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16. Abstract The U.S. Environmental Protection Agency's (EPA) newest emissions model, MOtor Vehicle Emission Simulator (MOVES), uses a disaggregate approach that enables the users of the model to create and use local <i>drive schedules</i> (drive cycles) in order to perform an accurate analysis. However, only the national average drive schedules are currently included in the default database of the model. Furthermore, the cold start and idling emissions and activity data of heavy duty diesel trucks (HDDVs) that are included in the MOVES model are based on a very limited number of data sources even though they are very important components of the total on-road mobile source emissions inventory. This report provides local drive cycles for different regions of Texas for different vehicle classes and roadway types as well as cold start and idling emissions rates for heavy-duty diesel trucks. The report also compares estimated emissions from MOVES for a sample of vehicles to real-world in-use emissions measurements. Furthermore, the technical and tactical issues of integrating the results of this study into MOVES for formal emissions analyses purposes are investigated and recommendations provided based on the findings.					
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**TEXAS-SPECIFIC DRIVE CYCLES AND IDLE EMISSIONS RATES  
FOR USING WITH EPA'S MOVES MODEL—FINAL REPORT**

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## **DISCLAIMER**

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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# CHAPTER 1: INTRODUCTION

## SIGNIFICANCE

The U.S. Environmental Protection Agency's (EPA) newest emissions model, Motor Vehicle Emission Simulator (MOVES), uses a disaggregate approach to estimate emissions rates and emissions inventories (1). This disaggregate approach enables MOVES to perform estimation at different analysis levels; however, only the national average driving patterns are included in the default database of the model. Furthermore, a review of the emissions data included in the MOVES model reveals that the cold start and idling emissions and activity data of heavy duty diesel trucks (HDDVs) that are incorporated into the model are based on a very limited number of data sources (2). This project addresses these gaps by:

- Developing local drive schedules for different regions of Texas based on a large-scale vehicle activity data collection.
- Characterizing the cold-start and idling emissions of HDDVs through a series of emissions measurements in a controlled environment.

State and local air quality and transportation agencies are required to estimate on-road vehicle emissions for different purposes including demonstrating progress toward attainment, maintenance state implementation plans (SIPs), and regional transportation planning. The flexible configuration of MOVES, which is based on a database-centered structure, gives more flexibility to users to control the local parameters. Most importantly, the driving patterns representing the different traffic conditions and average traffic speeds are not hard coded into the model. Users can create and use local *drive schedules* (equivalent to drive cycles in MOBILE models) in order to perform an accurate analysis. This feature is specifically helpful for project-level conformity analyses that deal with changes in traffic patterns. In addition to project-level analyses, the local drive cycles will enable the modelers to accurately estimate the emissions impacts of traffic movement for other purposes such as SIP and attainment demonstration analyses.

Furthermore, the current cold start and idling activity and emissions information in MOVES are based on a very limited number of observations that do not include a variety of

makes and model years. It is expected that the accuracy of the emissions local inventories can be increased if this information is available at the state level.

## **RESEARCH GOALS**

The main goals of this project were:

- To provide TxDOT with localized drive schedules for different regions of Texas.
- To develop cold start and normal idling emissions rates for heavy-duty diesel vehicles.

The research team executed two data collection efforts in parallel:

- A large scale data vehicle activity data using global positioning system (GPS) technology.
- A series of cold start and idling emissions measurements inside TTI's environmental chamber at the Environmental and Emissions Research Facility (EERF).

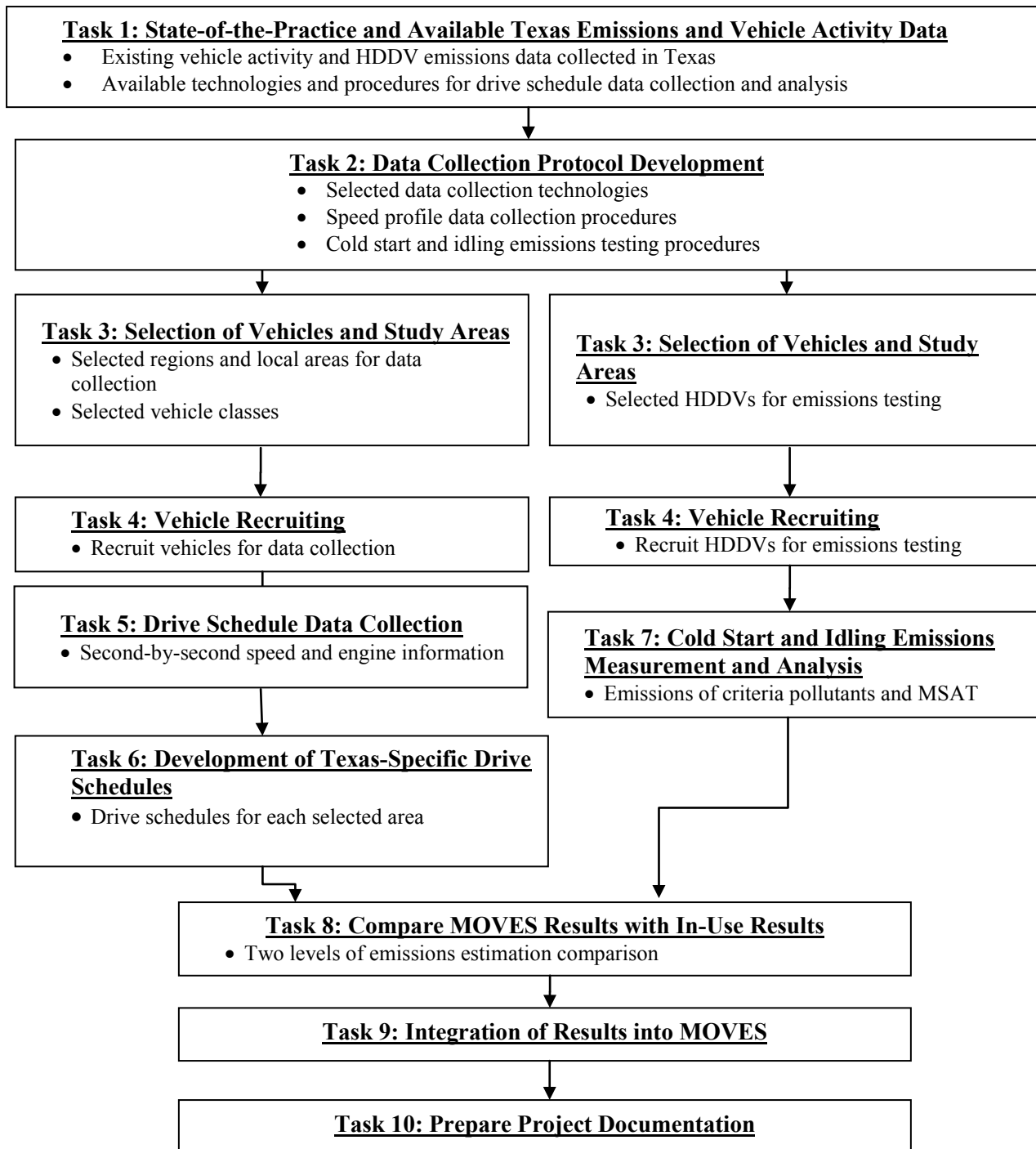
The GPS information were processed and analyzed to develop a set of localized drive schedules for major urban areas of Texas, i.e., Austin, El Paso, Dallas–Fort Worth, Houston, and San Antonio. The emissions test results were analyzed to determine the idling and cold start emission rates for newer HDDVs. This information provides TxDOT with the following:

- The foundation for TxDOT to accurately quantify the impact of on-road mobile sources and specifically the heavy-duty diesel sector.
- The basis to develop and quantify emissions reduction strategies such as idle reduction programs.
- For TxDOT districts, the ability to more accurately address criteria pollutants in NEPA project documentation and transportation conformity analysis.
- The methodology to expand and update the local drive cycles in the future.

## **RESEARCH TASKS AND APPROACH**

The project is divided into two phases, which were executed in parallel. Phase 1 deals with the data collection and development of local drive cycles for different regions of Texas, while Phase 2 addresses the cold start and idling emissions of HDDVs. See [Figure 1](#) for a flow diagram of the work plan.





