Eastern Research Group, Inc.

Updates to Heavy-Duty Emission Deterioration in EMFAC

Agreement No. 17AQP006

Report
Version 3

Prepared for:

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Executive Summary

Background

The objective of this study was to gather information to update heavy-duty (HD) truck emission rates in CARB's mobile emissions inventory model, EMFAC. In the EMFAC model, emissions are calculated as a combination of the zero-mileage emission rate ("controlled" emission level when the truck is new) plus the increase in emissions due to tampering, malfunctions, and mal-maintenance (TM&M). The EMFAC model assumes emissions are stable in the absence of TM&M actions. These EMFAC model updates are necessary in order for the model to more accurately represent emission deterioration of late-model (engine 2013 and newer) heavy-duty trucks with enhanced emission controls including selective catalytic reduction (SCR) systems, diesel particular filters (DPFs), and exhaust gas recirculation (EGR) systems. In order to obtain the data needed for these updates, on-board diagnostic (OBD) data from a large sample of the HD onroad fleet was gathered and analyzed to characterize the deterioration of powertrain components and of these aftertreatment control systems.

Methods

In order to update the EMFAC model's HD truck "TM&M action" categories and emission deterioration rates, the ERG team gathered OBD data from various on-road truck samples. OBD data was collected in-field from approximately 450 California-based trucks, and OBD data was also acquired from a large telematics service provider for a fleet with operation in California as well as a national fleet. The telematics data sample consisted of approximately 28,000 trucks operated in California and 180,000 trucks operated in the US. The in-field data collection was performed 2019 from various locations in southern and northern California, and the telematics samples were based on 2019 data.

The OBD data was used to determine truck malfunction indicator light (MIL) illumination rates, as well as the specific types of failures (TM&M actions). Analysis focused on malfunctions or failures that could cause an increase in truck emissions. The EMFAC model's existing TM&M categories were adjusted to align with the types of failures for late model (2013 and newer) trucks, based on the data collected for this program.

Using the mileage-based MIL rates (i.e. the MIL status is "Lamp On"), CARB developed a logarithmic function to model truck malfunction indicator light (MIL) illumination rates and TM&M category-specific failure frequencies as functions of mileage. CARB personnel also used results collected during durability demonstration vehicle (DDV) testing to estimate emission changes for each type of TM&M category, and consequently an overall emission impact rate (EIR) as the product of the TM&M failure frequency and emissions change, by TM&M category, for both oxides of nitrogen (NOx) and particulate matter (PM) emissions.

Results

The overall average MIL rate for the telematically-equipped fleet sample provided for this program ranged from approximately 6 % (California fleet, average fleet mileage of 101,377 miles) to 8 % (national fleet, average fleet mileage of 90,249 miles), whereas the MIL rate for the fleet field-tested in California was approximately 10% (average fleet mileage of 223,248 miles). The in-field fleet (from which roughly 250 vehicles were used to estimate a MIL illumination rate) had higher age and mileage distributions than the US and California telematically-equipped fleet, as shown in Figures ES-1 and ES-2. Results from the national telematics fleet were fitted to a logarithmic function to develop a mileage-based MIL illumination rate that ranged from 8% (0-100k miles) to 22% (at 1,000k miles). Based on these MIL rates and the TM&M categories scaled by the logarithmic MIL function, the new EIRs developed under this program are higher than the EMFAC 2017 EIRs at lower-mileages (roughly 0-500,000 miles), but then tend to reach a maximum value of roughly 90% (NOx) and 270% (PM) emissions increase rates, lower than the current EMFAC 2017 model.

Figure ES-1: Model Year Comparison of Fleet Counts

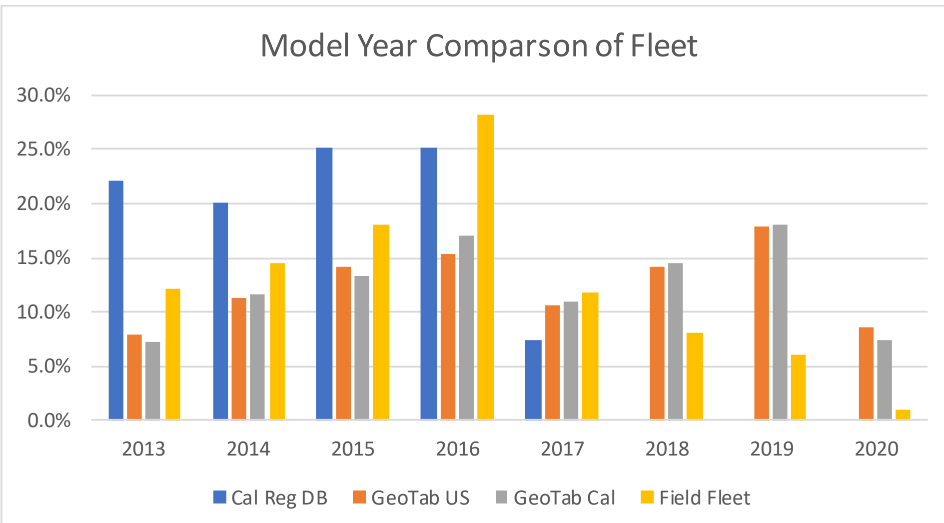
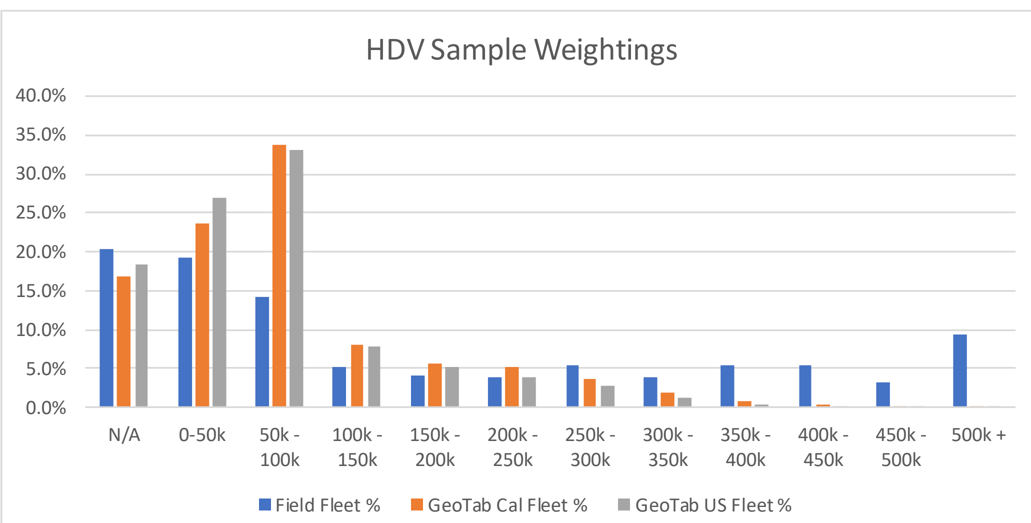


Figure ES-2: Field and Telematics Data Sample Weightings by Mileage Bins



Conclusions

This study presents initial results of truck powertrain and emission control system malfunction frequencies, emissions changes, and associated emissions impact rates developed under this work agreement. This will allow the EMFAC model to more accurately estimate and predict emissions from later model-year HD trucks as they age and deteriorate. Additional revisions to these estimates are anticipated as TM&M categories and their associated frequencies are refined. This may include adjustments to better account for multiple OBD codes contributing to the same TM&M category, or developing models to better predict individual TM&M category rates. Future adjustments are also likely as the list of “emission-related” codes from HD truck OBD systems are refined.

1.0 Introduction

This report documents a program conducted by ERG under contract to the California Air Resources Board (CARB) in order to gather data and perform analysis to update late model (model-year 2013 and newer) heavy-duty (14,001 lbs. and higher) diesel truck (HDDT) emission rates in CARB's on-road mobile source emissions factor model, EMFAC, which is used in California's air quality planning, rulemaking and inventory efforts.

The specific approach for EMFAC updates included consideration of new emission control technologies and component-specific diagnostics available through on-board diagnostic (OBD) systems (in this study, heavy-duty truck vehicle data networks compliant with either SAE J1939 or SAE J1979 standards are generally referred to as OBD). This data collection effort was necessary since existing EMFAC deterioration rates are based on vehicles without SCR and DPF systems.

Base emission rates for motor vehicles may be calculated on a concentration basis or as mass emissions per unit measure (such as distance, time, power or fuel). The CARB's EMission FACtors (EMFAC) model calculates statewide or regional emissions inventories by multiplying emissions rates with vehicle activity data from all types of motor vehicles, including passenger cars to heavy-duty trucks, operating on highways, freeways, and local roads in California.[1] For HDDTs of a given model year and mileage, running exhaust emissions in EMFAC are a combination of the emission rate of the fleet when it is new (otherwise known as the zero mile emission rate, ZMR) plus the incremental rate that emission levels increase with mileage due to degradation, tampering, and malfunctioning of engine and after-treatment systems (otherwise known as the deterioration rate, DR).[2] In the EMFAC model, running exhaust emissions are assumed to remain stable in the absence of tampering, malfunction and mal-maintenance (TM&M).

The intent of this program was to collect and use OBD data from target vehicles in order to revise existing TM&M categories and frequencies of occurrence to better represent powertrains and emission control technology performance of these late-model vehicles. The approach to collect this data, the specific OBD data that was used, and the methodology for calculating these category rates are described in this report.

To perform this work, ERG teamed with the University of California at Riverside's College of Engineering's Center for Environmental Research and Technology (CE-CERT) and their subcontractor, Andrew Burnette of MeasureMission to collect the necessary in-field OBD data. A large sample of OBD information from on-road HDDTs in California, telematics data was also acquired and used to update the HDDT deterioration rates in the EMFAC model.

[1] EMFAC2017 Volum I – User's Guide, March 1, 2018, Mobile Source Analysis Branch, Air Quality Planning & Science Division, California Air Resources Board, page 5

[2] California Air Resources Board, RFP Number 17AQP006, Page 4.

2.0 Materials and Methods

This section provides a description of the work performed to accomplish this study. As noted previously, the focus of this study was to update HDDT emissions deterioration rates in the EMFAC model, with consideration of new emission control technologies and component-specific diagnostics available through OBD systems. ERG followed a multi-tiered approach for collecting a large sample of OBD information from HDDTs, and used that data to assist CARB in updating the HDDT deterioration rates in the EMFAC model. This approach built on our prior experience with the EMFAC model and our experience in collecting and analyzing SAE J1939 and SAE J1979 data.

2.1 Study Plan

To initiate this program, ERG developed a study plan that provided details on all the necessary steps for accomplishing this work. As part of this effort, ERG developed draft forms to collect the necessary truck "metadata" (truck description data) and also the truck owner / driver information that our team attempted to collect from study participants in the field campaign (this form is provided in Appendix A). We also drafted target OBD (SAE J1939 and SAE J1979) parameters to be collected as part of our data collection campaign, and these parameter lists were revised over time to meet project requirements and data availability. The parameters used in this program are provided in Section 2.2.1 of this report. The study plan also outlined ERG's approach for conducting the data collection campaign, performing analysis to support the EMFAC updates and reporting. These efforts are described in the following subsections.

2.2 Data Collection Campaigns

ERG and our partners CE-CERT and MeasureMission used several approaches to collect OBD data from the 2013 and newer HDDT fleet in California. In-field data collection efforts were used to gather information from on-road fleets in both Southern and Northern California regions, and data was also sought from other sources such as I/M programs, special studies, telematics companies, and other organizations. An effort was made to collect a representative data sample in terms of various vehicle characteristics such truck manufacturer, model, model year and also engine manufacturers, vocation types, and ownership types, to the extent possible. The target fleet was engine model year (MY) 2013 and newer HDDT trucks operating in California that are no longer in their warranty period (although we collected data on all possible 2013 and newer HDDTs, regardless of mileage). Procedures were in place to account for sample bias in terms of malfunction indicator light (MIL) command status, repairs needed, vocations (such as a predominance of drayage trucks at the port) or other potential sampling bias factors. For example, repair shop data was not used to develop on-road MIL illumination or diagnostic trouble code (DTC) storage rates but was instead used to estimate the relative prevalence of types of DTCs (within emission category groupings). Results from sampling performed at truck stops and ports were considered for use in developing MIL/DTC rates. In addition, it was understood that MIL rates for telematically-equipped fleets could be biased low due to driver, owner or fleet response to the continual OBD monitoring and reporting, so these rates were compared with real on-road sample rates as a check for reasonableness.

2.2.1 In-Field Data Collection Campaign

This section summarizes preparation and quality control evaluations for the in-field data collection effort, the equipment used in the effort, and the approach for this effort. Preparation for the in-field effort began in the fall of 2018 (including equipment development and testing at several fleets in the Denver, Colorado area and follow-up testing at the EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. Actual fieldwork then commenced in February 2019 and continued through September 2019.

2.2.1.1 Equipment Evaluation and Preparation

With the support of EPA, ERG assessed several types of electronic control module (ECM) interrogation and data collection devices as part of our quality control process to evaluate data collection equipment. We anticipated most vehicles to be tested in the program would be SAE J1939 compliant, although we also envisioned encountering some SAE J1979 compliant trucks (such as late-model Volvo, Ford, Mack, or other vehicles that might broadcast SAE J1979 messages on the ISO 15765-4 CAN network to a SAE J1962 connector). This system confirmation evaluation was performed at various truck rental, repair and fleet facilities in Denver, Colorado with the support of personnel from the Colorado Department of Public Health and Environment (CDPHE), and follow-up testing was performed at EPA's NVFEL in Ann Arbor, Michigan. Equipment preparation testing was performed on a variety of 2013 and newer HDDTs, including trucks compliant with both J1939 and J1979 systems. Results from multiple data collection systems were then evaluated and compared with one another to assess test equipment suitability for this study. Based on this evaluation, the HEM Data Dawn Mini (provided by the US EPA for use in this program) and RA Consulting's Silver Scan software on a dedicated laptop with an appropriate CAN adapter (provided by Sara Forestieri of the California Air Resources Board) were selected for use in the upcoming program. Other than development of test configuration settings, no modifications were necessary for the Silver Scan or HEM Data equipment (the HEM Data logger's configuration file was modified to allow it to collect specific request-only diagnostic information from targeted controllers). ERG and EPA worked with HEM Data to ensure the necessary HDDT diagnostic information was appropriately collected and reported (using the data collected during the preparation study for an evaluation).

The HEM Data was configured to collect all diagnostic message 1 (DM1) (Active DTCs) data on both SAE J1939 Controller Area Network (CAN) 1 and 2 channels. DM1 is a broadcast message and requires no special data request. In addition, the logger was configured to request and store request-only diagnostic messages (again, both CAN1 and CAN2). The full list of requested messages is shown in Table 2-1:

Table 2-1: Diagnostic Messages Collected with the HEM Data DAWN Mini logger

Diagnostic Message	PGN	Parameter Group
DM1	65226	Active DTCs
DM2	65227	Historical DTCs
DM6	65231	Emission-Related Pending DTCs
DM12	65236	Emission-Related DTCs
DM23	64949	Emission-Related Historical DTCs
DM27	64898	All Pending DTCs
DM28	64896	Emission-Related Permanent DTCs

The HEM Data logger was configured to request Table 2-1 messages from the following controllers:

Table 2-2: Controllers Queried by the HEM Data Logger

Dec.	Hex	Controller
0	0	Engine #1
1	1	Engine #2
2	2	Turbocharger
3	3	Transmission #1
4	4	Transmission #2
18	12	Fuel System
34	22	Aux Valve Control
52	34	Ign Control Mod #1
53	35	Ign Control Mod #2
61	3D	Exh Emission Controller
70	46	Eng Valve Controller
81	51	Aftertreatment #1 intake
82	52	Aftertreatment #1 outlet
85	55	DPF Controller
86	56	Aftertreatment #2 gas intake
87	57	Aftertreatment #2 gas outlet
89	59	Atmospheric Sensor
90	5A	Powertrain Control Module
91	5B	Power Systems Manager
92	5C	Engine Injection Control Module

SAE J1939DA "Global Source Addresses", February 2018

In additional to the J1939 diagnostic data listed in Table 2-1, the HEM Data logger was also configured to automatically collect J1979 (OBDII) MIL and DTC information from vehicles that were J1979 compliant.

