDT Transient—the Heavy Heavy-Duty Diesel Truck (HHDDT) Transient cycle is the transient test mode in the CARB 5Modes (Figure A9).
- CBD—the Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (SAE J1376). The CBD cycle represents a "sawtooth" driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes (Figure A10).
- MC—Manhattan Bus Cycle (MC) is a chassis dynamometer test for urban buses. The Manhattan cycle was developed based on actual observed driving patterns of urban transit buses in the Manhattan core of New York City. The cycle is characterized by frequent stops and very low speed. Vehicle speed over the duration of the Manhattan driving cycle is shown in the following figure (Figure A11).
- 16-hour cycle— it is comprised of four 4-hour segments of the FTP and the CARB-5Modes cycles. For the purpose of ACES, the chassis cycles of FTP and CARB-5Modes were converted into engine dynamometer cycles by WVU, and the 16-hour (animal exposure) engine dynamometer test cycle represents a 50-50 split between 'urban'(transient operation)

and 'rural' (high speed cruise) operation. Sixteen hours cycle duration was selected because this is how long the engine is being run daily for the animal exposure (Figure A12).

- Mode 9 and Mode 11—are two steady-state operating conditions chosen from the old EPA 13 mode test cycle: Mode 9 (933 Nm, 1800 rpm) and Mode 11 (311 Nm, 1800 rpm).

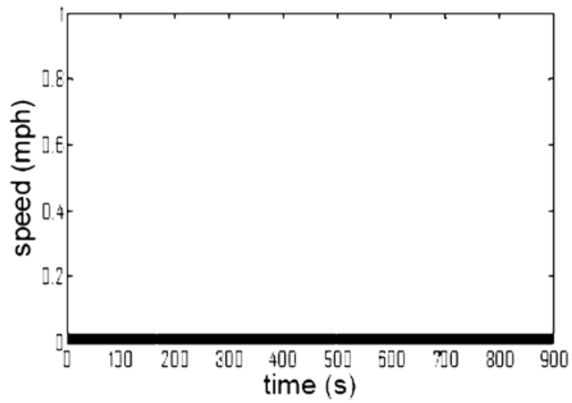

Figure A1. Idle Cycle

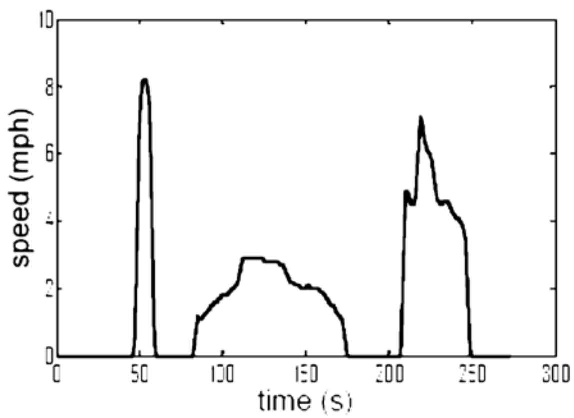

Figure A2. Creep Cycle [19]

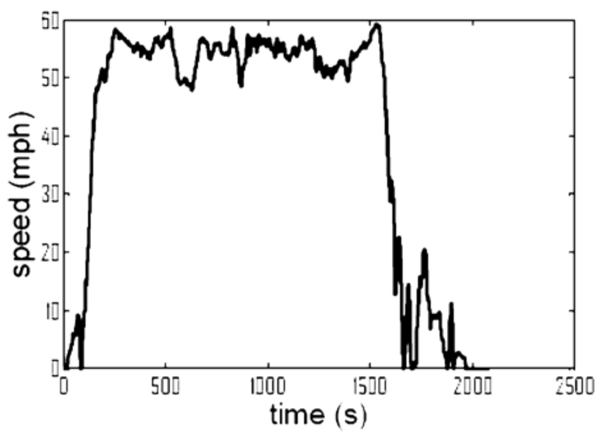

Figure A3. Cruise Cycle [19]

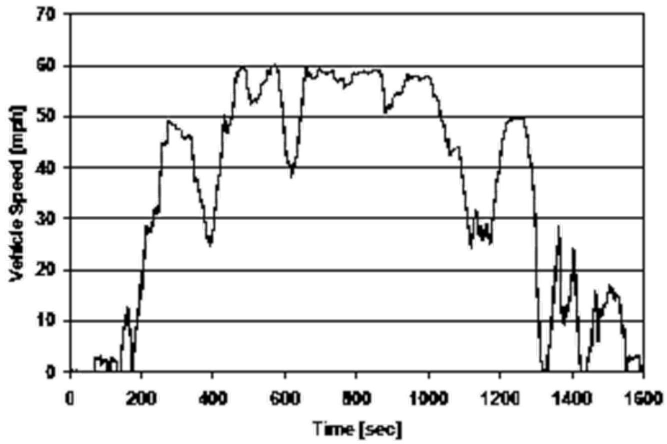

Figure A4. HW Cycle [20]