**Figure 1. Work Plan Flow Diagram.**

During Phase 1, a sample of target study areas and the target vehicle population is selected based on the regional activity and emissions data. Vehicles from target groups are recruited and instrumented with the selected activity recording instruments. The activity data are

collected and includes both supervised (driving on pre-determined routes during different periods of the day) and unsupervised (normal daily activity of the participants) approaches. The collected data include second-by-second speed and location information for all the vehicles and engine parameters readings for a small sample of test vehicles. After the predetermined data collection period, the data collection instruments are removed from the participant vehicles and data are downloaded then labeled properly. These data are processed and a database of speed profiles for different average speeds and road types is developed. The database also includes Texas-specific vehicle activity data obtained from other sources including TTI's previous and ongoing work, and EPA. Information from this database is analyzed and local drive schedules for different regions of Texas developed to be used with MOVES for emissions analysis. Comparisons are made between MOVES emissions rates and real-world on-road data obtained from previous and on-going emissions data collection efforts.

Phase 2 involves characterization of cold start and idling emissions from HDDVs. The research team compiles a database of data used in MOVES and also previous and ongoing emissions studies at TTI and other agencies such as Oak Ridge National Lab (ORNL) and EPA. The researchers then review these data and identify gaps in the current HDDVs' cold-start and idling emissions data. A small-scale emissions measurement effort will be designed to address these gaps. Test vehicles are selected based on a finding of the data reprocess. The selected sample of heavy-duty diesel trucks is tested for cold starts and idling emissions under two different engine loading conditions (low and high idle) in controlled environmental conditions inside TTI's environmental chamber. Vehicles are tested for Mobile Source Air Toxics (MSATs), diesel particulate matter (DPM), and other pollutants including oxides of nitrogen ( $\text{NO}_x$ ). A comparison is made between these observations and estimated emission from MOVES. Furthermore, the idling and cold-start activity data are compiled from available data sources including, but not limited to, previous and ongoing studies of TTI, ORNL, and EPA. These data will help TxDOT to better understand and estimate the emissions impact of idling and cold start in Texas, and will also be a valuable source of information to improve MOVES data in the future revisions. Finally, the research team inspects the technical and tactical issues with implementing the findings and results of this study into emissions analyses using MOVES.

## **REPORT ORGANIZATION**

This project consists of 10 tasks, nine of which provide the content for this report. Generally speaking, each chapter aligns to one task and its associated technical memorandum, although it should be noted that some tasks are combined as they occurred simultaneously in both Phase I and Phase II of the project.

### **Chapter 2**

[Chapter 2](#) aligns with Task 1, State-of-the-Practice and Available Texas Emissions and Vehicle Activity Data. A literature review of existing vehicle activity and heavy-duty diesel vehicle emissions data collected in Texas was conducted, as well as a review of available technologies and procedures for drive schedule data collection and analysis.

### **Chapter 3**

[Chapter 3](#), Test Protocol Development and Recruiting, covers Tasks 2 through 4. Task 2, Data Collection Protocol Development, provides a description of selected data collection techniques, speed profile data collection procedures, and cold start and idling emissions testing procedures. Task 3, Selection of Vehicles and Study Areas, covers the selection of regions and local areas for data collection and the classes of vehicles for Phase I. It also examines the selection of HDDVs for emission testing as part of Phase II. Task 4 describes vehicle recruitment efforts for both phases.

### **Chapter 4**

Phase I data collection is covered in [Chapter 4](#). Corresponding to Task 5, Drive Schedule Data Collection, the chapter discusses the collection of second-by-second speed and engine information.

### **Chapter 5**

Continuing with Phase I, [Chapter 5](#), Development of Texas-Specific Drive Schedules, provides an explanation of the creation of drive schedules for each of the regions studied (Task 6).

## **Chapter 6**

[Chapter 6](#) moves to Phase II, and corresponds with Task 7, Cold Start and Idling Emissions Measurement and Analysis. This chapter reports on the results of the emissions testing for criteria pollutants and MSAT.

## **Chapter 7**

[Chapter 7](#) reports on the activities of Task 8, which is the comparison of MOVES results and in-use results. The chapter covers two levels of emissions estimation comparison: operating mode (HDDV) and drive cycle (LDGV).

## **Chapter 8**

Task 9, Integration of Results into MOVES, is presented in [Chapter 8](#). This chapter presents recommendations for future integration of local drive schedules and HDDV emissions information into the MOVES model.

## **Appendices**

Six appendices provide additional details regarding the processes that the researchers used during the course of this project, and the accompanying results.

## **CHAPTER 2: STATE-OF-THE-PRACTICE AND AVAILABLE TEXAS EMISSIONS AND VEHICLE ACTIVITY DATA**

This chapter documents the findings of Task 1. The purpose of Task 1 was to develop an understanding of MOVES' modeling structure, its default drive schedules (drive cycles), and state-of-the practice in activity data collection and drive schedule development as well as the available Texas emissions and activity data. The research team conducted a search of published and unpublished material using personal contacts, databases such as the Transportation Research Board's TRIS database, Texas Department of Transportation (TxDOT) and Texas A&M Transportation Institute (TTI) libraries, U.S. Environmental Protection Agency, and California Air Resources Board (CARB) databases, and general web searches to obtain information on the subject. The findings from this literature review were used to build on the lessons and methodologies of past studies.

Air quality and associated environmental issues significantly affect public health. The transportation sector is a major contributor to the pollutants such as carbon monoxide (CO), hydrocarbons (HC) and volatile organic compounds (VOC), oxides of nitrogen (NO<sub>x</sub>), and particulate matter (PM) that are known to have a negative impact on human health. Transportation-based sources of pollution can typically be classified as "on-road," referring to vehicles used for moving passengers and/or freight, and "off-road," referring to vehicles and equipment used for purposes other than "on-road" such as aircraft and construction equipment (3). According to the study conducted by CCCEF in 2007, the on-road sources can account for 44 percent of carbon monoxide (CO) emissions, 33 percent of nitrogen oxide (NO<sub>x</sub>) emissions, and one percent of particulate matter (PM) emissions (4).

The Clean Air Act defines the EPA's responsibilities for protecting public health and improving the nation's air quality (5). The Act enables the EPA to set and enforce clean air standards that contribute to the improvement in human health. Also, the Act requires the EPA to develop and regularly update emissions factors and emissions estimation models for all emissions sources in the United States. As part of a broad array of strategies enacted to fulfill

these mandates, the EPA has employed a number of emissions estimation methodologies that can be used in the support of emissions reduction strategies.

The EPA had mandated the use of the MOBILE emissions model for use in the United States, but has recently adopted the MOVES model as its new, preferred emissions modeling methodology. Other emissions estimation methodologies include:

- The Emissions Factors (EMFAC) model that CARB had developed.
- The International Vehicle Emission (IVE) model that was developed for use in developing countries.
- The COmputer Program to calculate Emissions from Road Transport (COPERT) model that the European Commission Environmental Protection Agency had developed.

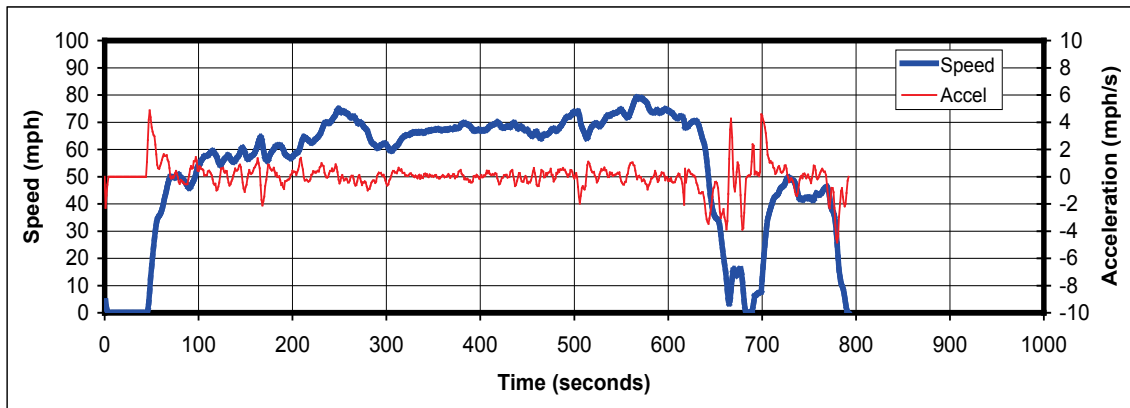
These methodologies are generally macroscopic in nature in that they estimate emissions at a regional scale but use some type of microscopic emissions information that is based on standard emissions measurements. This is necessary because macro level emissions estimation will vary greatly depending on travel behavior patterns within the areas being modeled. For example, two identical vehicles operating with the same average speed will generate different emissions based on stops, starts, and acceleration. To account for this, macroscopic models may either use microscopic emissions models capable of estimating changes in emissions because of traffic conditions, or construct driving cycles that are specific for different road types, vehicle classes, and traffic conditions. In many cases, this “drive cycle-based” approach is desirable because it does not require significant levels of highly accurate traffic movement data (3).