As part of our quality control process, data collected during the evaluation study by the specially-configured HEM Data logger were compared with data collected from the Silver Scan-equipped device, and based on this comparison, ERG concluded that differences in results between these two systems could be primarily attributed to the different loggers occasionally collecting data from different reporting controllers. The team proceeded with testing primarily with the HEM Data logger, but whenever possible during the main study, for trucks with the MIL commanded on, data was collected using both instruments (the HEM Data and the Silver Scan) to ensure data completeness and accuracy for trucks with fault codes.

2.2.1.2 Collection of Driver and Truck Information and Incentives

Appendix A provides the truck owner / driver information and also the truck metadata data collection forms that were developed for use in the field effort. However, due to field data collection staffing and time constraints, the field data collection team was limited to collection of truck metadata but not vocation or other driver operation information.

In order to streamline the process of collecting truck metadata, and to allow additional verification of data collected in the field, the field team collected truck information photographically, capturing digital images of all the necessary information for subsequent transcription, rather than writing information by hand in the field. This included capturing an overall photograph of the truck (including license plate and/or truck identifier), and also closeups of all engine power, certification and emission control labels. Photos were taken in sequence with preceding photos providing identifying information. Data were later entered and verified by staff.

Incentives were provided to drivers and study participants to facilitate participation in the field data collection campaign. Although the original incentive was set at $15, early in the program this was discovered to be insufficient to foster participation, and incentive amounts were increased. Overall, incentives to individuals ranged from $15 to $50, with an overall average incentive of $26 per truck (excluding group testing arrangements for testing multiple vehicles at fleets and repair shops).

2.2.1.3 Field Testing

Personnel from CE-CERT provided testing support for southern California, while MeasureMission provided northern California testing support. Each team (southern and northern) were equipped with EPA-provided HEM Data loggers specially configured for this study and also with Silver Scan software on Panasonic Toughbook laptop computers provided by CARB. Both the HEM Data loggers and the Silver Scan laptops were equipped with the necessary adaptors to connect to and communicate with both J1939 and J1962/J1979-compliant vehicles. Testing was performed according to the guidelines provided in Appendix B.

As per the study plan, our team targeted model year 2013 and newer HDDTs that were beyond their warranty period, regardless of MIL status. However, as requested by CARB during a project kickoff call, we expanded our data collection to all 2013 and newer HDDTs, regardless of mileage or warranty status. All OBD data collected for this program was collected voluntarily (truck drivers and owners were under no obligation to participate), and truck selection was performed without regard to the truck's MIL status, condition of aftertreatment control systems, or needed repairs. During the field collection effort, ERG attempted to acquire data on both in-state (California-registered) as well as out-of-state trucks (all data was collected in California). Also, as requested by CARB, our team prioritized later-model (model year 2016 and newer) high-mileage trucks, as these late model trucks would likely have a greater compliance rate with SAE J1939 standards, but earlier model-year trucks (2013 – 2015) were not excluded from the program. The ERG Team collected OBD data on all available model year 2013 and newer trucks that we encountered (dependent on driver participation). Some pre-2013 trucks were tested in the program, but data from these trucks were not included in the results.

An attempt was made to capture data from all trucks with the HEM Data logger. For trucks with a MIL commanded on, the field inspector also attempted to scan the truck with the SilverScan equipment. HEM Data files were primarily used for fault determinations and dispositions for this study. For trucks with the MIL commanded on, the HEM Data results were compared with the SilverScan results (whenever available) to ensure the results were consistent in terms of study disposition. If for some reason neither the SilverScan nor the HEM Data files provided meaningful results, this vehicle was dropped from the results compilation.

In addition to verbally recruiting drivers and offering a cash incentive, eligible candidates were provided English / Spanish recruiting brochures, as shown in Appendix C. The voluntary nature of the program was emphasized, and cash incentives were paid on-site at the time testing took place. As shown in Appendix C, two versions of the recruiting brochures were used, depending on whether or not an ELD disconnect was required for testing. Prior to the study, CARB had developed an arrangement with the California DOT to assist in case an ELD-removal trigger occurred. However, since the actual scan (with the ELD removed) did not require starting the engine, we are not aware of any ELD-removal triggers occurring.

In order to avoid possible inherent bias (toward vehicles in need of repairs or still within their warranty period) and to ensure we captured trucks in an in-use condition, our team prioritized testing at ports, commercial / rental fleets, and truck stops rather than at repair facilities. HEM Data files from in-use on-road trucks tested during prior CE-CERT studies were also compiled and reprocessed for use this study, and additional HEM Data collection from on-going CE-CERT testing was also performed to supplement study data. For HEM Data files that were compiled from prior programs, only one un-processed file was randomly selected from each eligible truck tested in the prior program in order to avoid double-counting.

A summary of in-field testing and other data compiled for this study is provided in Table 2-3. Note that data counts for prior studies are lower than the total study counts since only 2013 and newer HD diesel trucks were included. The three prior studies include:

- SCAQMD Study – In this study, CE-CERT collected and analyzed activity, operational and emissions data from heavy-duty vehicles in order to better understand the emissions and activity profiles of different vehicles and vocations (goods movement, delivery, refuse, school bus, & transit buses).

- ARB Activity Study – In this study, CE-CERT collected and analyzed activity and operational data from trucks that frequently stop as they deliver goods locally, operate at low speeds, are frequently turned off, or operate in other ways that could challenge the NOx reduction effectiveness of their selective catalytic reduction (SCR) system.

- ARB Aero Study – In this study, CE-CERT collected activity and operational data to assess the potential greenhouse gas emissions benefit that could be derived from improved aerodynamics of four trailer types (flatbed, tanker, curtainside and container chassis trailers) not currently required to meet CARB's existing tractor-trailer greenhouse gas regulation.

For these three prior studies, only diesel trucks were included in the sample, and selection was made based on engine model year (since engine model year is generally as new or newer than truck model year). Natural gas or other fuel types were excluded, as were trucks that were 2012 and older. A summary of trucks tested in the program is provided in Table 2-3.

During the field test program, the ERG team encountered 21 vehicles with the J1962-style connector (light-duty OBDII-style trapezoidal DLC). These vehicles broadcasted either SAE J1979 data or SAE J1939 data. For those vehicles with J1979 data, results were converted by ERG to J1939 DM formats for processing and analysis. Only one vehicle with J1979-format data reported a DTC, but that was a manufacturer-specific DTC that could not be mapped to a J1939 equivalent DM. All other vehicles either had no faults or the data were provided in J1939 format.

Table 2-3: Sources of In-Field Test Data

Data Source	Date Range	# of Trucks	Comments
Southern			
Port / drayage Operations	2/2019 – 3/2019	58	Study-specific configuration, testing at Clean Truck Assistance Center
Local delivery operations	4/2019	21	Study-specific configuration
Prior studies	6/2015 – 5/2018	95	HEM, Only DM1 parameters (MIL, SPN, FMI, OC), from current in-field study
Truck service and repair facilities	07/2019	147	Study-specific configuration, repair facility and used trucks sales depart (used trucks being prepared for sale, service before scans so potential MIL bias)
Northern			
Intermodal freight support	06/2019 – 08/2019	14	Study-specific configuration
Construction operations	06/24/2019	4	Study-specific configuration
Local utilities and solid waste services	06/2019 – 08/2019	45	Study-specific configuration
Port / drayage Operations	7//2019	2	Study-specific configuration
Both Southern and Northern			
Truck stops, IOOs, other individuals	06/2019 - 07/2019	21	Study-specific configuration

2.2.1.4 Collection of Data from Other Data Sources (non-field testing)

In addition to in-field data collection, ERG also explored collecting data from eligible trucks from other existing sources, including telematics / logistics services or other data sources.

Since a primary focus of this study was California-based trucks (operating or domiciled in California), ERG focused on collecting data from trucks operated in California. Ultimately, ERG acquired data from two sources, GeoTab and HEM Data. Data from each of these sources are described in the following subsections.

GeoTab: GeoTab is a privately held telematics company that provides US-based telematics services (among other services). ERG and GeoTab collaborated in order to develop telematics data results (DM1 MIL status and associated SPNs) suitable for use in this study. Due to privacy issues, individual-vehicle data extractions were not possible, but instead, representative data aggregations were developed to meet the needs of the study. GeoTab ultimately provided J1939-based DM1 information for 189,422 US-based HDDTs, 31,487 of which are California-based HDDTs (these were trucks that were present or operated in California at any point within the first 5 months of 2019). Actual counts were lower for various reported datasets since GeoTab eliminated lower-count records that did not meet their privacy rules. For these vehicle datasets, the following data was provided and used in ERG's analysis:

- Counts of vehicles by make; make/model; and make/model/model year, that constitute the US and California samples
- Counts of SPNs occurring for DM1 with illuminated MIL, by mileage bins (both US and California samples)
- Counts of MIL illumination, by mileage bins (both US and California samples)
- GeoTab also provided results of SPN-based market-basket analysis, a type of affinity analysis that reveals associations between items by identifying combinations that frequently occur together. This market-basket analysis was used to determine the probability of specific SPN associations in order to better understand SPN groupings for corrections to minimize double counting when developing TM&M frequency rates

Aggregation was applied by GeoTab in a manner to conform to their privacy filters, and this aggregation is not believed to have significantly affected the reported MIL or SPN rates used for this program. Occasionally, reported numbers are lower for some results provided by GeoTab in order to ensure their results conformed to privacy rules.

In order to avoid double counting, GeoTab provided SPN counts by VIN. Therefore, if SPN 1761 occurred 18 times for a specific vehicle during the period of evaluation, that SPN was only incremented one time in results provided for this program.

Vehicles were considered to have a fault if they had an active DM1 code (PGN 65226) and MIL status (SPN 1213) of 01 (MIL on) or MIL status of 10 with a Flash status (SPN 3038) of 01 (Short MIL Active). Other MIL or Flash SPN dispositions or an active disposition of other lamps (SPN 987 protect lamp, SPN 624 Amber Warming lamp, and SPN 623 Red Stop Lamp) were not considered emission-related faults for the purposes of this program.

SPNs were reported if they occurred at all during the month of February 2019. These were normalized to percentages within mileage bins to represent relative frequencies among TM&M groupings for vehicles with an illuminated MIL.

California MIL illumination rates were provided as average MIL illumination based on the number of operational days over the month of February 2019. US-based MIL illumination rates were based on the assumption that the overall US operational fraction is similar to that of California. Results were aggregated by mileage bins to provide mileage-based overall MIL illumination rates.

ERG categorization of SPNs provided by GeoTab is described in Section 2.3.2.

HEM Data: Through a partnership with Asset Appraisal, HEM Data has been acquiring J1939 diagnostic data (including DM1 MIL status and associated SPNs) on trucks being resold in the US. These are scans performed on trucks prior to resale. ERG initiated conversations with HEM Data in order to assess the feasibility of acquiring such J1939 diagnostic data for use in this study. Although many of these vehicles are non-California vehicles, many of these U.S.-based HDDTs would likely be similar to vehicles operating in California and were therefore believed to be representative of the California HDDT fleet. Although this data could be biased in terms of in-use failure rates (since these are trucks being sold, they might have a low bias in terms of DMs), it could also provide information regarding types of failures for those trucks for which codes (DMs) are present (i.e., they would provide additional information on the distribution of SPNs for trucks with an illuminated MIL). In order to minimize potential bias from ECM resets or repairs on resale, ERG requested trucks that had not recently been reset (DM21, distance travelled since codes cleared). The average distance since codes were cleared for trucks provided by HEM Data was 46,000 km. ERG acquired a sample of 50 trucks from HEM Data according to the following criteria:

- MY 2013 and newer
- 14,001 and heavier GVWR
- Diesel, on-road vehicles (no non-road, no non-diesel)
- Prefer vehicles that have not recently had codes cleared (HEM Data provided time/distance since DTCs cleared)
- Prefer higher mileage vehicles, but also prefer newer (2015 and newer) trucks by various manufacturers, in rough proportion to that shown below (by Manufacturer)
  - Ford, 12%
  - Freightliner, 24%
  - Hino, 4%
  - International, 9%
  - Isuzu, 4%
  - Kenworth, 13%
  - Mack, 2%
  - Peterbilt, 18%
  - Ram, 4%
  - Volvo, 8%
  - Western Star, 2%

The above distribution was based on the HDDT registration distribution provided by CARB for this study. Upon receipt, ERG incorporated the HEM Data diagnostic data into the in-field data the ERG team had collected, and these results were included in overall in-field analysis and reporting.

2.3 Data Analysis and Reporting

2.3.1 Overall Approach

The emissions rate increase of HDDTs as they age is represented in EMFAC through equations that estimate the new-vehicle pollutant emissions rate (also called the zero-mile emissions rate), and a deterioration rate. For heavy-duty vehicles, the deterioration rates in the model have been based on the quantification of vehicles with specific TM&M rates, and the specific impact of those conditions on emissions. As heavy-duty vehicle standards have become more stringent, more aftertreatment technologies are being used by manufacturers to meet these standards. The most stringent standards for heavy-duty diesel vehicles have been in place since the 2010 engine model year, including NO_x and PM standards of 0.2 g/bhp-hr for NO_x and 0.01 g/bhp-hr for PM.

The key assumption in EMFAC for estimating exhaust emissions is that the emissions of heavy-duty vehicles remain stable (i.e. the zero mile emission rate) in the absence of specific TM&M issues. The focus of this task was to build the emissions rate component of EMFAC for engine model year 2013+ HD vehicles based on the data accumulated during this program. The OBD information downloaded from the vehicle scans, collected from CE-CERT's prior special studies, and also acquired from GeoTab and HEM Data was used to revise MIL illumination rates, TM&M action categories and the frequency of occurrence of these TM&M actions. These data were used to form the basis of the revised TM&M categories and frequency rates.

The emissions equations have traditionally been of the following form:

$$ER_{my,p} = \left[ZMR_{my,p} + DR_{my,p} \times Odometer\right] \times SCF_{my,p} \qquad \textit{Equation 1}$$

Where:

$ER_{my,p}$ = Emissions rate for model year *my* and pollutant *p*;
$ZMR_{my,p}$ = Zero-mile emissions rate (g/mile) for model year *my* and pollutant *p*;
$DR_{my,p}$ = Emissions deterioration rate (g/mi/10k mi) for model year *my* and pollutant *p*;
Odometer = Vehicle odometer (miles) at a particular age; and
$SCF_{my,p}$ = Speed correction factor for model year *my* and pollutant *p*.