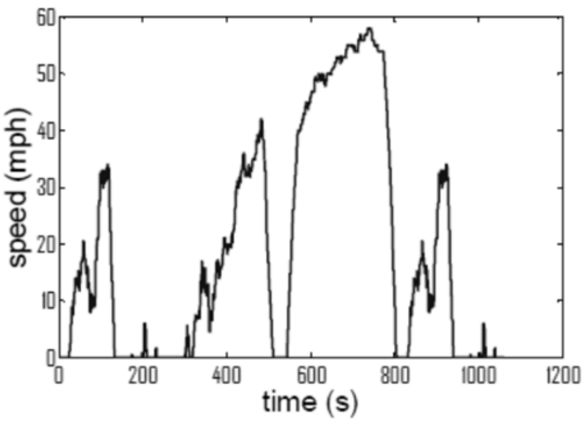

Figure A5. UDDS Cycle [19]

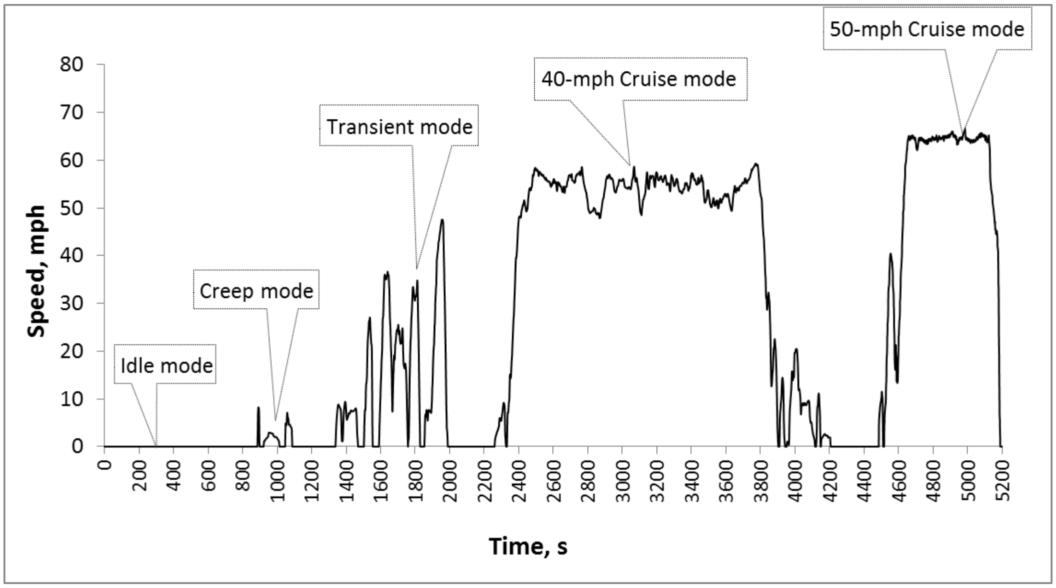

Figure A6. CARB 5Modes Cycle

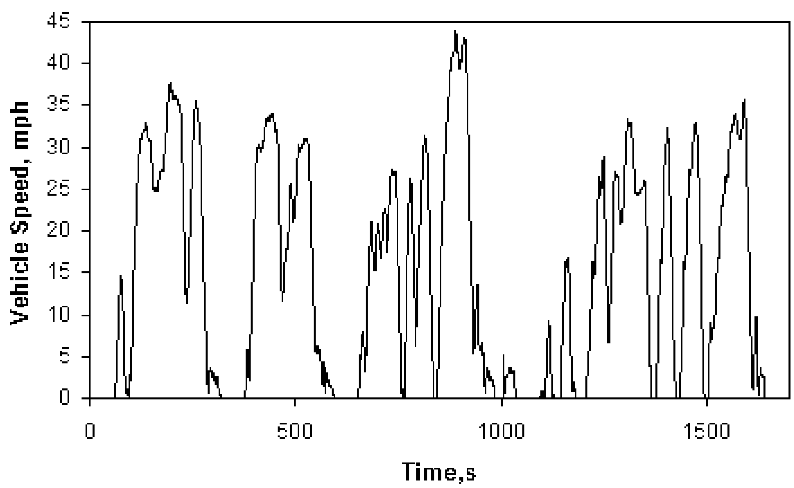

Figure A7. CSHVR Cycle [19]