## **THE DRIVE CYCLE CONCEPT**

A drive cycle or drive schedule is essentially a series of data points depicting speed over time and is an important concept in quantifying vehicle emissions. They are generally used for one of two purposes:

- Actual emissions testing, where vehicles are run through a drive cycle and emissions are measured.
- Emissions modeling and estimation, where drive cycles representing an array of roadway and vehicle types are applied to a model and emissions are estimated.

This research effort is focused on the development of drive cycles for the purposes of emissions estimation. Figure 2 shows an example of such drive cycles developed for an Urban Principal Arterial roadway under Level of Service (LOS) A (6). Macroscopic emissions modeling in MOVES models uses such drive cycles to transform instantaneous emissions into emissions factors. Thus, driving cycles not only affect the accuracy of emissions estimates but also provide a means of translating emissions from the microscopic level to the macroscopic level. At the microscopic level, actual emissions are obtained on a second-by-second basis through the application of drive cycles (testing). At the macroscopic level, total emissions are estimated by combining data related to individual vehicular emissions with various driving conditions as captured by the drive cycle.



**Figure 2. Drive Cycle for an Urban Principal Arterial or Other Freeway/Expressway at Level of Service A.**

Because these drive cycles provide a means of translating microscopic level vehicle activity to macroscopic level modeling, they are an important aspect of the emissions estimation process and must therefore reflect to the highest degree possible the actual driving conditions within the area being studied. This is particularly true at the local area for state and local air quality, and for transportation agencies that are required to estimate on-road vehicle emissions for a variety of different purposes including demonstrating progress toward attainment, maintaining state implementation plans, and regional transportation planning.

## EXISTING DRIVE CYCLES

Drive cycles come in two general forms. Transient driving cycles are those that involve numerous changes in vehicular behavior over time, such as frequent speed changes. Modal drive cycles, on the other hand, are generally characterized by protracted periods at a constant speed (3). Thus, transient drive cycles are characterized by periods of constant speed that are much shorter in duration than modal driving cycles.

Numerous different drive cycles have been developed to represent an array of driving conditions in various countries. The very first driving cycles in the United States were based on the Federal Test Procedure (FTP) developed for use in both vehicle certification testing and emissions inventory development. The FTP-72 cycle simulates an urban route with numerous starts and stops and was developed in 1972 based on data collected in the Los Angeles metropolitan area. The FTP-75 cycle is built off of the FTP-72 cycle but better represents aggressive, high-speed driving and the use of air conditioning. It features a third phase of 505 seconds that is identical to the first phase of FTP-72, but features a hot start. Supplemental Federal Test Procedure (SFTP) drive cycles further build off of the original FTP cycles by accounting for a wider range of driver behavior including more aggressive driving behavior, high-speed and/or high-acceleration driving, and rapid speed fluctuations. In the 1990s, CARB developed the Unified Cycle for use in California.

In the 1990s, the Economic Commission for Europe and the European Economic Community began working to develop European drive cycles, and those cycles that resulted from this effort are classified as model in nature, in that they feature more constant speeds and acceleration. The Extra Urban Driving Cycle (EUDC), the ECE 15 and the New European Driving Cycle (NEDC) are examples of these European drive cycles. There were recent efforts among European researchers to adapt the U.S. FTP-75 cycle to account for European traffic conditions. Manufacturers instrumented their vehicles to collect real-time driving information, and drivers were instructed to drive in “normal,” “gentle,” and aggressive” manners. Additional European-based drive cycles have been developed using the “Monte Carlo” statistical method where acceleration was simulated from speed versus time as a function of the cumulative distribution of acceleration for each speed level. Driving cycles were thus constructed according to one to three speed levels, two speed ranges, four classes of traffic conditions, and three gradient levels and vehicle types (3).



The 10-15 cycle is currently used for light-duty emissions certification and fuel economy estimation in Japan. This cycle features three 10 mode cycles with an additional 15-mode segment with a maximum speed of 70 km/h. Other international drive cycles include the Athens Driving Cycle (ADC), Institut national de recherche sur les transports et leur sécurité (INRETS) for commercial vehicles, the Perth Driving Cycle, and the Tehran Car cycle used in Iran.

## **OVERVIEW OF MOVES MODEL**

The previous EPA emissions model, MOBILE 6, is an emissions factor model that generates pollutant emissions factors for various vehicle classes based on data collected from dynamometer tests of predefined driving schedules. Emissions factors generated through these tests are coupled with vehicle activity information in the form of vehicle miles travelled (VMT) and average speed to calculate emissions. The EPA's newest emissions model, MOVES, uses a database-centered software framework and a disaggregate emissions estimation algorithm that includes many new features and provides much more flexibility for input and output options than the current MOBILE6.2 model (7). This approach enables MOVES to perform estimation at different analysis levels such as at the national, state, and local level. New input options and changes in the way MOVES handles existing information require the users to create local information for an accurate analysis. However, only the national average driving patterns are included in the default database of the model.

Users of the model specify vehicle types, time periods, geographical areas, pollutants, vehicle operating characteristics, and the road types being modeled. MOVES also incorporates estimates of energy consumption along with several coefficients including heating value, oxidization fraction, and carbon content. The model was designed to work with databases, allowing for new and updated data to be more easily incorporated into the model. The default database summarizes emissions information for the entire United States and is drawn from EPA research studies, Census Bureau vehicle surveys, Federal Highway Administration (FHWA) travel data, and other federal, state, local, industry, and academic sources.

The MOVES model is equipped with default drive cycles that are based on national-level data and are thus less reliable in accurately estimating emissions at the local level. Furthermore, the current cold start and idling activity and emissions information in the MOVES default cycles

are based on a very limited number of observations, which do not include a variety of makes and model years (8). The accuracy of local emission estimates can thus be increased if this information is developed and made available.

The flexible configuration of MOVES, which is based on a database-centered structure, gives more flexibility to users to control the local parameters. Most importantly, the driving patterns representing the different traffic conditions and average traffic speeds are not hard coded into the model. Users can create and use local drive schedules (equivalent to drive cycles in MOBILE models) to perform an accurate analysis. This feature is specifically helpful for project-level conformity analyses that deal with changes in traffic patterns. In addition to project-level analyses, the local drive cycles will enable modelers to accurately estimate the emissions impacts of traffic movement for other purposes such as SIP and attainment demonstration analyses.

### **Emissions Modeling and Driving Schedules in MOVES**

A drive cycle (also called drive schedule) is a second-by-second vehicle speed trajectory and is used in the MOVES model to determine the appropriate operating mode distributions for emissions and energy consumption processes. Drive cycles are necessary in emissions analysis because vehicle emissions can vary greatly depending on the manner in which vehicles are driven, especially for the current fleet of almost-entirely-catalyst-equipped vehicles that are sensitive to driving patterns and acceleration rates. Also, the various aspects of the roadway being travelled on such as speed limit, traffic conditions, road grade, and curvature further influence these factors.

The underlying methodology of the MOBILE family of models has been based on the estimation of mobile source emissions based on average operating characteristics over broad geographical areas. The most important shortcoming of this aggregate-level approach is that differences in driving patterns cannot be captured. For example, driving at 50 mph on a highway with a speed limit of 50 mph is treated the same as driving with the same speed on a freeway with 65 mph speed limit.