And:

Equation 2

$$ZMR_{my,p} = \frac{ER_{avg,p}}{\left[1 + EIR_p \times \left(\frac{Odometer_{avg}}{1{,}000{,}000}\right)\right]}$$

Where:

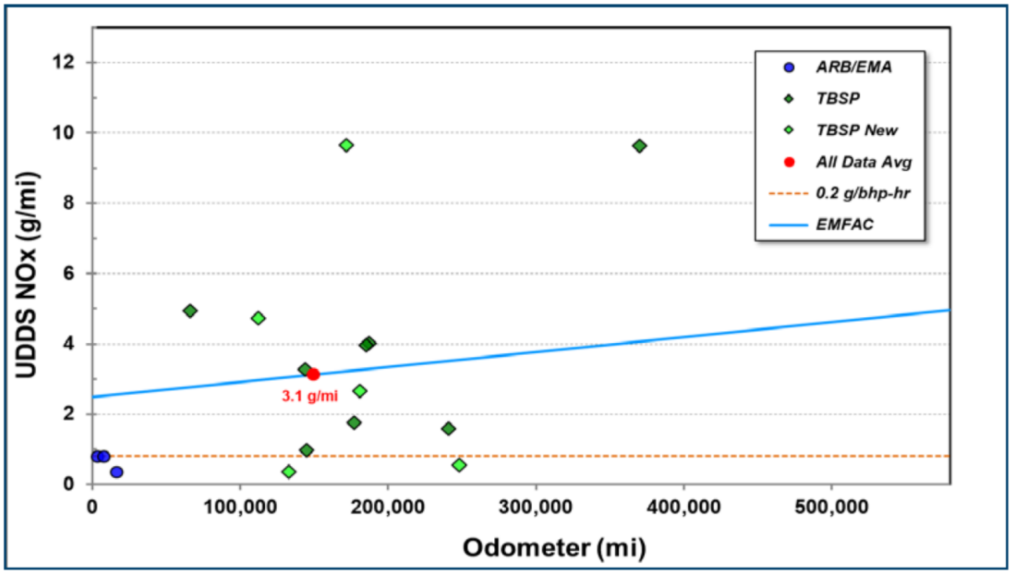
$ZMR_{my,p}$ = Zero-mile emissions rate (g/mile) for model year *my* and pollutant *p*;

$ER_{avg,p}$ = Average pollutant emissions rate (g/mile) for pollutant *p* for test conducted over the UDDS (see Figure 2-1);

EIR_p = Emissions Impact Rate (product of the tampering, mal-maintenance, and component malfunction [TM&M] frequency and emissions rate change [%] for a specific TM&M action) for pollutant *p*; and

$Odometer_{avg}$ = Average odometer (miles) (see Figure 2-1)

Figure 2-1: UDDS NO_x Emissions Rate for 2013+ model Year HDDTs



Source: EMFAC2017 An Update to California On-Road Mobile Source Emissions Inventory, Presentation on November 9th, 2017.

2.3.2 Categorizing Vehicle Faults

All data collected during this program was aggregated into results conforming to categories that aligned with SAE J1939 SPNs. Although SAE J1962 connectors (light-duty OBDII-style connecters) were encountered and tested during the field effort, none of the field testing yielded usable SAE J1979 data (the only J1979 DTCs encountered were manufacturer-specific and could not be decoded). In addition, all GeoTab and HEM Data results acquired from other programs / sources were limited to SAE J1939 data, so the following descriptions focuses on categorizing vehicle faults and developing TM&M categories using J1939 data. This process involved first mapping SPNs to SPN categories, which then were ultimately mapped to TM&M categories in coordination with CARB, as shown in Appendix D.

ERG used the February 2018 edition of the SAE J1939 Digital Annex[3] (DA) to define SPNs collected in this program. Although this document lists approximately 19,000 SPNs, nearly half of these are reserved as manufacturer-assignable and therefore could not be categorized or mapped to TM&M categories. ERG reviewed the remaining J1939 SPNs in order to identify

[3] SAE J1939, Digital Anne, 201805

those that could be emissions-related (including powertrain operation codes) and assigned them to one of the following SPN Categories:

Table 2-4: ERG's Categories for SAE J1939 SPNs

#	Category	#	Category
1	AECD Reporting	19	Gas Ox Cat (SI)
2	Aftertreatment - General	20	Glow Plug
3	Ambient Measurements	21	Hybrid Parameters
4	Auxiliary Valve	22	Ignition / Timing (SI)
5	Combustion Efficiency	23	Intake Measurements
6	Cylinder Head Bypass	24	NMHC Converting Cat
7	Diesel Ox Cat	25	NOx / Sensors
8	Diesel PM Filter	26	NOx Adsorber Cat
9	ECM, Sensors and Control	27	Non-Emissions Related
10	EECS (SI)	28	O2 Sensors
11	EGR System	29	PCV System
12	Engine Cooling/Temp	30	PM Sensors
13	Engine Mechanical	31	Reductant Delivery
14	Exhaust Measurements	32	SCR Catalyst
15	Exhaust Temperatures	33	Secondary Air System
16	Fault Reporting	34	Three-Way Cat (SI)
17	Fuel and Air Delivery	35	Turbocharger
18	Fuel System	36	Unknown or Mfr-specific SPN

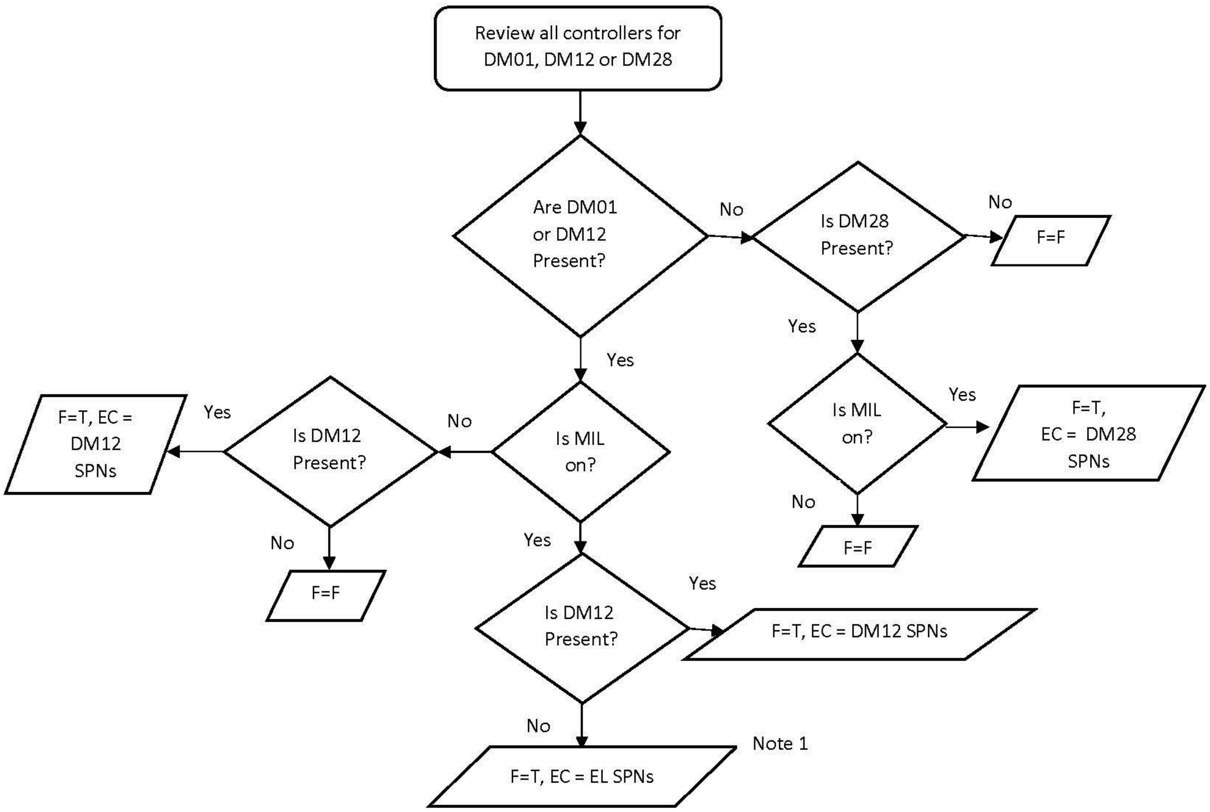
Based on this review, approximately 3500 SPNs were mapped to one of the above SPN categories. ERG then compared this initial categorization with the SPNs collected in the field study and also included in the GeoTab data (both California and US) and HEM Data extraction to ensure all commonly-encountered emissions-related SPNs would be categorized, and as a result of this evaluation, an additional 55 SPNs were mapped to one of the emission-related categories listed in Table 2-4. Although DM1 codes (SPNs) that trigger a MIL by definition are emissions-related, multiple SPNs can be stored in DM1 for any particular controller, and not all of them are necessarily emissions-related (only the MIL-trigger SPN needs to be emissions-related). Therefore, not all the SPNs reported by GeoTab were assigned an emissions-related SPN category. Those SPNs deemed to be non-emissions related were eliminated. In general, cabin comfort codes (HVAC), body and steering codes, brake codes, some electrical codes, and other non-powertrain SPN types were eliminated as non-emissions related. The full list of SPNs categorized as emissions-related and their emission-category assignments are provided in Appendix D.

ERG imported all the data collected in the field, along with the data collected from prior studies and data acquired from GeoTab and HEM Data into Statistical Analysis Software (SAS)[4] for analysis. As previously stated, not all DM1 SPNs for a controller with the MIL commanded

[4] https://www.sas.com/

on are necessarily emissions-related, so the following logic was used to determine vehicle fault status and SPN Categories.

Figure 2-2: SPN Fault and Categorization Logic



Legend:

F = T; Fault = True (vehicle is considered to have an emissions-related fault)

F = F; Fault = False (vehicle is considered to not have an emissions-related fault)

MIL on = MIL status (SPN 1213) of 01 (MIL on) OR MIL status of 10 with a Flash status (SPN 3038) of 01 (Short MIL Active)

EC = DM12 SPNs; Emissions characterization is based on the SPNs listed for DM12

EC = EL SPNs; Emissions Characterization is based on SPNs included in the emissions list (EL)

Note 1: If DM01 has only 1 SPN and that SPN is not on the EL, that SPN (and other similar SPNs in the PGN group) will be added to the EL (since it triggered MIL). If DM01 has 2 or more SPNs and none are on the EL, those deemed emissions-related (including other SPNs in the PGN group) will be added to the EL. If DM01 has 2 or more SPNs and at least one IS on the EL, no others will be added to the EL. Also, for vehicles with F=T, DM12 and DM28 SPNs not on the EL will be added to the EL.

Note 2: Some SPNs initially categorized as “emissions-related” were deemed non-emissions based on CARB input.

As shown in Figure 2-2, a vehicle was categorized as one with an emission-related fault when the MIL was commanded on and it had a DM1 code or if the vehicle had a DM12 code for any controller. If there was DM12 data for a controller, the DM12 SPNs were considered to be the emissions related SPNs. If there were multiple DM1 SPNs and no DM12s, the DM1 SPNs that were on the emissions-related list were considered to be emissions related.

In coordination with CARB, ERG then mapped all downloaded emission results to the revised TM&M categories listed in Table 2-5.

Table 2-5: Revised EMFAC TM&M Categories

Boost Control
Cold Start Strategies
EGR
Exhaust Gas Sensor Monitoring - oxygen
Fuel System Monitoring
Misfire Monitoring
NMHC Catalyst
NOx Sensor
PM Filter
PM Filter Frequent Regen
Reductant Delivery
SCR Catalyst
No Emissions Impact

As shown in Table 2-5, some SPNs were grouped into a TM&M category of "No Emissions Impact". These were "confirmed emissions-related" (either the sole DM1 SPN with MIL on, or a DM12 or DM28), but were deemed by CARB to not have a probable direct emissions-impact. These were retained in the TM&M category list to prevent an upward bias that could result from excluding MIL-illuminating SPNs with minimal emissions impact from our final analysis results.

The final list of "emission-related" SPNs, their occurrences in the combined dataset, and their final assignment to TM&M categories is shown in Appendix D. The final TM&M categories and determination of whether SPNs were deemed emissions related were made by CARB.

Using the final TM&M categories, ERG then categorized faults using logic shown in Figure 2-2 and mapped faults in the field data (non-GeoTab data) to the appropriate TM&M categories. Non-GeoTab data included data collected in the field, data collected during prior programs, and data acquired from HEM Data. The TM&M results for active faults were then placed into 50,000-mile bins, based on the odometer values noted during the field data collection effort. One or more TM&M categories were incremented for each vehicle with one or more SPNs associated with each TM&M category. Once a specific TM&M category was incremented for a vehicle, no additional counts were assigned to that category for that particular vehicle. Therefore, a TM&M category was only incremented once for a vehicle with multiple SPNs that all fell into the same TM&M category, in order to prevent double counting for multiple codes pertaining to the same fault.

The MIL status for trucks tested at service and repair shops was not included in the MIL determination for the field data, since many trucks at these shops were there to receive (or had recently received) repairs, and therefore they were likely to either have faults or have been recently reset after repairs were performed. Also, the visual MIL checks were not used for any fault or MIL command determination (other than for occasional verification of results, as needed).

ERG also imported all GeoTab SPNs (counts were provided in 50,000-mile bins) and mapped these to the appropriate TM&M categories previously developed with CARB (the same TM&M categories used for the field data). SPNs that were not emissions-related (i.e., not likely to trigger the MIL or have a direct emissions impact) were dropped. The total GeoTab SPN counts differed from GeoTab VIN counts since multiple SPNs may be reported per vehicle, and also since low SPN counts below GeoTab's privacy thresholds were not provided to ERG.

Since GeoTab SPN results were provided independent of vehicle (each SPN count represents a SPN-VIN set), an individual vehicle with multiple faults will contribute to multiple SPNs within the GeoTab results. For certain vehicles with multiple SPNs that fall within the same TM&M category, the multiple counts within that TM&M category could result in an overweighting for that category, if the multiple SPNs are associated with the same malfunction. In order to provide data that could be used to adjust for this, GeoTab provided results of SPN-based market-basket analysis (a type of affinity analysis that reveals associations between items by identifying combinations that frequently occur together). This market-basket analysis was used to list the probability of specific SPN associations, in order to better understand "real-world" SPN groupings and apply corrections to minimize TM&M "double-counting" (multiple unique SPNs that contribute to the same TM&M category) when developing TM&M frequency rates. For the initial affinity analysis correlation performed at 85%, no emission-related trends were seen, so GeoTab performed the affinity analysis again at a 60% correlation rate, and still no emission-related trends were seen (no emission-related SPNs were seen to have a 60% correlation).

ERG then reviewed the field data in an effort to gain additional information on possible TM&M "double counting" corrections that could be applied to the GeoTab data. To do this, ERG reviewed all occurrences of multiple SPNs within the same TM&M category occurring for individual vehicles within the 457 field-study vehicle dataset. These adjustments would only be appropriate to apply to the GeoTab data, since GeoTab reported SPNs independently of vehicles. No adjustment was necessary for the field data, as individual TM&M categories were not incremented more than once per vehicle for the field data. Results of this analysis are provided in Table 2-6. In Table 2-6, "Active" refers to only the "Active" emission related DTCs with MIL on, per study definitions. "All" refers to "Active", "Pending", and "Historical" emission related DTCs, per study definitions. None of the "All" DTCs represented different types of duplicate SPNs for the same vehicle (i.e., showing the same pending and active SPN, for example, or the same SPN reported under different DMs). Note that no TM&M "correction / reduction" was applied to the "No Emissions Increase" category, due to the methodology used to determine this category.