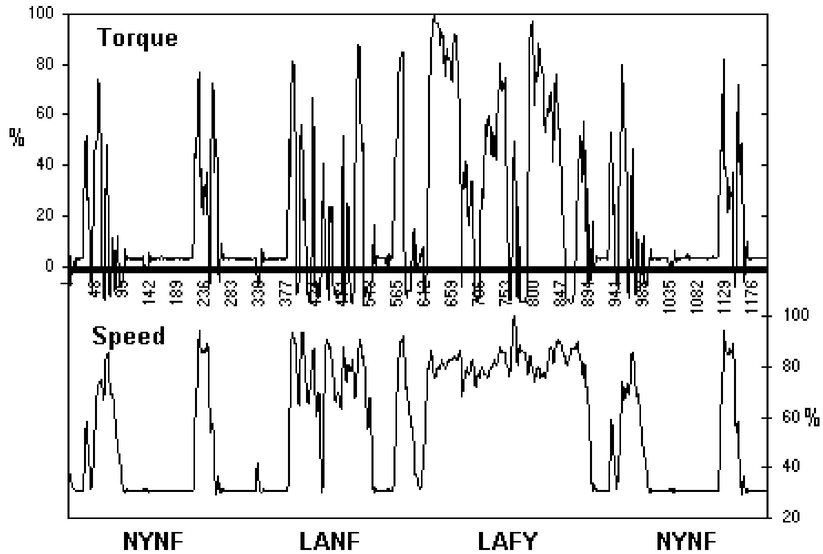

Figure A8. FTP Transient Cycle [19]

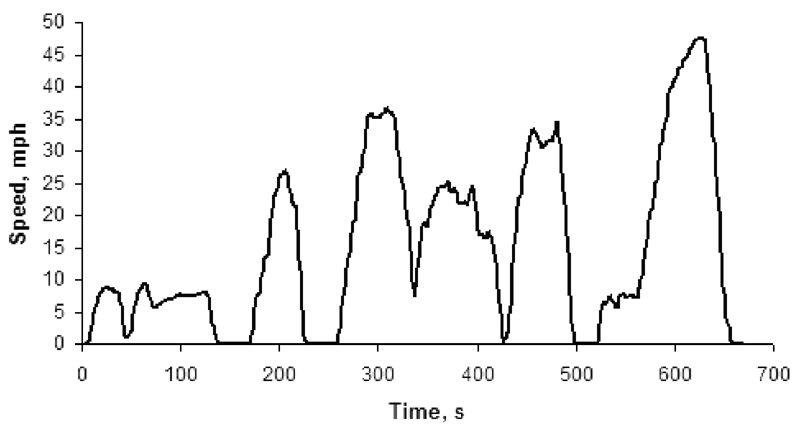

Figure A9. HHDDT Transient Cycle [19]

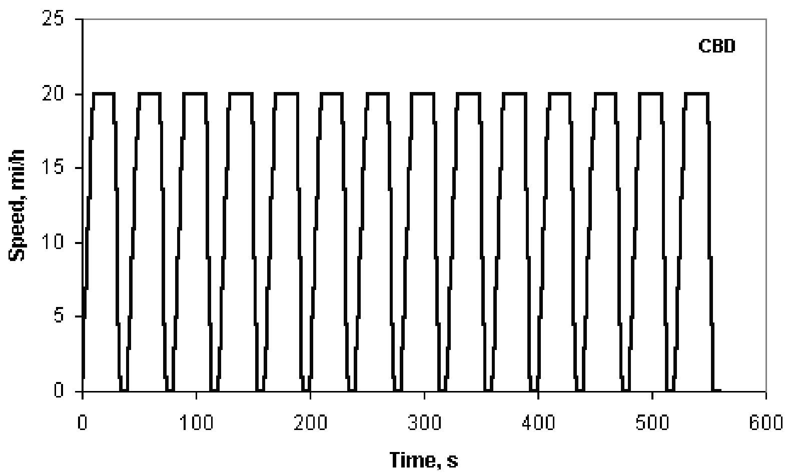

Figure A10. CBD Cycle [19]