Unlike the aggregate approach that was used for the MOBILE model, MOVES uses a disaggregate measure called Vehicle Specific Power (VSP), which is a combined measure of instantaneous speed, acceleration, road grade, and road load (8). For medium- and heavy-duty

vehicles, VSP is converted to another parameter called Scaled Tractive Power (STP). The emissions associated with any given driving pattern are modeled based on distribution of time spent in operation modal bins that, in turn, are defined based on VSP/TSP and speed values. In addition to exhaust emissions, MOVES also provides estimates of start, brake wear, tire wear, and extended idling emissions.

Drive schedules that represent typical operations at different average speeds for each vehicle type operating on a road are used to translate average speed information into VSP distributions. VSP and STP are calculated on a second-by-second basis for a vehicle operating over these drive schedules based on the following equations:

$$VSP = \frac{A \times u + B \times u^2 + C \times u^3 + M \times u \times a}{M}$$

$$STP = VSP \times \frac{M}{f_m}$$

In these equations,  $u$  is the instantaneous speed of the vehicle,  $a$  is the instantaneous acceleration of the vehicle including the impact of the grade ( $a = a_{vehicle} + \sin(\text{atan}(G/100))$ ) where  $G$  is the road grade in percent,  $A$  is a rolling resistance term,  $B$  is a rotating resistance term,  $C$  is a drag term,  $M$  is the vehicle's mass, and  $f_m$  is the power scaling factor for medium- and heavy-duty vehicles.

In the MOVES model for each vehicle group, the running activities (i.e., non-start and non-idling) and associated emissions are organized into operating mode bins. The vehicle activity grouping is based on the instantaneous VSP/TSP and speed as shown in [Table 1](#). The 23 operating modes represent ranges of vehicle speed and VSP/TSP values for running emissions estimations. The model uses 16 operating modes for running energy consumption estimation (7). MOVES' energy consumption estimate includes total energy consumption, fossil fuel energy consumption, and petroleum fuel energy consumption.

Meanwhile, the model's mass emissions estimate includes:

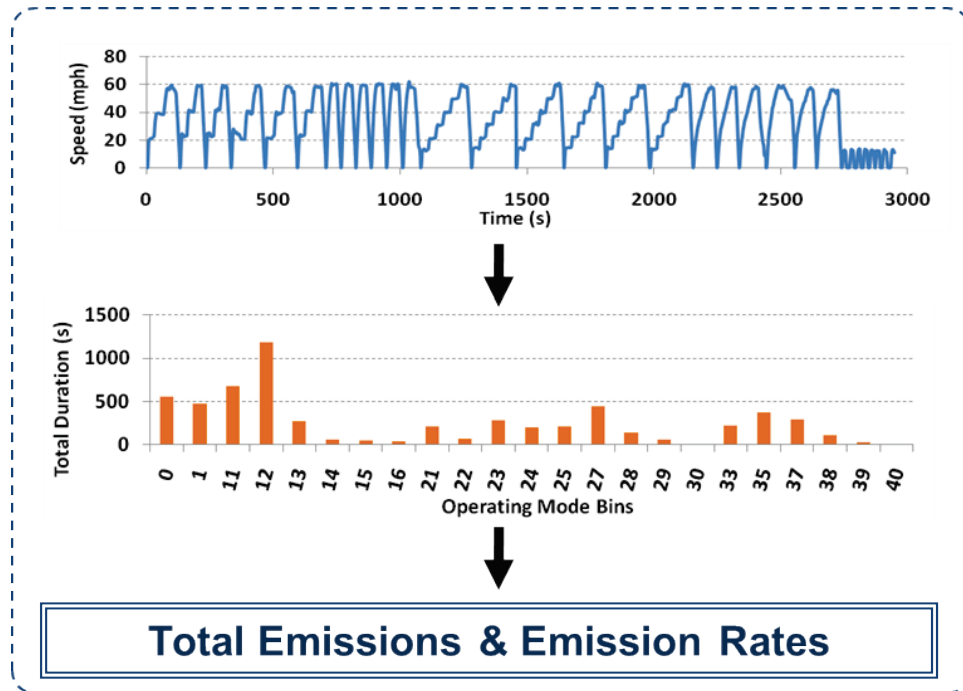
- Total gaseous hydrocarbons (THC), CO, NO<sub>x</sub>, sulfate PM.
- Tire wear and brake wear particles under 2.5 μm in size.
- Methane (CH<sub>4</sub>).
- Nitrous oxide (N<sub>2</sub>O).
- CO<sub>2</sub> on an atmospheric basis.

- The “CO<sub>2</sub> (carbon dioxide)-equivalent” of CO<sub>2</sub> combined with N<sub>2</sub>O and CH<sub>4</sub>.

Corresponding emissions rates for each of these bins are then used to calculate emissions for any driving pattern based on the distribution of time spent in the bins. [Figure 3](#) graphically demonstrates this process. This approach adds major flexibility to emissions analysis because the emissions of any given drive schedule can be estimated.

**Table 1. Operating Mode Bin Definitions for Running Emissions.**

Operating Mode ID	Operating Mode Description	VSP (kW/Tonne) or TSP (skW)	Vehicle Speed ( <i>u</i> , mph)	Vehicle Acceleration ( <i>a</i> , mph/sec)
0	Deceleration/Braking			$a_t \leq -2.0$ OR ( $a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$ )
1	Idle		$-1.0 \leq u < 1.0$	
11	Coast	VSP/STP < 0	$0 \leq u < 25$	
12	Cruise/Acceleration	$0 \leq \text{VSP/TSP} < 3$	$0 \leq u < 25$	
13	Cruise/Acceleration	$3 \leq \text{VSP/TSP} < 6$	$0 \leq u < 25$	
14	Cruise/Acceleration	$6 \leq \text{VSP/TSP} < 9$	$0 \leq u < 25$	
15	Cruise/Acceleration	$9 \leq \text{VSP/TSP} < 12$	$0 \leq u < 25$	
16	Cruise/Acceleration	$12 \leq \text{VSP/TSP}$	$0 \leq u < 25$	
21	Coast	VSP/TSP < 0	$25 \leq u < 50$	
22	Cruise/Acceleration	$0 \leq \text{VSP/TSP} < 3$	$25 \leq u < 50$	
23	Cruise/Acceleration	$3 \leq \text{VSP/TSP} < 6$	$25 \leq u < 50$	
24	Cruise/Acceleration	$6 \leq \text{VSP/TSP} < 9$	$25 \leq u < 50$	
25	Cruise/Acceleration	$9 \leq \text{VSP/TSP} < 12$	$25 \leq u < 50$	
27	Cruise/Acceleration	$12 \leq \text{VSP/TSP} < 18$	$25 \leq u < 50$	
28	Cruise/Acceleration	$18 \leq \text{VSP/TSP} < 24$	$25 \leq u < 50$	
29	Cruise/Acceleration	$24 \leq \text{VSP/TSP} < 30$	$25 \leq u < 50$	
30	Cruise/Acceleration	$30 \leq \text{VSP/TSP}$	$25 \leq u < 50$	
33	Cruise/Acceleration	VSP/TSP < 6	$50 \leq u$	
35	Cruise/Acceleration	$6 \leq \text{VSP/TSP} < 12$	$50 \leq u$	
37	Cruise/Acceleration	$12 \leq \text{VSP/TSP} < 18$	$50 \leq u$	
38	Cruise/Acceleration	$18 \leq \text{VSP/TSP} < 24$	$50 \leq u$	
39	Cruise/Acceleration	$24 \leq \text{VSP/TSP} < 30$	$50 \leq u$	
40	Cruise/Acceleration	$30 \leq \text{VSP/TSP}$	$50 \leq u$	



**Figure 3. Emissions Estimation Process in MOVES.**

Despite the structural flexibility of the MOVES model, which enables users to model different driving patterns, EPA has released the model with only national average driving schedules incorporated. There is a strong agreement in the scientific community that the driving characteristics of each area are unique due to different vehicle fleet composition, driving behavior, and road network topography (9, 10, 11). To take full advantage of the MOVES features, users must provide local drive schedules as well as other local inputs.