Table 2-6: SPN / TM&M Double Counting for In-Field Data

TM&M Category	Total # of field vehicles with this TM&M Category		Total # of Veh/TM&M Dups		Duplicate Percentage		Adjustment Factor	
	Active*	All*	Active	All	Active	All	Active	All
Boost Control	2	10	0	4	0	28.57	1	0.7143
Fuel System Monitoring	6	17	0	1	0	5.56	1	0.9444
NMHC Catalyst	1	2	1	2	50	50	0.5	0.5
NOx Sensor	13	24	0	2	0	7.69	1	0.9231
No Emissions Impact	25	N/A	3	N/A	10.7	N/A	1	1
PM Filter	4	28	1	2	20	6.67	0.8	0.9333
Reductant Delivery	9	38	8	19	47.06	33.33	0.5294	0.6667
SCR Catalyst	5	15	0	1	0	6.25	1	0.9375

ERG then applied the double-counting weighting results, by mileage bins, to the California and US fleets. The frequencies of TM&M Categories were grouped by mileage bins in 50,000-mile increments until 500,000 miles, then a final bin of all vehicles greater than 500,000 miles. The California results are based on the field data combined with GeoTab's California-based results, and the US results are based on the field data (California) combined with GeoTab's US-based results. For GeoTab, California results are vehicles with at least some operation recorded in California between January 2019 through the end of May 2019. GeoTab's California and US-based results were collected during the month of February 2019, and counts are based on SPN/VIN combination (if the SPN occurred at all for a vehicle during the month of February 2019, that SPN number was incremented). ERG provided "unadjusted" results, as well as results with adjustments made for possible SPN overlap within TM&M categories, both for "active" code adjustments and "all" code adjustments, as previously described and presented in Table 2-6. Ultimately, as shown in Appendix E, unadjusted TM&M category counts were used for the preliminary emissions determination presented in this report. These determinations, as well as the overall method for calculating the emission impact rate, are preliminary drafts and will likely be refined before EMFAC implementation

GeoTab also provided data to ERG for use in calculating MIL rates for California and the US. The datasets were similar to those used for the SPN reporting (with the exception of SPN exclusions applied by GeoTab in order to enforce their privacy filters). GeoTab average MIL rates and average operational days (both for the month of February 2019) were provided to ERG, and these values were used to calculate estimated MIL rates for the GeoTab fleet sample. In addition, ERG calculated MIL rates from the field data, and results of both GeoTab and field MIL rates are provided in the Results section of this report. Since GeoTab only collected DM1 (not DM12 or DM28), only MIL status is reported for GeoTab data. However, for the field data, either DM1 MIL status or DM12 (emission-related) codes were sufficient to categorize a vehicle as fault = true (as shown in Figure 2-2), so both fault = true and MIL status are reported for field data (these two are similar but not identical, since trucks occasionally had a DM12 code with no MIL commanded on for that controller). As mentioned previously, trucks measured at repair and service centers were not included in the MIL determination for the field data, since many of these trucks were at the repair facility to receive (or had received) repairs, and therefore they were likely to either have faults or have been recently reset after repairs were performed.

ERG provided the data collected throughout the study to CARB, who developed US-based MIL rates, TM&M rates, and emission impact rates based on the data acquired during this study and also other data sources, such as CARB's durability demonstration vehicle (DDV) testing data.

In order to develop US-based rates, the overall average operational (usage) fraction determined for California trucks was applied to the US-based fleet. CARB binned mileage within 100,000-mile bins and developed a logarithmic function to fit the data. Scaling is relative to 90,249 miles, since that is the average odometer reading CARB calculated for the US-based 180,892-vehicle GeoTab fleet (this was the fleet subsample for which MIL results were provided). A line was fit to datapoints between 0 and 500,000 miles, and MIL rates beyond that point were calculated with the fitted-line's equation.

Starting with SPN / TM&M counts provided in Appendix D, CARB reviewed DDV reports and other data in relation to fault codes collected for this program in order to develop draft estimates of emission impact rates (EIRs) for the various failure modes categorized in this program. During this process, CARB changed some SPN counts to zero for several SPNs (specifically SPNs in "EGR", "Misfire Monitoring", "PM Filter", and "Reductant Delivery"), as they were not believed to be faults that would trigger the MIL (e.g. SCR inducement) or have a direct impact on emissions (i.e., DEF line heater issues in a warm California climate or wheel-based vehicle speed faults likely wouldn't directly impact emissions). These SPNs that were changed to zero are shown in red font in Appendix E. These determinations, as well as the overall method for calculating the emission impact rate, are preliminary drafts and will likely be refined before EMFAC implementation. The GeoTab results in these TM&M category counts have not been corrected for double counting.

As previously noted, CARB's TM&M frequency category counts are based on results shown in Appendix E, which are based the counts listed in Appendix D, but with certain SPNs "nulled". The EIRs were developed based on data collected and analysis performed during this program, using TM&M frequencies based on each TM&M category's overall average occurrence in the combined GeoTab US-based sample and the field sample. These TM&M frequencies are combined with estimated emission change percentages to develop TM&M-specific impact rates which are then combined for an overall NOx and PM EIR (again, at 90,249 miles). These NOx and PM EIRs are then scaled by scaling factors developed for the fitted MIL rate that CARB developed in order to develop new NOx and PM EIRs based on this program's data, as presented in Section 3.

2.4 Final Report and Data

This document is the report which includes a description of all tasks conducted for the project. Descriptions of all study activities and methodologies are provided in the preceding sections, and analysis and results are presented in the following Section 3. Section 3 also contains revised TM&M categories, emissions impacts, and revised EIRs based on study data. The revised EIRs will enhance the modeled accuracy and representativeness of EMFAC’s HDDT emissions.

3.0 Results

This section presents results of the data collected and analyzed as described in Section 2. Note that these results are preliminary and therefore subject to change pending further analysis.

Table 3-1 presents truck counts, MIL rates, and fault rates by 50,000 mile bins for vehicles tested in California, including results from the HEM Data Dashboard and prior studies, but excluding vehicles from service and repair facilities, since these facilities and may have bias associated with vehicles recently reset or awaiting repairs. As indicated previously, and denoted in Figure 2-2, a vehicle was categorized as one with an emission-related fault when the MIL was commanded on with a DM1 code or if the vehicle had a DM12 code, hence there was a very slight difference between MIL and fault rate for vehicles tested in the field.

Table 3-1: Field Data Vehicle Counts, MIL and Fault Rates

Mileage Group	Field Count (Trucks)	DM1 MIL Rate	Fault Rate
Unknown	63	14.29%	15.87%
0-50k	60	5.00%	5.00%
50k - 100k	44	6.82%	6.82%
100k - 150k	16	6.25%	6.25%
150k - 200k	13	15.38%	23.08%
200k - 250k	12	16.67%	16.67%
250k - 300k	17	0.00%	0.00%
300k - 350k	12	8.33%	8.33%
350k - 400k	17	11.76%	11.76%
400k - 450k	17	5.88%	5.88%
450k - 500k	10	30.00%	30.00%
500k +	29	13.79%	13.79%
Total / Average	**310**	**10.00%**	**10.65%**

Table 3-2 presents California and US truck counts and MIL rates by 50,000-mile bins for results provided by GeoTab. These GeoTab MIL rates are based on DM1 MIL illumination averaged over the month of February 2019, as described in Section 2. A separate fault rate determination (vs. MIL rate) was not made for GeoTab data, since DM12 codes were not available.

Table 3-2: GeoTab Vehicle Counts and DM1 MIL Rates

Mileage Group	California Vehicle Count	California MIL Rate	US Vehicle Count	US MIL Rate
Unknown	4975	1.73%	33251	0.79%
0-50k	6989	3.36%	48634	4.91%
50k - 100k	9960	6.14%	59750	10.51%
100k - 150k	2376	9.11%	14393	12.87%
150k - 200k	1684	11.51%	9320	15.73%
200k - 250k	1528	12.95%	7053	16.34%
250k - 300k	1112	11.61%	4969	15.23%
300k - 350k	540	15.97%	2287	17.15%
350k - 400k	213	12.37%	872	16.06%
400k - 450k	88	14.19%	300	15.90%
450k - 500k	44	17.80%	105	23.44%
500k +	21	0.00%	48	0.00%
Total / Average	**29530**	**6.10%**	**180982**	**8.15%**

The data from Tables 3-1 and 3-2 are presented graphically in Figure 3-1 (comparison of MIL and fault rates for the data collected in this program) and Figure 3-2 (field and GeoTab sample weightings by mileage bin). These results were developed by binning the field data in 50,000 mile bins, and determining fleet counts within each of these mileage bins, for MIL rates, fault rates, and fleet counts. Each fleet (field, GeoTab California, and GeoTab US) were calculated independently, on a percentage basis.

Figure 3-1: MIL and Fault Rates for Field and GeoTab Data

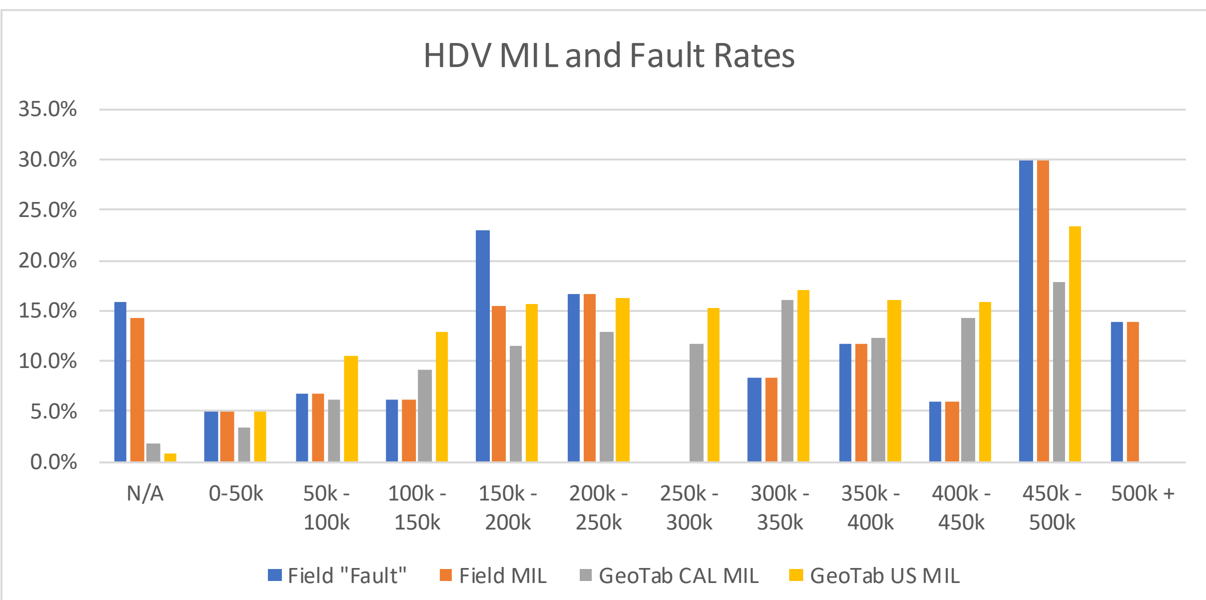


Figure 3-2: Field and GeoTab Data Sample Weightings by Mileage Bins

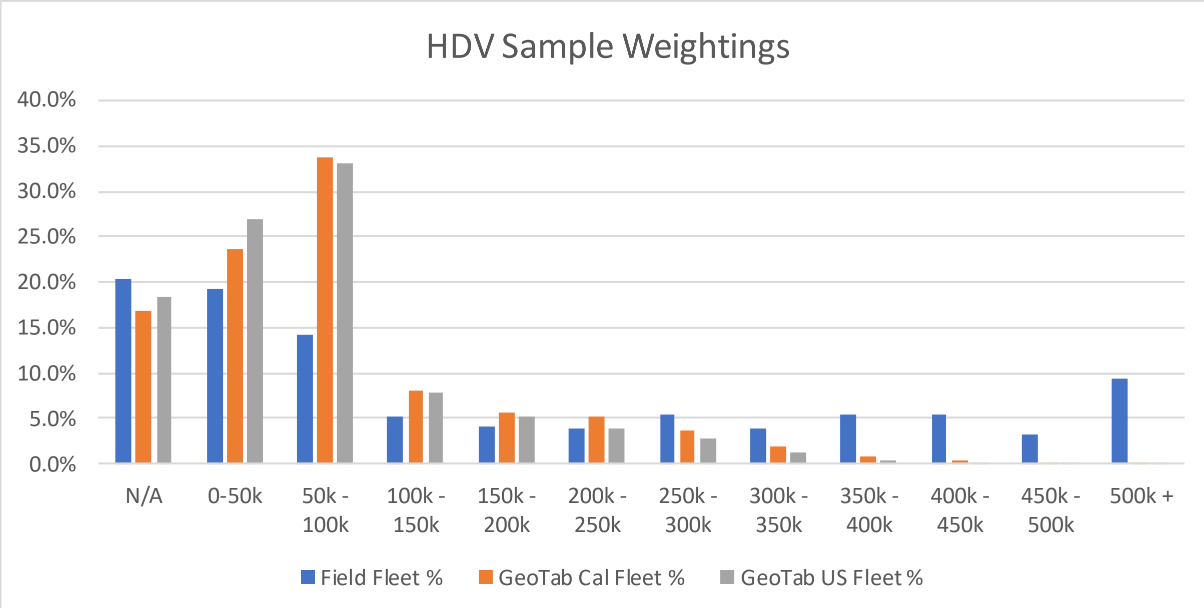


Table 3-3 compares truck counts by anonymized manufacturer for a 2016 California registration database extraction, US and California GeoTab datasets, and the trucks that were field tested and data used in this program, excluding trucks from service and repair facilities. As stated previously, trucks from service and repair facilities were not used in MIL determinations due to potential bias that could be associated with testing at a repair facility. CARB provided the 2016 California database extraction, which was the most current available at the time. The relative percentage for these different fleet samples are shown graphically in Figure 3-3 for those manufacturers that comprised more than 1% of the California registered heavy-duty fleet. Since GeoTab was reported independently of manufacturer, no adjustments were made based on the registration database comparison.