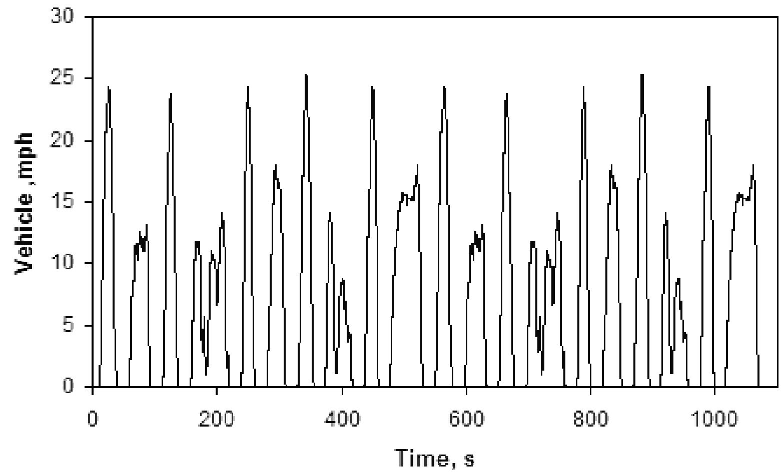

Figure A11. Manhattan Bus Cycle [19]

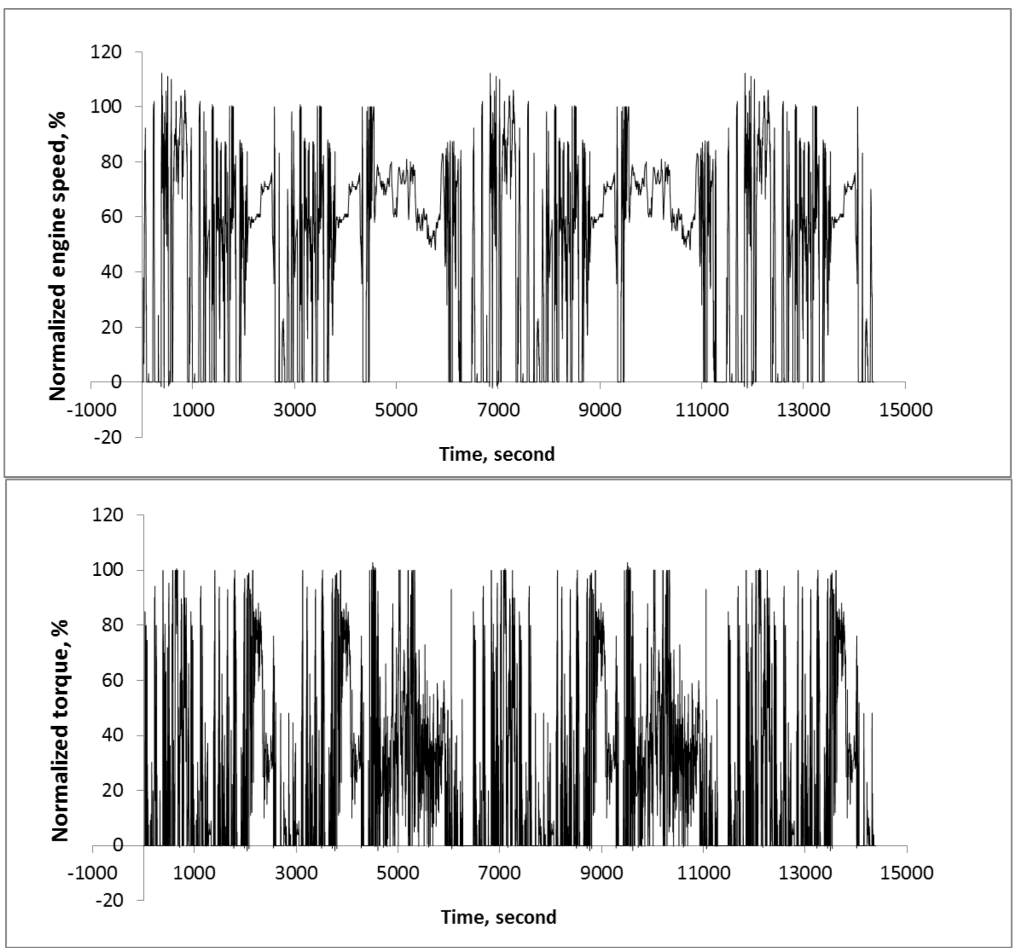

Figure A12. 4-hour Sub-cycle of 16-hour Cycle [10]

Appendix 2. DieselPM.mdb

(Available upon request)