In the MOVES model, driving cycles can be represented in one of two different ways. The first method uses speed profiles, which the MOVE model converts into operating mode distributions and average speeds. The second method uses operating mode distributions where speed is allocated into corresponding bins shown in Table 1. Theoretically, both approaches should yields the same results.

In its macro level analysis, MOVES uses “composite” driving schedules that are representative of driving patterns aggregated across different types of roadways, roadway characteristics, and driver behaviors. Thus, while these composite cycles are effective in large-scale emissions modeling, they are less effective in terms of micro level analysis such as for specific roadways or specific vehicle classes. In its initial phases of development, MOVES was focused primarily on macro-scale applications such as what would occur at the county or

regional level. However, recent developments on the model have focused on micro-scale applications at the roadway link level, project level, and other similar levels such as specific expressways and interchanges (the term “link” refers to a particular type and length and roadway for modeling purposes). This has required the development of link-specific and/or project-level driving cycles for use in the MOVES model.

The national default case uses 40 different drive schedules mapped to specific vehicle types and roadway types, but MOVES can accommodate any number of drive schedules. [Table 2](#) shows a summary of the default drive schedules for MOVES. Each drive schedule’s average speed is used to determine the weighting of that schedule for a given road type and source type, based on the average speed distribution. For each of the speed bins in the speed distribution, the model selects the two associated driving cycles with average speeds that bracket that bin’s average speed. The VSP distributions for each driving schedule are then averaged together and weighted by the proximity of the speed bin average speed to the driving schedule average speeds.

**Table 2. Default MOVES Drive Schedules.**

Vehicle Class	Drive Schedule ID	Roadtype	Average Speed	MOVES Road Type			
			(mph)	2	3	4	5
Light Duty	1033	Freeway	8.71909	✓		✓	
	1043	Freeway	15.733	✓		✓	
	1021	Freeway	20.6006	✓		✓	
	153	Freeway	30.5	✓		✓	
	1020	Freeway	46.132	✓		✓	
	1019	Freeway	58.7949	✓		✓	
	1018	Freeway	64.3993	✓		✓	
	1017	Freeway	66.3632	✓		✓	
	1041	Non-Freeway	18.5781		✓		✓
	1030	Non-Freeway	25.379		✓		✓
	1029	Non-Freeway	31.0232		✓		✓
	1026	Urban Non-Freeway	43.2662				✓
	1011	Rural Non-Freeway	49.0722		✓		
	1025	Urban Non-Freeway	52.8263				✓
	1024	Non-Freeway	63.66		✓		✓
	101	Freeway & Non-Freeway	2.5	✓	✓	✓	✓
	199	Ramp - Freeway & Non Freeway	34.6	✓	✓	✓	✓
	1009	Freeway & Non-Freeway	73.7991	✓	✓	✓	✓
158	Freeway & Non-Freeway	76	✓	✓	✓	✓	
Medium Duty And Buses	401	Non-Freeway (Bus Only)	15		✓		✓
	402	Non-Freeway (Bus Only)	30		✓		✓
	403	Non-Freeway (Bus Only)	45		✓		✓
	299	Ramp - Freeway & Non-Freeway *	31	✓	✓	✓	✓
	201	Freeway & Non-Freeway *	4.6	✓	✓	✓	✓
	202	Freeway & Non-Freeway *	10.7	✓	✓	✓	✓
	203	Freeway & Non-Freeway *	15.6	✓	✓	✓	✓
	204	Freeway & Non-Freeway *	20.8	✓	✓	✓	✓
	205	Freeway & Non-Freeway *	24.5	✓	✓	✓	✓
	206	Freeway & Non-Freeway *	31.5	✓	✓	✓	✓
	251	Freeway & Non-Freeway *	34.4	✓	✓	✓	✓
	252	Freeway & Non-Freeway *	44.5	✓	✓	✓	✓
	253	Freeway & Non-Freeway	55.4	✓	✓	✓	✓
	254	Freeway & Non-Freeway	60.4	✓	✓	✓	✓
255	Freeway & Non-Freeway	72.8	✓	✓	✓	✓	
Heavy Duty	501	Non-Freeway (Refuse Truck Only)	2.2		✓		✓
	399	Ramp - Freeway & Non-Freeway	25.3	✓	✓	✓	✓
	301	Freeway & Non-Freeway **	5.8	✓	✓	✓	✓
	302	Freeway & Non-Freeway	11.2	✓	✓	✓	✓
	303	Freeway & Non-Freeway	15.6	✓	✓	✓	✓
	304	Freeway & Non-Freeway	19.4	✓	✓	✓	✓
	305	Freeway & Non-Freeway	25.6	✓	✓	✓	✓
	306	Freeway & Non-Freeway	32.5	✓	✓	✓	✓
	351	Freeway & Non-Freeway	34.3	✓	✓	✓	✓
	352	Freeway & Non-Freeway	47.1	✓	✓	✓	✓
	353	Freeway & Non-Freeway	54.2	✓	✓	✓	✓
	354	Freeway & Non-Freeway	59.4	✓	✓	✓	✓
	355	Freeway & Non-Freeway	71.7	✓	✓	✓	✓

\* Not applied to buses  
\*\* Not applied to refuse trucks

## Roadway Types in MOVES

MOVES uses a simplified road classification based on the Highway Performance Monitoring System (HPMS) functional classes as shown in [Table 3 \(7\)](#). Functional classes are differentiated as rural and urban; within each of these classifications, six separate categories are used to distinguish the type of roadway based primarily on purpose or function within the regional roadway. An advantage of using HPMS-based functional class definitions is that these classifications include not only distinctions between interstate, collector, and local roadways, but also distinctions between rural and urban roadways.

**Table 3. Summary of MOVES Road Types.**

Road Type ID	Description	HPMS Functional Type
1	Off Network	Off Network
2	Rural Restricted Access	Rural Interstate
3	Rural Unrestricted Access	Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector, and Local
4	Urban Restricted Access	Urban Interstate and Urban Freeway/Expressway
5	Urban Unrestricted Access	Urban Principal Arterial, Minor Arterial, Collector, and Local

## Vehicle Classes in MOVES

The primary vehicle classification used in the MOVES model is “SourceType” for on-road vehicles. The classifications roughly correspond to HPMS vehicle classes (see [Table 4](#)).



**Table 4. MOVES Vehicular Source Types.**

Vehicle Class	Source Type ID	Description
Light Duty	11	MotorCycle
	21	Passenger Car
	31	Passenger Truck: SUV, Pickup Truck, Minivans - Two-Axle/Four-Tire Single Unit
	32	Light Commercial Trucks - Two-Axle/Four-Tire Single Unit
Buses & Medium-Duty	41	Intercity Buses
	42	Transit Buses
	43	School Buses
	52	Single-Unit Short-Haul Trucks
	53	Single-Unit Long-Haul Trucks
	54	Single- Unit Motor Homes
Heavy Duty	51	Refuse Trucks
	61	Combination Short-Haul Trucks
	62	Combination Long-Haul Trucks

Vehicular classifications in the form of these source types must be used if emissions are to be accurately estimated in the MOVES model. Estimated populations for these classifications must be generated or collected if the estimates for each region are to be accurate. A primary source for this information is the FHWA’s *Highway Statistics*. The FHWA defines these various classifications as follows (12):

- **Motorcycles.** Includes all two- or three-wheeled motorized vehicles that have saddle-type seats and are steered using handlebars rather than a wheel. This type includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheeled motorcycles.
- **Passenger Cars.** Includes all sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and also includes passenger vehicles pulling recreational or other light trailers. This category includes passenger cars vehicles that are pickup trucks and vans.
- **Other Two-Axle, Four-Tire, Single-Unit Vehicles.** Includes all two-axle, four-tire vehicles, not classified as passenger cars. This classification includes pickup trucks (not classified as passenger cars), panels, vans, and other vehicles such as campers, motor homes, ambulances, and hearses.
- **Buses.** Includes all vehicles manufactured as traditional passenger-carrying buses with two-axles, six-tires, and three or more axles.

- **Single-Unit Trucks.** This category includes all trucks that operated on a single frame. These vehicles may have two axles, three axles, or four or more axles.
- **Combination.** This category includes vehicles with multiple axles and consisting of multiple units, one of which is a tractor or straight truck power-unit.