Table 3-3: By-Manufacturer Comparison of Fleet Counts

Manufacturer	2016 Cal Reg DB Count	GeoTab US Count	GeoTab CA Count	Field Test Count
OEM #1	5			
OEM #2	247	436	37	1
OEM #3	26			
OEM #4	145	169	6	
OEM #5	24			
OEM #6	37	8		
OEM #7				17
OEM #8	4			
OEM #9	10706	808	159	13
OEM #10	22240	73858	12059	132
OEM #11				1
OEM #12	19			
OEM #13	25			
OEM #14	3505	6791	1274	

Manufacturer	2016 Cal Reg DB Count	GeoTab US Count	GeoTab CA Count	Field Test Count
OEM #15	2	4462	11	3
OEM #16	8608	66468	11328	8
OEM #17	3865	123	32	
OEM #18	158	328	16	
OEM #19	11083	7690	1619	48
OEM #20	115			
OEM #21	1579	7743	593	6
OEM #22				5
OEM #23	462			
OEM #24				12
OEM #25	10			
OEM #26	4			
OEM #27				5
OEM #28	15894	7223	1422	45
OEM #29	236			
OEM #30	1			
OEM #31	3736			
OEM #32	114			
OEM #33	1			
OEM #34		54		
OEM #35	7543	12002	2764	12
OEM #36	648	1208	151	2
(blank)	4657			
Total	95699	189371	31471	310

Figure 3-3: By Manufacturer Comparison by Fleet

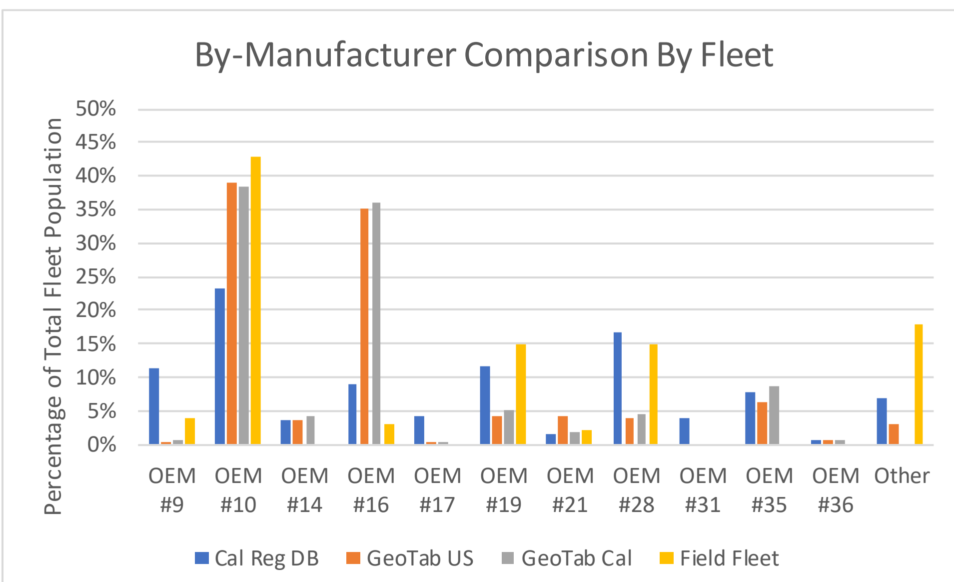
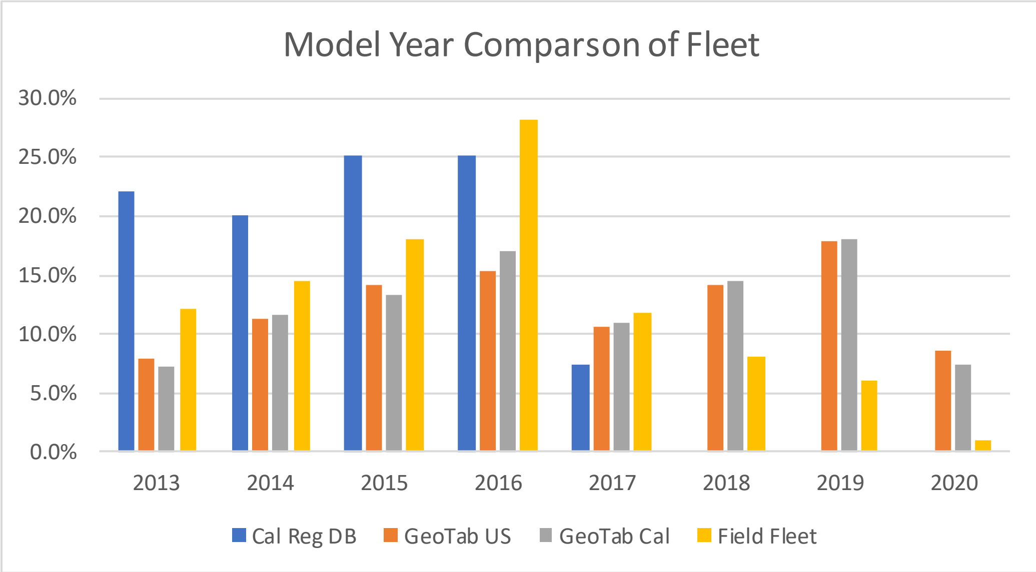


Table 3-4 compares vehicle counts by model year for a 2016 California registration database extraction, US and California GeoTab datasets, and the trucks that were field tested for this program, excluding trucks from service and repair facilities. Results of trucks older than 2013 were not used in this program. This information is shown graphically in Figure 3-4.

Table 3-4: Model Year Comparison of Fleet Counts

Model Year	2016 Cal Reg DB Count	GeoTab US Count	GeoTab CA Count	Field Test Count
Unlisted	4310			
2010				1
2011				6
2012				8
2013	20264	14954	2207	36
2014	18323	21394	3529	43
2015	22947	26723	4042	53
2016	23065	29017	5188	83
2017	6790	20004	3318	35
2018		26525	4383	24
2019		33775	5481	18
2020		16121	2270	3
Total	91389	188513	30418	310

Figure 3-4: Model Year Comparison of Fleet Counts



The information collected in this program has been provided to CARB in order to model mileage-based MIL illumination rates, frequency rates, and overall emissions impacts for the revised TM&M categories developed in this program. This information will be used to update EMFAC emissions estimates for model year 2013 and newer heavy-duty vehicles operated in California.

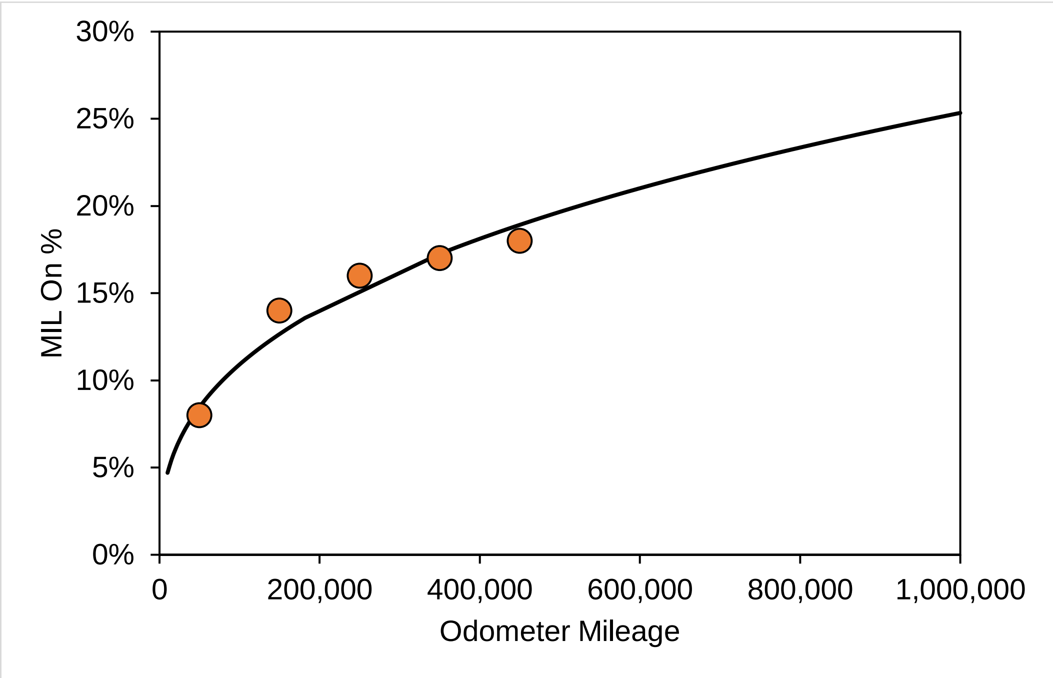
Table 3-5 lists the actual and modeled MIL illumination rates generated by CARB using the approach described in Section 2. The modeled points project MIL illumination rates beyond 500,000 miles, where actual data points were limited in the telematically-equipped fleet from which these results are based. Figure 3-5 graphically presents the MIL-on data points and the fitted line generated by CARB. The equation for the fitted line is:

$$y = 0.0446799912\ln(x) - 0.3995045273 \qquad \text{Equation 3}$$

Table 3-5: Actual and Fitted MIL Rates based on GeoTab US Data

Mileage Group	Actual Data Point	CARB Fitted Point
0-100k	8%	8%
100k – 200k	14%	13%
200k - 300k	16%	15%
300k - 400k	17%	17%
400k - 500k	18%	19%
500k - 600k	N/A	20%
600k - 700k	N/A	22%
700k - 800k	N/A	23%
800k - 900k	N/A	24%
900k – 1,000k	N/A	25%
1,000k – 1,100k	N/A	26%

Figure 3-5: MIL Illumination Rate based on GeoTab US Data



4.0 Discussion

Several different datasets were collected in support of this study, including both in-field data and data collected telematically. The mileage distribution tended to be higher, and ages older, for the trucks from which the in-field data was collected than the telematics fleet. The model year distributions of the fleets are compared in Figure 3-4, and it's noteworthy that the in-field and telematics data sets were collected in 2019, while and the registration sample was drawn in 2016, so these differences should be kept in mind when considering fleet model year distributions.

As shown in Tables 3-1 and 3-2 and Figure 3-1, MIL rates trends tended to align fairly well among the various datasets (in-field vs. GeoTab), especially when considering differences in age and mileage between the fleets.

The data collected in this program will be used to develop revised estimates for mileage-based MIL illumination rates, frequency rates, and overall emissions impacts for the revised TM&M categories developed in this program. These EMFAC model updates are necessary in order for the model to more accurately represent emission deterioration of late-model (engine 2013 and newer) heavy-duty trucks with enhanced emission controls including selective catalytic reduction (SCR) systems, diesel particular filters (DPFs), and exhaust gas recirculation (EGR) systems.

5.0 Summary and Conclusions

This study was performed to collect OBD information from 2013 and newer heavy-duty diesel trucks in order to better characterize the frequency of tampering, malfunction and mal-maintenance of these vehicle's engine and aftertreatment components. This information will be used by CARB to update the heavy-duty deterioration module in CARB's mobile emissions inventory model, EMFAC, and utilize the new frequency rate data to update EIRs in EMFAC.

OBD data was collected from over 400 California-based in-use trucks, and also acquired from a telematics service provider for approximately 28,000 trucks operated in California and 180,000 trucks operated in the US. This OBD data consisted primarily of MIL illumination rates and fault code characterization. The focus of this effort was on characterizing types and rates of fault codes pertaining to the powertrain or emission control system that indicated a problem that could result in an emissions increase.

Emission and powertrain component failures were originally categorized based on downloaded OBD data (from both the in-field data collection effort and telematics data), and these were then aggregated into revised EMFAC model TM&M actions, which aligned closely with the TM&M action categories currently utilized in the EMFAC 2017 model.

There are a number of data sources CARB may look into to understand emissions increase due to aftertreatment or engine malfunction, including manufacturer-submitted durability demonstration vehicle (DDV) testing data, CARB's in-use test programs (e.g. Truck and Bus Surveillance Program), and plume capture studies, After careful assessment of these data sources, they can be used to estimate and corroborate emission change estimates and EIRs for various categorized groups of fault codes encountered for these trucks.

6.0 Recommendations

This report presents initial results of heavy-duty vehicle OBD data collection and characterization to assist CARB in developing TM&M frequencies, emissions changes, and associated emissions impact rates for model year 2013 and newer heavy-duty diesel vehicles. As previously described in Section 2, the telematics SPN data was provided as counts independent of VIN, so one truck could contribute to multiple SPN counts. For multiple SPNs that fall within the same TM&M category, this can result in an overweighting of that TM&M category, in particular if the multiple SPNs from an individual truck are associated with the same malfunction / problem. GeoTab performed affinity analysis that showed no emissions-SPN correlation at 85% or 60% levels, and ERG also performed analysis to determine the extent of any potential overweighting based on field data (as described in Section 2 and presented in Table 2-6). However, due to the limited amount of field data, the true nature and extent of TM&M double counting is not fully characterized, so for this first iteration of results, no adjustments have been applied to TM&M categories to adjust for this double counting. As additional SPN correlation data becomes available in the future (i.e., through additional studies and data sources), results can be adjusted to account for this.

Although MIL-on results from the telematics fleet aligned within the MIL command range of the sampled on-road fleet, future analysis could focus on additional adjustments to ensure the true MIL-on rate of the California on-road fleet is accurately represented by the telematics-based results provided in this report. This could include MIL-on adjustments based on roadside pullover data or other data sources. Confirmation of projected MIL illumination rates for trucks with more than 500,000 miles would be worthwhile, and also of trucks that are not telematically-equipped.

As can be seen by comparing Appendices D and E, some SPNs were set to zero if they were believed to not trigger the MIL or have a direct impact on emissions. Since nulling out SPNs that do trigger the MIL but don’t have a direct impact on emissions can result in an overestimation of of MIL-related emissions impacts, future efforts to distinguish between these two groups of SPNs (non-MIL versus MIL with minimal emissions impact) and re-assigning counts to the latter category (MIL illumination but minimal emissions impact) could further improve the modeled emissions estimates. These counts will likely be refined by CARB during future iterations. CARB is also looking into other approaches using in-use testing data and field plume capture emission factor data.

7.0 Glossary of terms, Abbreviations and Symbols

ABB – Abbreviation definition
AECD – alternative emission control device
CARB – California Air Resources Board
CE-CERT - the University of California at Riverside's College of Engineering's Center for Environmental Research and Technology
DA – Digital Annex
DDV – durability demonstration vehicle testing
DLC – diagnostic link connector
DM – diagnostic message (J1939)
DPF – diesel particulate filter
DR – deterioration rate
DTC – diagnostic trouble code (J1979)
ECM – Electronic Control Module
EECS – evaporative emissions control system
EGR – exhaust gas recirculation
EIR – emission impact rate
ELD – Electronic Logging Device
EPA – U.S. Environmental Protection Agency.
ERG – Eastern Research Group, Inc.
EECS – Evaporative emissions control system
EMFAC – CARB's mobile source emissions inventory model
FMI – failure mode identifier (SAE J1939)
GVWR – gross vehicle weight rating
HD – heavy-duty
HDDT – Heavy-duty diesel truck
HVAC – heating, ventilation and air conditioning
MIL – Malfunction indicator light
NMHC – non-methane hydrocarbon
NOx – oxides of nitrogen
NVFEL - EPA's National Vehicle and Fuel Emissions Laboratory
OBD – On-Board Diagnostic (used to indicate J1962/J1979 and J1939 systems)
OC – Occurrence count (SAE J1939)
PCV – positive control ventilation
PGN – Parameter Group Number
PM – particulate matter
SAE – Society of Automotive Engineers
SAE J1939 - Society of Automotive Engineers standard SAE J1939
SAE J1979 - Society of Automotive Engineers standard SAE J1979
SCR – Selective Catalytic Reduction
SPN – suspect parameter number (J1939)
TM&M – Tampering, malfunction and mal-maintenance
VIN – vehicle identification number
ZMR – zero-mile emission rate

Appendix A

Heavy-Duty OBD Data Collection Form

CARB HD EMFAC Deterioration Operational and Vehicle Information

Owner Interview

Date of Scan		Contact Name	
Establishment Name		Form completed by	
Establishment Type	☐Repair Shop ☐OEM ☐Truck Stop ☐Commercial/Transit Fleet ☐Enforcement ☐Port ☐Other____________		
Ownership	☐Fleet ☐IOO	License Plate		Truck ID	
Vocation		Est Annual Miles	
State of Registration:		State of Domicile	
Service Type	☐Local Delivery ☐In-state operation & delivery ☐Interstate operation		
Weekday/Weekend Ops?	☐Weekday ☐Weekend ☐Both		
Seasonal Operation?	☐All Year ☐Other (describe)________________________________		
Warranty Status	☐In Warranty ☐ Extended Warranty ☐Out of Warranty ☐Don't Know		
Driver Reported MIL Status	☐On ☐Off ☐Don't Know		
If MIL on, are there plans to repair?			
Engine replacement / repower / repair history			

Truck Information

VIN:			
License Plate		Truck ID	
Truck Class (circle)	4 5 6 7 8	Truck type (i.e., walk-in, box truck, bus, etc.)	
Make		**Model**		**Model Year**	
Primary Fuel Type		Hybrid	❑ Yes ❑ No ❑ Unk
Odometer	**__ , __ __ __ , __ __ __ . __ ❑ km ❑ miles**		
MIL Bulb Check (key on / engine off)	**❑ MIL Illuminates ❑ MIL Does Not Illuminate**		
Engine-on MIL Status	**❑ MIL Illuminated ❑ No MIL**		
Connector Style	**❑ J1939 (round heavy-duty style)**	**❑ J1962 (trapezoidal LD OBD style)**	
Engine Mfr.		Engine Model		Engine Year	
Engine Serial #		Engine Family	
Engine Displacement	❑In^3 ❑ L	Configuration	❑V-block ❑ Inline
Rated Power		Units	❑ HP ❑ Other (_____________)
Rated Torque		Units	❑ Ft-lbs ❑ Other (_____________)
Rated Speed (Power)	RPM	Rated Speed (Torque)	RPM
Emission control equipment: ❑ TWC/OC/WU ❑ NAC ❑ SCR ❑ DPF ❑ PTOX ❑ HO2S/O2S ❑ EGR/EGR-C ❑ Other______________ ______________			
* TWC/OC/WU = three-way/oxidizing catalyst/warm-up catalyst; NAC=NOx adsorption catalyst; SCR =selective catalytic reduction; DPF=diesel particulate filter; PTOX = periodic trap oxidizer; H02S/02S=heated/oxygen sensor; EGR/EGR-C=exhaust gas recirculation / cooled EGR			
Truck ELD disconnected for testing	❑ Yes ❑ No (truck not equipped with ELD)		

Notes: Trucks of primary interest are 2013 and newer, regardless of mileage or MIL status. Whenever possible, obtain bold-faced items (make, model, model year, odometer, MIL bulb and MIL status) for 2012 and older trucks. Always prioritize 2013+ over older trucks, and if more 2013+ trucks are available than can be tested, prioritize those with higher mileage.

Appendix B

Heavy-Duty OBD Field Procedures

Summary of steps for collecting diagnostic message (DM) / diagnostic trouble code (DTC) data from trucks in the CARB HD EMFAC Deterioration Rate Update Study

Ensure all candidates understand that participation is strictly voluntary, no enforcement action will result, and there is no pass/fail. Please refer to recruitment flier.

Trucks of interest: Scans on 2013 and newer heavy-duty (14,001 lbs. and greater gvwr) diesel-powered vehicles, regardless of malfunction indicator light (MIL) status, mileage, faults or repairs required, registered state or warranty status. Attempt to obtain general make, model, model year, odometer and MIL status information for model year 2012 and older heavy-duty diesel trucks (HDDTs).

For each scanned vehicle (2013+), determine the vehicle ID to be used to uniquely identify the vehicle and data record. Generally, this will be the fleet name and fleet ID on the door or side of hood, or the license plate ID if a fleet ID is not available. Then, take the following pictures:

Photos

1st photo should ALWAYS be of the vehicle ID (of the truck door, hood, or license plate). This is used to identify the group of images associated with that vehicle. Then, take pictures of the following:

- License plate (if that is different than the vehicle ID)
- Overall truck (to identify truck type and manufacturer)
- Open hood, take overall picture of engine
- All engine labels (certification label, family, emission controls, and/or any other labels). Remove grease and dirt from label before photograph so all label information is legible.
- All truck identifying labels on side of door or at door jamb (VIN, year of MFR, make, build year, etc.). May need to clean label prior to photographing.
- Diagnostic connector in truck's interior (both with and without ELD, if so equipped)
- Odometer (ensure the display is active (key on) if the odometer is LED or LCD)
- Before releasing truck, ensure all photos are clear and legible for future data transcription

Data Collection

Conduct owner Interview, collect and record as much information as possible in first table (Owner Interview Table) of the data collection form. Then, collect and record as much truck information as possible in the second table (Truck Information Table) of the data collection form. *Note, much of the truck information can be acquired from the photographs, minimizing field time. However, the truck's MIL bulb check (key on / engine off) and the MIL check (engine on) must be independently performed and results recorded in the data collection form.* ***PERFORM MIL BULB CHECK (key on / engine off) AND ILLUMINATION CHECK (engine running for a few seconds to determine if the MIL turns off) BEFORE SCAN BEGINS.***

Data Download

Once photos and data collection have been performed, perform data download from truck's DLC with the HEM Data logger (or SilverScan if that is being used). HEM Data logger will have appropriate configuration file. Note, that if two people are available, photos and data collection may be performed simultaneously, ***taking care to not start truck while under-hood photography and data collection are taking place. If MIL is commanded on, attempt to download data with both the HEM Data AND the SilverScan.***

All electronic data must be provided with "vehicle ID". This shall be provided as the folder name of the folder containing each HEM Data file (or included in the "Description" field in the SilverScan file).

HEM Data procedures
To perform scan with HEM Data logger, first ensure correct configuration file is stored on HEM Data logger (configuration file should collect J1939 and OBD (ISO 15765-4) data and will be prepared before fieldwork). Ensure logger prefs file specifies autobaud detection.

Remove ELD, if necessary, and install HEM Data logger on truck's DLC. An adapter cable will be necessary if truck is equipped with round Deutsch J1939 connector.

After logger is installed and flashing blue, turn key to on position (do NOT start truck) and collect data with key on for 2 to 3 minutes AFTER the logger LED indicator begins flashing green.

After 2-3 minute data collection period, turn truck off, wait for HEM Data LED to transition from flashing red (HEM Data is terminating the file) to flashing blue (idle). Once the LED is flashing blue, remove HEM Data logger from truck's DLC and reconnect the ELD. If time permits, connect the HEM Data to a laptop and move the IOS and GPS files just created into a folder created on the laptop which identifies the date and truck ID of the truck just scanned. Also, if time permits, process the data and review the csv and htm files to ensure valid data and results have been obtained.

SilverScan Procedures (if SilverScan is used)
If the SilverScan is used, ensure laptop computer date and timestamp are correct. Prepare SilverScan device for data collection according to user instructions ("Silver Scan-Tool Instructions Revised 1_23_18 - updated.pdf"). Ensure truck make/model/model year are provided in the SilverScan's "Vehicle" field and the vehicle ID is provided in the SilverScan's "Description" field. Ensure all "standard" DMs and data (DM1=Active, DM2=Previous, DM6=Emission Pending, DM12=Emission, DM23=Emission Previous, DM27=All Pending, DM28=Emission Permanent) from all relevant controllers including Engine 1 & 2 (0x00 & 01), Transmission 1 & 2 (0x03 & 4), Exhaust Emission Controller (Controller 0x3D), Aftertreatment 1 intake/outlet (0x51 & 0x52), DPF (0x55) and any other relevant controllers.

- If truck has round Deutsch 1939 connector, perform scan as conventional heavy-duty truck (black is 250 kbit/s, green is 500 kbit/s)
- If truck has trapezoidal J1962 connector (i.e., Volvo or other with light-duty-style connector), ensure scans are performed as light-duty (with light-duty J1979 communication box and trapezoidal connector).

Remove ELD, if necessary, and perform scan with key on ***but without starting engine***.
Once scan is complete, save output as xml file, *.txt output, PDF output, and save extended log file

After Testing:
Reinstall ELD, and start truck to ensure MIL was not triggered on during testing. Provide owner / driver with incentive, obtain signature confirming receipt and amount of incentive and complete and sign the ELD-disconnect form the recruiting flier (if ELD was disconnected). ***The signed ELD-disconnect form has a point of contact for driver if any problems or questions should arise.***

Appendix C

Recruiting Brochures

VOLUNTARY ENGINE OBD SCAN

NO ENFORCEMENT ACTION WILL RESULT FROM THIS TEST

ERG and the University of California, under contract to the California Air Resources Board, are collecting data from 2013 and newer heavy-duty trucks.

Data collected include the following:

- **Operational information and truck history** (a brief driver interview)
- **Truck type, engine, mileage, and other details** (visual/photographic inspection)
- **A read-only scan of your truck's computer**

This program is <u>voluntary</u> and not part of mandatory enforcement

There is NO PASS OR FAIL and no repairs will be required as part of this testing

NO personal information will be released, data will only be used for emissions modeling

This will NOT alter your truck or affect your engine or performance in any way

The process is less than 15 minutes, and a $30 incentive is offered for your participation

---

Inspector: Please complete the following information if ELD is disconnected for testing

On ________________ (date), Vehicle (VIN#) __ __ __ __ __ __ __ __ __ __ __ __ __ __ __ __ __

was tested by a representative of the California Air Resources Board (CARB) in support of Contract 17AQP006 (*Updates to Heavy-Duty Emission Deterioration in EMFAC*). This study is being performed to update California's vehicle emissions model. This test required the ELD to be disconnected from this truck's ECM port to accommodate the testing equipment.

ELD disconnected (time)_____________ ELD re-connected (time)_____________

Signed: _____________________

If you have any questions or issues, please contact Michael Sabisch, ERG project manager under contract to CARB, at 512-407-1828 or michael.sabisch@erg.com

UCR College of Engineering- Center for Environmental Research & Technology

ERG

CALIFORNIA AIR RESOURCES BOARD

Escaneo Voluntario de OBD

NINGUNA ACCIÓN DE APLICACIÓN RESULTARÁ DE ESTA PRUEBA

ERG y la Universidad de California, bajo contrato con la Junta de California Air Resources Board, están recolectando datos de camiones pesados hechos después de 2012.

Los datos recogidos incluyen los siguientes:

- **Información operacional e historia del camión** (una breve entrevista al conductor)
- **Tipo de camión, motor, kilometraje y otros detalles** (inspección visual / fotográfica)
- **Un escaneo de solo lectura de la computadora de su camión**

Este programa es <u>voluntario</u> y no forma parte del cumplimiento obligatorio

NO hay aprobación ni falla y no se requerirán reparaciones como parte de esta prueba

NO se divulgará información personal, los datos son solo para el modelo de emisiones

Esto NO alterará su camión ni afectará su motor o rendimiento de ninguna manera

El proceso toma menos de 15 minutos y se ofrece un incentivo de $30 por su participación

---

Inspector: Please complete the following information if ELD is disconnected for testing

En la ____________ (fecha), el vehículo (VIN) __ __ __ __ __ __ __ __ __ __ __ __ __ __ __ __ __ fue probado por un representante de la Junta de Recursos del Aire de California (CARB) en apoyo del Contrato 17AQP006 (Actualizaciones del Deterioro de Emisiones de Uso Pesado en EMFAC). Este estudio se está realizando para actualizar el modelo de emisiones de vehículos de California. Esta prueba requiere que el ELD se desconecte del puerto de ECM de este camión para acomodar el equipo de prueba.

ELD desconectado (tiempo)______________ ELD reconectado (tiempo)______________

Firmado: ______________________

If you have any questions or issues, please contact Michael Sabisch, ERG project manager under contract to CARB, at 512-407-1828 or michael.sabisch@erg.com (English only)

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CALIFORNIA
AIR RESOURCES BOARD

VOLUNTARY ENGINE OBD SCAN

NO ENFORCEMENT ACTION WILL RESULT FROM THIS TEST

ERG and the University of California, under contract to the California Air Resources Board, are collecting data from 2013 and newer heavy-duty trucks.

Data collected include the following:

- **Operational information and truck history** (a brief driver interview)
- **Truck type, engine, mileage, and other details** (visual/photographic inspection)
- **A read-only scan of your truck's computer**

This program is voluntary and not part of mandatory enforcement

There is NO PASS OR FAIL and no repairs will be required as part of this testing

NO personal information will be released, data will only be used for emissions modeling

This will NOT alter your truck or affect your engine or performance in any way

The process is less than 15 minutes, and a $30 incentive is offered for your participation

If you have any questions or issues, please contact Michael Sabisch, ERG project manager under contract to CARB, at 512-407-1828 or michael.sabisch@erg.com

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ESCANEO VOLUNTARIO de OBD

NINGUNA ACCIÓN DE APLICACIÓN RESULTARÁ DE ESTA

ERG y la Universidad de California, bajo contrato con la Junta de California Air Resources Board, están recolectando datos de camiones pesados hechos después de 2012.

Los datos recogidos incluyen los siguientes:

- **Información operacional e historia del camión** (una breve entrevista al conductor)
- **Tipo de camión, motor, kilometraje y otros detalles** (inspección visual / fotográfica)
- **Un escaneo de solo lectura de la computadora de su camión**

Este programa es <u>voluntario</u> y no forma parte del cumplimiento obligatorio

NO hay aprobación ni falla y no se requerirán reparaciones como parte de esta prueba

NO se divulgará información personal, los datos son solo para el modelo de emisiones

Esto NO alterará su camión ni afectará su motor o rendimiento de ninguna manera

El proceso toma menos de 15 minutos y se ofrece un incentivo de $30 por su participación

If you have any questions or issues, please contact Michael Sabisch, ERG project manager under contract to CARB, at 512-407-1828 or michael.sabisch@erg.com (English only)

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Apendix D

Original HD EMFAC Study SPN to TM&M Mapping

TM&M Category	*SPN*	*SAE J1939 SPN Name*	*SPN Counts*	*Cat Total*
Boost Control	102	Engine Intake Manifold #1 Pressure	1548	5905
Boost Control	103	Engine Turbocharger 1 Speed	325	
Boost Control	641	Engine Variable Geometry Turbocharger Actuator #1	2347	
Boost Control	1127	Engine Turbocharger 1 Boost Pressure	260	
Boost Control	1172	Engine Turbocharger 1 Compressor Intake Temperature	409	
Boost Control	1173	Engine Turbocharger 2 Compressor Intake Temperature	15	
Boost Control	1176	Engine Turbocharger 1 Compressor Intake Pressure	36	
Boost Control	1188	Engine Turbocharger Wastegate Actuator 1 Position	9	
Boost Control	1189	Engine Turbocharger Wastegate Actuator 2 Position	23	
Boost Control	2629	Engine Turbocharger 1 Compressor Outlet Temperature	66	
Boost Control	2630	Engine Charge Air Cooler 1 Outlet Temperature	89	
Boost Control	2631	Engine Charge Air Cooler Outlet Pressure	140	
Boost Control	2792	Engine Variable Geometry Turbocharger (VGT) Air Control Shutoff Valve	12	
Boost Control	5285	Engine Charge Air Cooler 1 Efficiency	4	
Boost Control	5541	Engine Turbocharger 1 Turbine Outlet Pressure	127	
Boost Control	5542	Engine Turbocharger 1 Turbine Desired Outlet Pressure	181	
Boost Control	6713	Engine Variable Geometry Turbocharger Actuator Software Identification	311	
Boost Control	6888	Engine Turbocharger Wastegate Actuator 4 Temperature	3	
Cold Start Strategies	3061	Engine Cold Start Emission Reduction Strategy System Monitor	360	544
Cold Start Strategies	5548	Engine Cold Start Fuel Igniter Command	184	
EGR	27	Engine Exhaust Gas Recirculation 1 Valve Position	743	6757
EGR	51	Engine Throttle Valve 1 Position 1	872	
EGR	411	Engine Exhaust Gas Recirculation 1 Differential Pressure	998	
EGR	412	Engine Exhaust Gas Recirculation 1 Temperature	404	
EGR	2659	Engine Exhaust Gas Recirculation 1 Mass Flow Rate	989	
EGR	2791	Engine Exhaust Gas Recirculation 1 Valve 1 Control 1	894	
EGR	3058	Engine Exhaust Gas Recirculation System Monitor	1303	
EGR	4752	Engine Exhaust Gas Recirculation 1 Cooler Efficiency	243	
EGR	5019	Engine Exhaust Gas Recirculation 1 Outlet Pressure	18	
EGR	5321	Engine Intake Manifold Pressure System Monitor	212	
EGR	5444	Engine Crankcase Breather Oil Separator Speed	81	
Exh Gas Sensor Monitoring - oxygen	3217	Engine Exhaust 1 Percent Oxygen 1	20	34
Exh Gas Sensor Monitoring - oxygen	3256	Engine Exhaust 2 Percent Oxygen 1	14	
Fuel System Monitoring	94	Engine Fuel Delivery Pressure	538	8678
Fuel System Monitoring	95	Engine Fuel Filter Differential Pressure	380	
Fuel System Monitoring	96	Fuel Level 1	495	
Fuel System Monitoring	105	Engine Intake Manifold 1 Temperature	225	
Fuel System Monitoring	157	Engine Fuel 1 Injector Metering Rail 1 Pressure	3600	
Fuel System Monitoring	164	Engine Fuel Injection Control Pressure	334	
Fuel System Monitoring	633	Engine Fuel Actuator 1 Control Command	11	
Fuel System Monitoring	651	Engine Fuel 1 Injector Cylinder 1	189	
Fuel System Monitoring	652	Engine Fuel 1 Injector Cylinder 2	134	
Fuel System Monitoring	653	Engine Fuel 1 Injector Cylinder 3	148	
Fuel System Monitoring	654	Engine Fuel 1 Injector Cylinder 4	171	
Fuel System Monitoring	655	Engine Fuel 1 Injector Cylinder 5	129	
Fuel System Monitoring	656	Engine Fuel 1 Injector Cylinder 6	194	
Fuel System Monitoring	658	Engine Fuel 1 Injector Cylinder 8	6	