Table 2 shows how road types and vehicle classes are combined to identify required drive cycle development. As shown in the table, the heavy-duty and medium-duty drive schedules are shared between urban/rural and freeway/non-freeway roads with few exceptions, i.e., buses and low-speed refuse trucks. The light-duty drive schedules can be divided into three different categories: shared between all road types, freeway only, and non-freeway only. The categories provided in Table 2 are used in this research study to determine the drive schedules to be developed.

## TECHNIQUES AND PROCEDURES FOR DRIVE CYCLE DATA COLLECTION

In their simplest form, drive schedules represent a mapping of a vehicle's velocity over time. These data are used in the MOVES model's emissions estimation process. However, driving behavior, which cannot be fully captured by examining just average velocity, can vary greatly depending on various factors that are likely unique to each area. Therefore, to accurately assess the impact from transportation emissions in an area, drive schedules should ideally reflect characteristics of real local vehicle usage patterns. This requires the collecting speed data for numerous vehicle classes over a number of roadway functional classes at different times of the day.

Different technologies have been used to collect this real-world data for developing representative drive schedules, namely:

- Chase cars (CC).
- Instrumented vehicles (IV).
- Global Positioning System (GPS).
- Engine control unit (ECU) data loggers.
- Speed sensors.

## Chase Cars

Chase cars and instrumented vehicles were used in developing speed correction drive cycles that were incorporated in the MOBILE6 model as well as drive cycles for light-duty vehicles in MOVES (13). In the CC approach, driver behavior is mimicked, and speed and acceleration data are recorded by following sample vehicles with an IV that uses laser-based equipment to measure the distance between the CC and the equipped vehicle. In CC-based data collection activities, a suitable target vehicle is identified out of the general population of vehicles on a roadway and the instrumented car begins to follow. The laser equipment on the CC measures the distance between the CC and the target vehicle. Using the pursuing vehicle's speed and the distance that the laser equipment had provided, researchers can develop a speed profile for the target vehicle on the roadway link.

There is an additional CC-oriented approach known as "floating car" data collection, wherein the driver of the monitored vehicle is directed to drive at what is deemed to be the mean speed of surrounding vehicles. The major drawback of this particular approach in terms of developing facility-specific driving cycles is that it usually represents the behavior of a single driver.

The high cost of using these technologies has limited their application to small driver/vehicle sample sizes. Vehicle emissions are not only vehicle based but also depend on drivers' behavior. Capturing this behavior requires large-scale, real-world data collection efforts. The advancement in new speed collection technologies, such as GPS and accelerometers, has brought new opportunities for large-scale drive schedule data collection.

Moorey, Limanond, and Niermeier (2000) raised the following concerns about the use of CC data (14):

- Potential inaccuracies in data that the current chase car protocol and equipment had introduced. (Specifically, range-finding lasers are often unable to maintain a lock on target vehicles when going over bumps and around slight curves. There is also the potential for large errors in measuring target vehicle acceleration.)
- Variation in the amount of data collected being representative of the region's traffic conditions.
- Differences in driving behavior data recorded from target vehicles and from chase vehicles under "non-lock" conditions (when no targets are available).

Some of these issues can potentially be addressed through improving the laser technology used in collecting CC data or to develop an appropriate scanning radar or scanning lidar system. It has also been recommended that the use of non-lock chase car data be minimized or even eliminated from the drive cycle development process. Furthermore, the following three recommended changes to CC data acquisition protocols have been made:

- Utilize simpler chase car routes and simplify target car data collection procedures.
- Utilize a simplified target vehicle selection procedure.
- Utilize traffic density measures as opposed to visual assignment of LOS.

Data derived from CC collection often have to be cleaned and processed. Processing is necessary because the chase car is not directly measuring the speed of the target vehicle.

Common data processing might include (15):

1. Computing second-by-second target vehicle speeds and consolidating data into a single processed data set for the area being studied. Fortran programs such as Clean1E and Clean2E can be used in this process.
2. Smoothing laser range data may be done next, which involves filtering raw target vehicle range measurements to “smooth the effects of discrete bins.” Missing range data might be linearly interpolated from non-missing values.
3. Smoothing of raw chase car speed may next be done along with, if obtained during observations, GPS-based speed measurements that may be smoothed with a quadratic seven-point filter.
4. Chase car speed trace selection.
5. Computation of target vehicle speed.
6. Road grade calculations can be accomplished using second-by-second GPS-based altitude measurements.
7. Removal of leading and trailing idle for the start and stop of each drive.
8. Combine drive run files.

CC data collection has been used extensively in the development of numerous drive cycles (9). For example, the Sierra Research Group (SRG) used data obtained through CC protocols in developing driving cycles for the EPA in a 1997 study. In 1995, the EPA initiated that study after fundamental problems with the MOBILE5 emissions model were observed. Sierra researchers were tasked by the EPA to develop a methodology for generating new driving

cycles that would be facility specific and reflect area-wide driving patterns to address the observed problems with the MOBILE5 model.

In developing this new drive cycle development process, Sierra used speed and time data from three databases developed in 1992 in the greater metropolitan Los Angeles area; Spokane, WA; and Baltimore, MD. During these data collection efforts, a range-finder laser system collected second-by-second speed time profiles from hundreds of target vehicles assumed to represent typical driving behavior. In the Los Angeles study, the chase car followed predefined routes, locking on to target vehicles with the laser while simultaneously collecting data on variables such as road grade, type of vehicle targeted, road facility type, and LOS, in addition to speed and acceleration. The chase car was equipped with video recording equipment and manual recording equipment for visual observations made by the driver and observer. A camcorder (Sony CCDF70), installed between the front and back seats, recorded the traffic in front of the chase car, including a partial view of traffic in adjacent lanes. The system was not visible to other motorists as they drive by the chase car, and the system does not appear to be noticed when drivers in front of the chase car glance in their rear-view mirrors.

Researchers used a GM pulse-generator-type speed sensor to collect speed measurements. However, this system sometimes produced spikes in speed readouts, especially for speeds below 10 mph. To compensate for this effect, SRG developed a supplemental speed measurement system that was comprised of four mounted shaft magnets and a pick-up coil. The magnet generated a pulse every time it passed the pick-up coil. These pulses were recorded by a counter/timer chip. The count was then translated to speed.

The road grade measurement system consisted of two Lucas Nova Sensor unidirectional accelerometers mounted perpendicular to each other. One was installed parallel to the lateral direction, and is used to estimate the lateral acceleration occurring when the wheels on the chase car rotate. The other accelerometer was parallel to the longitudinal direction of the chase car, and was used to estimate the vehicle's longitudinal acceleration, which consists of the speed acceleration due to the driver and the acceleration due to the roadway grade.

### **Self-Contained Instrumented Vehicles**

In this approach, trip data are collected directly from the vehicle through the use of data collection equipment installed within the vehicle itself. This equipment can take many forms,

including GPS-based units and equipment that connects to the vehicular on-board diagnostic (OBD) port and J-BUS. However, the essential difference between this approach and CC data collection is that data are collected directly from the vehicle as opposed to being observed through a chase car. Often, the data obtained through these methods will be combined with survey data in order to provide additional data regarding driver behavior.

The most significant advantage of self-contained IV (or naturalistic driving) data is that the data are real world. However, where CC data represent a broad sample of vehicles, naturalistic data are more heavily influenced by the individual driver. Thus, researchers using such data need to ensure that the vehicles and the drivers involved in the data collection represent the general characteristics of travel in the study region.

GPS-based technologies are increasingly the preferred method for acquisition of naturalistic driving data. Given the GPS's ability to accurately record location, GPS-based approaches to data collection offer several advantages:

- It allows for easier allocation of data based on geography.
- GPS technology has been shown to perform well with regard to commercial vehicle tracking (15).

However, equipment used in these types of studies may require professional installation and calibration depending on the configuration of the equipment and the electrical systems of the vehicles being tested. GPS-based collection efforts might also be complicated by the need to integrate location data with a Geographic Information System (GIS) map. This requires the tagging of GPS data points to geographic areas represented in the GIS map, but this is a relatively straightforward process that GIS software generally supports.