TM&M Category	*SPN*	*SAE J1939 SPN Name*	*SPN Counts*	*Cat Total*
Fuel System Monitoring	664	Engine Fuel 1 Injector Cylinder 14	5	
Fuel System Monitoring	679	Engine Fuel Injection Control Pressure Regulator	5	
Fuel System Monitoring	931	Engine Fuel Supply Pump Actuator	6	
Fuel System Monitoring	1077	Engine Fuel Injection Pump Controller	22	
Fuel System Monitoring	1078	Engine Fuel Injection Pump 1 Speed/Position Sensor	3	
Fuel System Monitoring	1239	Engine Fuel Leakage 1	293	
Fuel System Monitoring	1347	Engine Fuel Pump Pressurizing Assembly #1	104	
Fuel System Monitoring	1349	Engine Fuel 1 Injector Metering Rail 2 Pressure	4	
Fuel System Monitoring	2797	Engine Fuel 1 Injector Group 1	3	
Fuel System Monitoring	2798	Engine Fuel 1 Injector Group 2	9	
Fuel System Monitoring	3055	Engine Fuel System Monitor	278	
Fuel System Monitoring	3659	Engine Fuel 1 Injector Cylinder 1 Actuator 2	10	
Fuel System Monitoring	3660	Engine Fuel 1 Injector Cylinder 2 Actuator 2	18	
Fuel System Monitoring	3661	Engine Fuel 1 Injector Cylinder 3 Actuator 2	22	
Fuel System Monitoring	3662	Engine Fuel 1 Injector Cylinder 4 Actuator 2	15	
Fuel System Monitoring	3663	Engine Fuel 1 Injector Cylinder 5 Actuator 2	19	
Fuel System Monitoring	3664	Engine Fuel 1 Injector Cylinder 6 Actuator 2	21	
Fuel System Monitoring	4192	Engine Fuel Filter Water Level sensor	3	
Fuel System Monitoring	4257	Engine Fuel 1 Injector Group 3	45	
Fuel System Monitoring	5357	Engine Fuel Injection Quantity Error for Multiple Cylinders	505	
Fuel System Monitoring	5418	Engine Fuel Actuator 1	0	
Fuel System Monitoring	5571	High Pressure Common Rail Fuel Pressure Relief Valve	22	
Fuel System Monitoring	5585	Engine Fuel 1 Injector Metering Rail 1 Cranking Pressure	703	
Fuel System Monitoring	6653	Engine Fuel 1 Injector Metering Rail 1 Cold Start Pressure	9	
Misfire Monitoring	1322	Engine Misfire for Multiple Cylinders	126	611
Misfire Monitoring	1323	Engine Cylinder 1 Misfire Rate	118	
Misfire Monitoring	1324	Engine Cylinder 2 Misfire Rate	31	
Misfire Monitoring	1325	Engine Cylinder 3 Misfire Rate	50	
Misfire Monitoring	1326	Engine Cylinder 4 Misfire Rate	70	
Misfire Monitoring	1327	Engine Cylinder 5 Misfire Rate	57	
Misfire Monitoring	1328	Engine Cylinder 6 Misfire Rate	159	
NMHC Catalyst	4765	Aftertreatment 1 Diesel Oxidation Catalyst Intake Temperature	230	1120
NMHC Catalyst	4766	Aftertreatment 1 Diesel Oxidation Catalyst Outlet Temperature	118	
NMHC Catalyst	4796	Aftertreatment 1 Diesel Oxidation Catalyst Missing	38	
NMHC Catalyst	5018	Aftertreatment 1 Diesel Oxidation Catalyst System	110	
NMHC Catalyst	5298	Aftertreatment 1 Diesel Oxidation Catalyst Conversion Efficiency	452	
NMHC Catalyst	5310	Aftertreatment 1 Diesel Particulate Filter NMHC Conversion Efficiency	172	
NOx Sensor	3216	Engine Exhaust 1 NOx 1	3261	8085
NOx Sensor	3218	Engine Exhaust 1 Gas Sensor 1 Power In Range	212	
NOx Sensor	3224	Engine Exhaust 1 NOx Sensor 1 Preliminary FMI	15	
NOx Sensor	3226	Aftertreatment 1 Outlet NOx 1	4043	
NOx Sensor	3228	Aftertreatment 1 Outlet Gas Sensor 1 Power In Range	251	
NOx Sensor	5024	Engine Exhaust 1 NOx Sensor Heater Ratio	132	
NOx Sensor	5031	Aftertreatment 1 Outlet NOx Sensor Heater Ratio	171	
PM Filter	81	Aftertreatment 1 Diesel Particulate Filter Intake Pressure (use SPN 3609)	231	10469
PM Filter	3064	Aftertreatment Diesel Particulate Filter System Monitor	337	
PM Filter	3242	Aftertreatment 1 Diesel Particulate Filter Intake Temperature	353	
PM Filter	3246	Aftertreatment 1 Diesel Particulate Filter Outlet Temperature	444	
PM Filter	3250	Aftertreatment 1 Diesel Particulate Filter Intermediate Temperature	129	

TM&M Category	*SPN*	*SAE J1939 SPN Name*	*SPN Counts*	*Cat Total*
PM Filter	3251	Aftertreatment 1 Diesel Particulate Filter Differential Pressure	2347	
PM Filter	3609	Aftertreatment 1 Diesel Particulate Filter Intake Pressure	51	
PM Filter	3610	Aftertreatment 1 Diesel Particulate Filter Outlet Pressure	1381	
PM Filter	3703	Diesel Particulate Filter Active Regeneration Inhibited Due to Inhibit Switch	44	
PM Filter	3711	Diesel Particulate Filter Active Regeneration Inhibited Due to Low Exhaust	13	
PM Filter	3713	Diesel Particulate Filter Active Regeneration Inhibited Due to System Timeo	275	
PM Filter	3719	Aftertreatment 1 Diesel Particulate Filter Soot Load Percent	1018	
PM Filter	3720	Aftertreatment 1 Diesel Particulate Filter Ash Load Percent	350	
PM Filter	3750	Aftertreatment 1 Diesel Particulate Filter Conditions Not Met for Active Re	7	
PM Filter	3936	Aftertreatment Diesel Particulate Filter System	716	
PM Filter	4077	Aftertreatment 1 Fuel Pressure 2	42	
PM Filter	4795	Aftertreatment 1 Diesel Particulate Filter Missing	116	
PM Filter	5319	Aftertreatment 1 Diesel Particulate Filter Incomplete Regeneration	219	
PM Filter	5741	Aftertreatment 1 Outlet Soot	49	
PM Filter	5742	Aftertreatment Diesel Particulate Filter Temperature Sensor Module	1148	
PM Filter	5747	Aftertreatment 1 Outlet Soot Sensor Heater	293	
PM Filter	5835	Aftertreatment 1 Particulate Sensor	772	
PM Filter	6773	Aftertreatment 1 Particulate Sensor Regeneration Status	78	
PM Filter	7323	Aftertreatment 1 Particulate Sensor Heater Low Side Driver Preliminary FMI	56	
PM Filter Frequent Regen	5397	Aftertreatment 1 Diesel Particulate Filter Regeneration too Frequent	862	862
Reductant Delivery	1761	Aftertreatment 1 Diesel Exhaust Fluid Tank Volume	2089	15927
Reductant Delivery	3031	Aftertreatment 1 Diesel Exhaust Fluid Tank Temperature 1	1367	
Reductant Delivery	3360	Aftertreatment 1 Diesel Exhaust Fluid Controller 1	70	
Reductant Delivery	3361	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1	1284	
Reductant Delivery	3362	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Input Lines	791	
Reductant Delivery	3363	Aftertreatment 1 Diesel Exhaust Fluid Tank Heater	402	
Reductant Delivery	3364	Aftertreatment 1 Diesel Exhaust Fluid Tank Quality	1465	
Reductant Delivery	3515	Aftertreatment 1 Diesel Exhaust Fluid Temperature 2	26	
Reductant Delivery	3516	Aftertreatment 1 Diesel Exhaust Fluid Concentration	90	
Reductant Delivery	3521	Aftertreatment 1 Diesel Exhaust Fluid Property	398	
Reductant Delivery	4094	NOx limits exceeded due to Insufficient Diesel Exhaust Fluid Quality	439	
Reductant Delivery	4096	NOx limits exceeded due to Empty Diesel Exhaust Fluid Tank	98	
Reductant Delivery	4331	Aftertreatment 1 Diesel Exhaust Fluid Actual Dosing Quantity	122	
Reductant Delivery	4334	Aftertreatment 1 Diesel Exhaust Fluid Doser 1 Absolute Pressure	785	
Reductant Delivery	4337	Aftertreatment 1 Diesel Exhaust Fluid Doser 1 Temperature	37	
Reductant Delivery	4340	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 1 State	523	
Reductant Delivery	4342	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 2 State	520	
Reductant Delivery	4344	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 3 State	493	
Reductant Delivery	4353	Aftertreatment 1 Diesel Exhaust Fluid Doser Heating Mode Request	30	
Reductant Delivery	4354	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 1	65	
Reductant Delivery	4355	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 2	59	
Reductant Delivery	4356	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 3	26	
Reductant Delivery	4357	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 4	161	
Reductant Delivery	4374	Aftertreatment 1 Diesel Exhaust Fluid Pump 1 Motor Speed	277	

TM&M Category	***SPN***	***SAE J1939 SPN Name***	***SPN Counts***	***Cat Total***
Reductant Delivery	4375	Aftertreatment 1 Diesel Exhaust Fluid Pump Drive Percentage	161	
Reductant Delivery	4376	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Diverter Valve	169	
Reductant Delivery	4406	Aftertreatment 2 Diesel Exhaust Fluid Doser Heating Mode Request	3	
Reductant Delivery	5246	Aftertreatment SCR Operator Inducement Severity	2010	
Reductant Delivery	5392	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Loss of Prime	7	
Reductant Delivery	5394	Aftertreatment 1 Diesel Exhaust Fluid Doser Valve 1	654	
Reductant Delivery	5435	Aftertreatment 1 Diesel Exhaust Fluid Pump State	35	
Reductant Delivery	5488	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 5 State	143	
Reductant Delivery	5491	Aftertreatment 1 Diesel Exhaust Fluid Line Heater Relay 1	248	
Reductant Delivery	5745	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Heater	134	
Reductant Delivery	5746	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Heater Relay	210	
Reductant Delivery	5798	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Heater Temperature	21	
Reductant Delivery	5841	Diesel Exhaust Fluid Quality Malfunction	5	
Reductant Delivery	6802	Aftertreatment 1 Diesel Exhaust Fluid Dosing System Frozen	481	
Reductant Delivery	7107	Aftertreatment 1 Diesel Exhaust Fluid Pump	29	
SCR Catalyst	4335	Aftertreatment 1 SCR Dosing Air Assist Absolute Pressure	50	7552
SCR Catalyst	4336	Aftertreatment 1 SCR Dosing Air Assist Valve	3	
SCR Catalyst	4339	Aftertreatment 1 SCR Feedback Control Status	323	
SCR Catalyst	4358	Aftertreatment 1 SCR Differential Pressure	22	
SCR Catalyst	4360	Aftertreatment 1 SCR Intake Temperature	208	
SCR Catalyst	4363	Aftertreatment 1 SCR Outlet Temperature	323	
SCR Catalyst	4364	Aftertreatment 1 SCR Conversion Efficiency	3799	
SCR Catalyst	4377	Aftertreatment 1 Outlet NH3	90	
SCR Catalyst	4382	Aftertreatment 1 Outlet NH3 Gas Sensor Heater Preliminary FMI	10	
SCR Catalyst	4384	Aftertreatment 2 Diesel Exhaust Fluid Actual Dosing Quantity	5	
SCR Catalyst	4792	Aftertreatment 1 Selective Catalytic Reduction System	44	
SCR Catalyst	4794	Aftertreatment 1 SCR System Missing	216	
SCR Catalyst	5743	Aftertreatment 1 SCR Temperature Sensor Module	1198	
SCR Catalyst	5842	SCR Monitoring System Malfunction	89	
SCR Catalyst	5848	Aftertreatment 1 SCR Intermediate NH3	920	
SCR Catalyst	5851	Aftertreatment 1 SCR Intermediate NH3 Sensor Power In Range	48	
SCR Catalyst	5853	Aftertreatment 1 SCR Intermediate NH3 Sensor Heater Preliminary FMI	20	
SCR Catalyst	5862	Aftertreatment 1 SCR Intermediate Temperature	175	
SCR Catalyst	5864	Aftertreatment 2 SCR Intermediate Temperature	9	