A less high-tech approach for collecting speed data is to use a speed sensor mounted externally to the vehicle, generally in conjunction with the vehicle wheel. The speed sensor generates electric charges as the vehicle's wheel rotates, allowing for vehicle speed calculation (16).

### **GPS and OBD Logging Technologies**

GPS technology is capable of recording location and speed information at the same time. GPS units can automatically record significant amounts of vehicle activity data at one-second intervals. Furthermore, the equipment is small, relatively inexpensive, and can be easily installed

in any vehicle to collect routine activity data from a large-scale population sample without requiring the driver to interact with the unit.

The Department of Defense's removal of the deliberate scrambling of GPS accuracy (i.e., selective availability [SA]) in May 2000 has greatly improved the positional accuracy of GPS. However, the use of GPS in a moving vehicle will always represent measurement accuracy problems that cannot be completely overcome (11). Obstructions of the sky such as tree canopies, buildings, and overpasses temporarily block or distort satellite signals to a GPS receiver on a moving vehicle, therefore causing inaccurate GPS data readings.

Jackson et al. evaluated the ability of GPS receivers to accurately determine the second-by-second operating mode of a vehicle in the real-world transportation network by comparing it to speed obtained from an OBD Version 2 (OBD II) Scan Tool (17). The research identified that GPS is weakest when satellite signals are blocked as well as during acceleration near intersections. It was recommended that given the importance of acceleration for emissions, correction methods should be used to address this issue. Speed data from other sources such as ECU and accelerometers can be used to compensate for these shortcomings.

Oak Ridge National Lab (ORNL) has used a complex data acquisition system to collect large scale vehicle activity data for HDDVs. The data acquisition system includes GPS receivers, wind speed and vehicle weight sensors, and ambient air and road surface temperature probes. These data were collected, archived, and analyzed, then a set of drive schedules was developed for HDDVs (13). The same set of equipment is currently being used for activity data collection on medium-duty trucks in Tennessee.

All vehicles manufactured after 1996, including American, Asian, and European models, come equipped with an OBD port. Through a connection with these ports, equipment such as the DashDAQ Series II data logger and Auterra A-500 DashDyno SPD In-Vehicle Automotive Computer can measure fuel economy, horsepower and torque, speed, and acceleration. These units are generally capable of recording all errors in all vehicle systems under normal driving conditions, meaning that it is not necessary to keep a vehicle in a garage or other enclosed environment where it is often difficult to reproduce various external conditions that might affect driving behavior. GPS-based technologies are often used in conjunction with these OBD-based technologies to provide location information.

## **METHODOLOGIES FOR DRIVE CYCLE DEVELOPMENT**

After data collection has occurred, drive cycles can be developed. The methodologies by which this can be accomplished are generally classified into three groups (18):

- Extrapolation method.
- Selection method.
- Simulation method.

There are additional methods, but with significant drawbacks. For example, cluster analysis may be used to bin all micro-trips prior to combining them into cycles, but this approach can miss extreme driving episodes. Facility-specific driving cycles have also been developed for freeways and arterials using a “snippet” (change in traffic density for a given freeway or a change in the physical link to or from the network) approach. In this approach, micro-trips are divided by snippets and then rejoined to determine acceleration and deceleration.

### **Extrapolation Method**

In this method, all acceleration phases are constant and the average parameters of the cycle are reproduced repeatedly. Operational modes for synthetic cycles are thus smoothed into phases of steady speed and acceleration. Cycles developed under this method are easy to follow by a car on a chassis dynamometer but are not necessarily representative of real driving conditions (3).

### **Selection Model**

Under this approach, which is among the most widely accepted for developing drive cycles, representative time speed sequences for certain summary drive characteristics are collected and linked by idle phases. Micro-trip definition is key to this method and is generally defined as a trip that begins at rest and has at least 2 consecutive seconds of 0 speed. The most representative trips are those that minimize the difference between the parameters and the complete set of data in a certain category of driving cycles. A drive cycle may then be constructed by splicing micro-trips that are selected from survey data and then matching summary features of the resulting speed-time trace with those of the full sample (3).



## **Simulation Model**

In this method, data are collected to synthesize a representative driving cycle by tracking paths through a joint speed-acceleration matrix. Random number generation simulates the probability component in which a time sequence of speeds is produced with various characteristics. German driving cycles have been developed using this method (3).

## **General Drive Cycle Methodology Issues**

Drive cycles must be developed so that they best represent driving patterns within the various groups they are structured to represent. As such, an initial step in developing drive cycles is to group trip data based on roadway functional class. Because emissions are highly sensitive to second-by-second changes in speed and acceleration, the data being grouped are generally second-by-second micro-trips.

In terms of grouping micro-trips by functional class, a common method is to sort trips based on the functional class of the roadway and the observed LOS. Based on the availability of data and the need to perform a robust statistical analysis, it may be necessary to combine various functional classes or LOS-based micro-trips into broader categories. For example, it is unlikely that sufficient micro-trips will be generated on rural roadways that fall within a LOS C or worse. As such, it may be necessary to group all micro-trips collected on rural roadway segments into one group. Conversely, urban roadways are likely to generate micro-trips that cover a wide range of LOSs. As such, these trips can likely be combined into LOS-specific groupings for every urban roadway type. A sample size of 3,600 single second records is advised (16).

After micro-trip data have been categorized according to functional class and LOS, the next step in drive cycle development is to construct joint speed-acceleration frequency distributions (SAFD). During this step, each second-by-second record is labeled in terms of its speed (generally in 5 mph intervals) and in terms of acceleration (generally in terms of 1 mph/s intervals). SAFDs are generated for each functional class/LOS category developed in the initial stage of cycle development. After SAFDs have been developed, numerous statistics with regard to the cycle data set can be developed for each functional class/LOS category. These include:

- Average non-idle speed, which refers to the mean speed when the vehicle is not fully at rest (i.e., speed equals 0 mph).
- “Cruise mode,” which refers to speed records with an acceleration close to 0 mph/s.

- Average cruise speed, which refers to the average speed during these periods.

After SAFD development, candidate cycle construction can occur. Since it is not practical to simply aggregate all data into a very long speed-time trace, due mainly to the computing effort that would be involved, it is desirable to make candidate cycles as short as possible. For example, the LA4 drive cycle, which is used in the EPA's FTP, is 23 minutes (1,372 seconds) long. When deciding on speed measurements and constructing individual speed-time traces, it is important to ensure that (16):

- They represent the distribution of speeds and accelerations in the entire data set.
- They preserve multi-second driving patterns as measured.
- They are short enough in length for practical emissions testing use or implementation as input driving schedules within MOVES.

For freeway-specific cycles, it is rare that vehicles will come to a complete stop (speed of 0 mph/s.) As such, for developing these types of cycles it is necessary to utilize "trip segments" as opposed to micro-trips. A trip segment may be defined as a speed trace whose endpoints have any of the following conditions (16):

- The vehicle came to a complete stop as defined by at least two seconds of 0 speed.
- There was a time discontinuity of more than 1 second from one record to the next within the chronologically sorted data for a specific driving group.
- A contiguous portion of data was identified with a minimum time of 120 seconds that started and ended at cruise speed (near 0 mph/s acceleration).

After these steps have occurred, trip segments should be selected for cycle development.

This can be accomplished through the use of:

- Trip Segment Chaining Constraints—Constraints are imposed such that only certain combinations can be chained together.
- Cycle Construction Logic—A "seed" sample of trip segments for some subset of the desired cycle time is selected at random.

After trip segments have been selected, statistical programs can next be used to construct the cycles that best represent the driving patterns within the groups.

As part of a 2003 study that the EPA had sponsored, the Eastern Research Group (ERG) developed a series of driving cycles for heavy-duty vehicles for use in the MOVES model (19). This effort occurred as MOVES was being developed, and the drive cycles developed as part of

this study did not account for vehicle weight and road grade. It was therefore noted that these cycles should be regarded as a temporary solution to describing heavy-duty vehicle driving behavior. Also, it was noted that the samples used during data collection were likely not representative of the general heavy-duty vehicle fleet in that researchers could only use data from vehicles that happened to be instrumented at the time, which might not be representative in terms of vehicle type and vehicle usage.