Appendix E

Revised HD EMFAC Study SPN to TM&M Mapping

TM&M Category	SPN	SAE J1939 SPN Name	SPN Counts	Cat Total
Boost Control	102	Engine Intake Manifold #1 Pressure	1548	5905
Boost Control	103	Engine Turbocharger 1 Speed	325	
Boost Control	641	Engine Variable Geometry Turbocharger Actuator #1	2347	
Boost Control	1127	Engine Turbocharger 1 Boost Pressure	260	
Boost Control	1172	Engine Turbocharger 1 Compressor Intake Temperature	409	
Boost Control	1173	Engine Turbocharger 2 Compressor Intake Temperature	15	
Boost Control	1176	Engine Turbocharger 1 Compressor Intake Pressure	36	
Boost Control	1188	Engine Turbocharger Wastegate Actuator 1 Position	9	
Boost Control	1189	Engine Turbocharger Wastegate Actuator 2 Position	23	
Boost Control	2629	Engine Turbocharger 1 Compressor Outlet Temperature	66	
Boost Control	2630	Engine Charge Air Cooler 1 Outlet Temperature	89	
Boost Control	2631	Engine Charge Air Cooler Outlet Pressure	140	
Boost Control	2792	Engine Variable Geometry Turbocharger (VGT) Air Control Shutoff Valve	12	
Boost Control	5285	Engine Charge Air Cooler 1 Efficiency	4	
Boost Control	5541	Engine Turbocharger 1 Turbine Outlet Pressure	127	
Boost Control	5542	Engine Turbocharger 1 Turbine Desired Outlet Pressure	181	
Boost Control	6713	Engine Variable Geometry Turbocharger Actuator Software Identification	311	
Boost Control	6888	Engine Turbocharger Wastegate Actuator 4 Temperature	3	
Cold Start Strategies	3061	Engine Cold Start Emission Reduction Strategy System Monitor	360	544
Cold Start Strategies	5548	Engine Cold Start Fuel Igniter Command	184	
EGR	27	Engine Exhaust Gas Recirculation 1 Valve Position	743	6353
EGR	51	Engine Throttle Valve 1 Position 1	872	
EGR	411	Engine Exhaust Gas Recirculation 1 Differential Pressure	998	
EGR	412	Engine Exhaust Gas Recirculation 1 Temperature	0	
EGR	2659	Engine Exhaust Gas Recirculation 1 Mass Flow Rate	989	
EGR	2791	Engine Exhaust Gas Recirculation 1 Valve 1 Control 1	894	
EGR	3058	Engine Exhaust Gas Recirculation System Monitor	1303	
EGR	4752	Engine Exhaust Gas Recirculation 1 Cooler Efficiency	243	
EGR	5019	Engine Exhaust Gas Recirculation 1 Outlet Pressure	18	
EGR	5321	Engine Intake Manifold Pressure System Monitor	212	
EGR	5444	Engine Crankcase Breather Oil Separator Speed	81	
Exh Gas Sensor Monitoring - oxygen	3217	Engine Exhaust 1 Percent Oxygen 1	20	34
Exh Gas Sensor Monitoring - oxygen	3256	Engine Exhaust 2 Percent Oxygen 1	14	
Fuel System Monitoring	94	Engine Fuel Delivery Pressure	538	8678
Fuel System Monitoring	95	Engine Fuel Filter Differential Pressure	380	
Fuel System Monitoring	96	Fuel Level 1	495	
Fuel System Monitoring	105	Engine Intake Manifold 1 Temperature	225	
Fuel System Monitoring	157	Engine Fuel 1 Injector Metering Rail 1 Pressure	3600	
Fuel System Monitoring	164	Engine Fuel Injection Control Pressure	334	
Fuel System Monitoring	633	Engine Fuel Actuator 1 Control Command	11	
Fuel System Monitoring	651	Engine Fuel 1 Injector Cylinder 1	189	
Fuel System Monitoring	652	Engine Fuel 1 Injector Cylinder 2	134	
Fuel System Monitoring	653	Engine Fuel 1 Injector Cylinder 3	148	
Fuel System Monitoring	654	Engine Fuel 1 Injector Cylinder 4	171	
Fuel System Monitoring	655	Engine Fuel 1 Injector Cylinder 5	129	
Fuel System Monitoring	656	Engine Fuel 1 Injector Cylinder 6	194	
Fuel System Monitoring	658	Engine Fuel 1 Injector Cylinder 8	6	
Fuel System Monitoring	664	Engine Fuel 1 Injector Cylinder 14	5	

TM&M Category	SPN	SAE J1939 SPN Name	SPN Counts	Cat Total
Fuel System Monitoring	679	Engine Fuel Injection Control Pressure Regulator	5	
Fuel System Monitoring	931	Engine Fuel Supply Pump Actuator	6	
Fuel System Monitoring	1077	Engine Fuel Injection Pump Controller	22	
Fuel System Monitoring	1078	Engine Fuel Injection Pump 1 Speed/Position Sensor	3	
Fuel System Monitoring	1239	Engine Fuel Leakage 1	293	
Fuel System Monitoring	1347	Engine Fuel Pump Pressurizing Assembly #1	104	
Fuel System Monitoring	1349	Engine Fuel 1 Injector Metering Rail 2 Pressure	4	
Fuel System Monitoring	2797	Engine Fuel 1 Injector Group 1	3	
Fuel System Monitoring	2798	Engine Fuel 1 Injector Group 2	9	
Fuel System Monitoring	3055	Engine Fuel System Monitor	278	
Fuel System Monitoring	3659	Engine Fuel 1 Injector Cylinder 1 Actuator 2	10	
Fuel System Monitoring	3660	Engine Fuel 1 Injector Cylinder 2 Actuator 2	18	
Fuel System Monitoring	3661	Engine Fuel 1 Injector Cylinder 3 Actuator 2	22	
Fuel System Monitoring	3662	Engine Fuel 1 Injector Cylinder 4 Actuator 2	15	
Fuel System Monitoring	3663	Engine Fuel 1 Injector Cylinder 5 Actuator 2	19	
Fuel System Monitoring	3664	Engine Fuel 1 Injector Cylinder 6 Actuator 2	21	
Fuel System Monitoring	4192	Engine Fuel Filter Water Level sensor	3	
Fuel System Monitoring	4257	Engine Fuel 1 Injector Group 3	45	
Fuel System Monitoring	5357	Engine Fuel Injection Quantity Error for Multiple Cylinders	505	
Fuel System Monitoring	5418	Engine Fuel Actuator 1	0	
Fuel System Monitoring	5571	High Pressure Common Rail Fuel Pressure Relief Valve	22	
Fuel System Monitoring	5585	Engine Fuel 1 Injector Metering Rail 1 Cranking Pressure	703	
Fuel System Monitoring	6653	Engine Fuel 1 Injector Metering Rail 1 Cold Start Pressure	9	
Misfire Monitoring	1322	Engine Misfire for Multiple Cylinders	126	126
Misfire Monitoring	1323	Engine Cylinder 1 Misfire Rate	0	
Misfire Monitoring	1324	Engine Cylinder 2 Misfire Rate	0	
Misfire Monitoring	1325	Engine Cylinder 3 Misfire Rate	0	
Misfire Monitoring	1326	Engine Cylinder 4 Misfire Rate	0	
Misfire Monitoring	1327	Engine Cylinder 5 Misfire Rate	0	
Misfire Monitoring	1328	Engine Cylinder 6 Misfire Rate	0	
NMHC Catalyst	4765	Aftertreatment 1 Diesel Oxidation Catalyst Intake Temperature	230	1120
NMHC Catalyst	4766	Aftertreatment 1 Diesel Oxidation Catalyst Outlet Temperature	118	
NMHC Catalyst	4796	Aftertreatment 1 Diesel Oxidation Catalyst Missing	38	
NMHC Catalyst	5018	Aftertreatment 1 Diesel Oxidation Catalyst System	110	
NMHC Catalyst	5298	Aftertreatment 1 Diesel Oxidation Catalyst Conversion Efficiency	452	
NMHC Catalyst	5310	Aftertreatment 1 Diesel Particulate Filter NMHC Conversion Efficiency	172	
NOx Sensor	3216	Engine Exhaust 1 NOx 1	3261	8085
NOx Sensor	3218	Engine Exhaust 1 Gas Sensor 1 Power In Range	212	
NOx Sensor	3224	Engine Exhaust 1 NOx Sensor 1 Preliminary FMI	15	
NOx Sensor	3226	Aftertreatment 1 Outlet NOx 1	4043	
NOx Sensor	3228	Aftertreatment 1 Outlet Gas Sensor 1 Power In Range	251	
NOx Sensor	5024	Engine Exhaust 1 NOx Sensor Heater Ratio	132	
NOx Sensor	5031	Aftertreatment 1 Outlet NOx Sensor Heater Ratio	171	
PM Filter	81	Aftertreatment 1 Diesel Particulate Filter Intake Pressure (use SPN 3609)	231	6395
PM Filter	3064	Aftertreatment Diesel Particulate Filter System Monitor	337	
PM Filter	3242	Aftertreatment 1 Diesel Particulate Filter Intake Temperature	0	
PM Filter	3246	Aftertreatment 1 Diesel Particulate Filter Outlet Temperature	0	
PM Filter	3250	Aftertreatment 1 Diesel Particulate Filter Intermediate Temperature	0	
PM Filter	3251	Aftertreatment 1 Diesel Particulate Filter Differential Pressure	2347	

TM&M Category	SPN	SAE J1939 SPN Name	SPN Counts	Cat Total
PM Filter	3609	Aftertreatment 1 Diesel Particulate Filter Intake Pressure	51	
PM Filter	3610	Aftertreatment 1 Diesel Particulate Filter Outlet Pressure	1381	
PM Filter	3703	Diesel Particulate Filter Active Regeneration Inhibited Due to Inhibit Switch	0	
PM Filter	3711	Diesel Particulate Filter Active Regeneration Inhibited Due to Low Exhaust	0	
PM Filter	3713	Diesel Particulate Filter Active Regeneration Inhibited Due to System Timeo	0	
PM Filter	3719	Aftertreatment 1 Diesel Particulate Filter Soot Load Percent	0	
PM Filter	3720	Aftertreatment 1 Diesel Particulate Filter Ash Load Percent	0	
PM Filter	3750	Aftertreatment 1 Diesel Particulate Filter Conditions Not Met for Active Re	0	
PM Filter	3936	Aftertreatment Diesel Particulate Filter System	716	
PM Filter	4077	Aftertreatment 1 Fuel Pressure 2	42	
PM Filter	4795	Aftertreatment 1 Diesel Particulate Filter Missing	116	
PM Filter	5319	Aftertreatment 1 Diesel Particulate Filter Incomplete Regeneration	219	
PM Filter	5741	Aftertreatment 1 Outlet Soot	49	
PM Filter	5742	Aftertreatment Diesel Particulate Filter Temperature Sensor Module	0	
PM Filter	5747	Aftertreatment 1 Outlet Soot Sensor Heater	0	
PM Filter	5835	Aftertreatment 1 Particulate Sensor	772	
PM Filter	6773	Aftertreatment 1 Particulate Sensor Regeneration Status	78	
PM Filter	7323	Aftertreatment 1 Particulate Sensor Heater Low Side Driver Preliminary FMI	56	
PM Filter Frequent Regen	5397	Aftertreatment 1 Diesel Particulate Filter Regeneration too Frequent	862	862
Reductant Delivery	1761	Aftertreatment 1 Diesel Exhaust Fluid Tank Volume	2089	10583
Reductant Delivery	3031	Aftertreatment 1 Diesel Exhaust Fluid Tank Temperature 1	1367	
Reductant Delivery	3360	Aftertreatment 1 Diesel Exhaust Fluid Controller 1	70	
Reductant Delivery	3361	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1	1284	
Reductant Delivery	3362	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Input Lines	791	
Reductant Delivery	3363	Aftertreatment 1 Diesel Exhaust Fluid Tank Heater	0	
Reductant Delivery	3364	Aftertreatment 1 Diesel Exhaust Fluid Tank Quality	1465	
Reductant Delivery	3515	Aftertreatment 1 Diesel Exhaust Fluid Temperature 2	0	
Reductant Delivery	3516	Aftertreatment 1 Diesel Exhaust Fluid Concentration	90	
Reductant Delivery	3521	Aftertreatment 1 Diesel Exhaust Fluid Property	398	
Reductant Delivery	4094	NOx limits exceeded due to Insufficient Diesel Exhaust Fluid Quality	439	
Reductant Delivery	4096	NOx limits exceeded due to Empty Diesel Exhaust Fluid Tank	98	
Reductant Delivery	4331	Aftertreatment 1 Diesel Exhaust Fluid Actual Dosing Quantity	122	
Reductant Delivery	4334	Aftertreatment 1 Diesel Exhaust Fluid Doser 1 Absolute Pressure	785	
Reductant Delivery	4337	Aftertreatment 1 Diesel Exhaust Fluid Doser 1 Temperature	0	
Reductant Delivery	4340	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 1 State	0	
Reductant Delivery	4342	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 2 State	0	
Reductant Delivery	4344	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 3 State	0	
Reductant Delivery	4353	Aftertreatment 1 Diesel Exhaust Fluid Doser Heating Mode Request	0	
Reductant Delivery	4354	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 1	0	
Reductant Delivery	4355	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 2	0	
Reductant Delivery	4356	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 3	0	
Reductant Delivery	4357	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 4	0	
Reductant Delivery	4374	Aftertreatment 1 Diesel Exhaust Fluid Pump 1 Motor Speed	277	

TM&M Category	*SPN*	*SAE J1939 SPN Name*	*SPN Counts*	*Cat Total*
Reductant Delivery	4375	Aftertreatment 1 Diesel Exhaust Fluid Pump Drive Percentage	161	
Reductant Delivery	4376	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Diverter Valve	169	
Reductant Delivery	4406	Aftertreatment 2 Diesel Exhaust Fluid Doser Heating Mode Request	0	
Reductant Delivery	5246	Aftertreatment SCR Operator Inducement Severity	0	
Reductant Delivery	5392	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Loss of Prime	7	
Reductant Delivery	5394	Aftertreatment 1 Diesel Exhaust Fluid Doser Valve 1	654	
Reductant Delivery	5435	Aftertreatment 1 Diesel Exhaust Fluid Pump State	35	
Reductant Delivery	5488	Aftertreatment 1 Diesel Exhaust Fluid Line Heater 5 State	0	
Reductant Delivery	5491	Aftertreatment 1 Diesel Exhaust Fluid Line Heater Relay 1	248	
Reductant Delivery	5745	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Heater	0	
Reductant Delivery	5746	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Heater Relay	0	
Reductant Delivery	5798	Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit 1 Heater Temperature	0	
Reductant Delivery	5841	Diesel Exhaust Fluid Quality Malfunction	5	
Reductant Delivery	6802	Aftertreatment 1 Diesel Exhaust Fluid Dosing System Frozen	0	
Reductant Delivery	7107	Aftertreatment 1 Diesel Exhaust Fluid Pump	29	
SCR Catalyst	4335	Aftertreatment 1 SCR Dosing Air Assist Absolute Pressure	50	7552
SCR Catalyst	4336	Aftertreatment 1 SCR Dosing Air Assist Valve	3	
SCR Catalyst	4339	Aftertreatment 1 SCR Feedback Control Status	323	
SCR Catalyst	4358	Aftertreatment 1 SCR Differential Pressure	22	
SCR Catalyst	4360	Aftertreatment 1 SCR Intake Temperature	208	
SCR Catalyst	4363	Aftertreatment 1 SCR Outlet Temperature	323	
SCR Catalyst	4364	Aftertreatment 1 SCR Conversion Efficiency	3799	
SCR Catalyst	4377	Aftertreatment 1 Outlet NH3	90	
SCR Catalyst	4382	Aftertreatment 1 Outlet NH3 Gas Sensor Heater Preliminary FMI	10	
SCR Catalyst	4384	Aftertreatment 2 Diesel Exhaust Fluid Actual Dosing Quantity	5	
SCR Catalyst	4792	Aftertreatment 1 Selective Catalytic Reduction System	44	
SCR Catalyst	4794	Aftertreatment 1 SCR System Missing	216	
SCR Catalyst	5743	Aftertreatment 1 SCR Temperature Sensor Module	1198	
SCR Catalyst	5842	SCR Monitoring System Malfunction	89	
SCR Catalyst	5848	Aftertreatment 1 SCR Intermediate NH3	920	
SCR Catalyst	5851	Aftertreatment 1 SCR Intermediate NH3 Sensor Power In Range	48	
SCR Catalyst	5853	Aftertreatment 1 SCR Intermediate NH3 Sensor Heater Preliminary FMI	20	
SCR Catalyst	5862	Aftertreatment 1 SCR Intermediate Temperature	175	
SCR Catalyst	5864	Aftertreatment 2 SCR Intermediate Temperature	9	