Data were obtained for this effort from three sources:

- Second-by-second driving data from TxDOT dump trucks that were equipped with data loggers based on Cummins QuickCheck™ and attached to the vehicle's serial data port following the J1587/J1708 protocol.
- Truck activity data from a Battelle study that used GPS-based units installed on 140 vehicles.
- Truck activity data that Jack Faucett and Associates collected from 30 GPS-equipped trucks.

The drive cycles were developed from micro-trips that matched speed acceleration, and specific vehicle characteristics of the non-idle driving portions of the overall data set. The data collected for this effort required varying levels of preparation to be used in the drive cycle development. It was determined that the GPS data from Faucett and Battelle would require substantial effort to repair to the extent that it could be used in the drive cycle development. (It was difficult, if not impossible, to determine from the data whether the vehicles were idling or moving, as vehicle speeds in these studies were never observed to be 0 mph.) As such, ERG undertook a series of quality control protocols in order to properly use the data.

The 154 total vehicles in the final data set were divided into three categories:

- **Heavy heavy-duty vehicles**—Vehicles with a gross vehicle weight rating of 33,001 lb and greater.
- **Non-parcel medium heavy-duty vehicles**—Vehicles with a gross vehicle weight rating from 19,501 to 33,000 lb and were not used for postal/parcel service.
- **Parcel medium heavy-duty vehicles**—Vehicles with a gross vehicle weight rating from 19,501 to 33,000 lb and were specifically designated as being used for postal/parcel service.

During drive cycle development, micro-trips were designated as being either freeway (equal to or greater than three miles in length) or non-freeway (less than three miles). As such, there were a total of six different combinations of vehicle type/usage and trip designation. An average vehicle speed for all six of these micro-trip designations was calculated and binned into speed bins (rounded to the nearest 5 mph) that were identified through an analysis of the overall data set. The drive cycles were then constructed by combining the micro-trips with actual driving, with the micro-trips being selected based on speed, acceleration, and VSP.

In a 2010 ERG study, the above approach was used to build a series of drive schedules for light-duty vehicles based on data collected in Kansas City as part of Kansas City Emissions Study that ERG conducted in 2004 (20). The developed drive-schedules were used to demonstrate the transition to the MOVES model for developing updated emissions inventories and to provide a preliminary analysis of the likely impacts of the transition on the emissions inventories.

In a 2008 study, ORNL led a data collection and analysis effort for use in examining real-world driving behavior for Class-8 heavy-duty long-haul trucks (21). In Phase 1 of the study, a pilot was conducted to test a data collection system for use in subsequent stages.

- A total of 106 channels of information were collected from vehicles in this stage including:
  - Location.
  - Velocity.
  - Altitude.
  - Pitch.
  - Various measures of driving behavior.
  - Various engine performance measures.
- Mass air flow data were obtained from vehicular data buses.
- Exhaust temperature was taken with a type-K thermocouple installed in the exhaust manifold.
- NO<sub>x</sub> was measured in the combined exhaust stream.

In addition, the following components were used to collect various data points:

- Vehicle weight–Air Weigh 5800.
- Weather information–Vaisala WXT510 Weather Transmitter.

- Road Surface Temperature–RoadWatch equipment.

A data acquisition system (DAS) was developed that used a SOMAT eDAQ unit, which was selected due to its:

- Modular format.
- Ability to interface with a variety of sensors.
- Number of available channels.
- Ability to synchronize multiple units.
- Overall durable housing.

Vehicles were instrumented with the equipment and driven over predetermined routes on Interstate and U.S. state highways from October 2005 through January 2006. The instrumented vehicle made the following trips:

- Two round trips from Chicago, IL, to Portland OR.
- One trip from Maine to Tampa FL, to Detroit, MI.
- One trip from Maine to Orlando, FL, to Detroit, MI.

After these runs were completed, data were extracted from the eDAQ unit and analyzed.

ORNL concluded based on its initial data analysis that:

- “A DAS should be selected on the basis of its ability to store data in an easily extractable format.”
- “Accurate and reliable time stamping is of critical importance for data analyses and comparison purposes.”
- “An indicator should be provided for those periods in which data are inadvertently not collected for various technical reasons. This indicator should explicitly tell when data are missing so that the analysis will not have to infer such information. Without such an indicator, data synchronization would be a problem.”
- “The collection of data can be done at a rate that is much less than 100 Hz. A rate of 2-to-10 Hz is felt to be sufficient.”
- “The data collection rate should be the same for all performance measures.”
- “Data handling and processing, especially with extremely large data sets, were found to be extremely resource-intensive and therefore need to be appropriately accounted for in the project planning.”

In Phase 2, six long-haul trucks and 10 trailers were equipped with the instrumentation developed in Phase 1. Data were collected for nearly 700,000 VMT for a total of over 200 gigabytes of data covering a 12-month period of operation, then reduced from 106 to 60 channels. Engine performance data were collected with a J1939 Vehicle Data Bus and location-related data were collected with a VBOX unit. ORNL used a DCGenT software tool for generating the driving duty cycles from the data collected in this phase.

In a series of studies for CARB and the California Department of Transportation (Caltrans) conducted in 2000, second-by-second speed data were collected in four areas of California (22). Routes for data collection were selected from trip-weighted random samples of origin- and destination-based trips obtained from each of the four study areas regional demand travel models. Routes were driven in the AM peak, PM peak, and off-peak on both congested and uncongested roads. In all, about 100 routes, across all three time periods, were driven about two to four times each. Routes were selected such that data were collected in urban and rural areas.

Data were collected through chase car procedures and were digitally time stamped. It contained second-by-second chase data but also contained “composite” trace data, which were created by combining target vehicle speeds when a target was being followed with chase car speeds when there was no target vehicle (such as in situations where the target car exited from the desired route). Roadway type was defined per definition used in the HPMS. Researchers reported that efforts at categorizing observed congestion in a manner that attempted to match LOS designations defined in the *Highway Capacity Manual* was beneficial.

## **Other Examples of Drive Cycle Development**

### *Chinese Drive Cycles (23)*

In a 2008 study, researchers developed Chinese-specific drive schedules with data collected in 11 cities. A CC technique was used that employed professional drivers directed to follow traffic along pre-defined routes. Specially designed instruments were used to determine vehicle speed and a GPS receiver (with speed sensor for data quality purposes) was used for determining locations. The researchers identified road type and time-of-day as the most important factors affecting driving patterns and thus classified road types as freeways, arterials

and residential roads and divided time-of-day into peak (7:00–9:30 a.m.; 5:00–7:00 p.m.) and off-peak hours for a total of six categories.

Data were collected between 2003 and 2006, and covered at least one week for all cities, except for two of the smaller cities. Each day of collection covered the morning peak, the afternoon off-peak hour, and the evening peak hours. Researchers observed that if the routes and sampling time were properly selected and designed, that the aggregation of samples collected could cover most driving situations. However, it was believed that these situations occur in different proportions than what would be observed over the entire network. As such, the samples collected under this study were adjusted by using a traffic adjustment factor (TAF). The TAF is essentially the share of each driving situation out of the entire volume of traffic.

#### *Bangkok, Thailand (24)*

In developing driving cycles for use in the assessment of exhaust emissions in Bangkok, Thailand, researchers first developed a methodology for identifying links where driving characteristics would best represent real traffic conditions for most vehicles traveling in the city. This was done by first analyzing traffic flow data to determine the average speed of vehicles travelling within the city. Researchers next selected major roads in a manner that the distribution of vehicle speeds on all roads would closely match the average speed identified in the first step. Seven roads were selected through this process for collecting traffic information.

Actual data collection was accomplished through the use of a real-time logging system that was installed in an early 1990s model sedan that travelled the seven designated roads from November to December 2003. Each selected route was driven for a period of two weeks. Data were collected during the morning peak period (7:00 a.m.–9:00 a.m.), as it was determined that the morning peak typically had the highest traffic volumes and therefore the highest levels of fuel consumption and emissions.

Researchers used the data from the on-road collection to calculate acceleration (and deceleration) during every second of each trip. Other driving parameters that were calculated included:

- Average speed.
- Average running speed.
- Time in acceleration.

- Time in deceleration.
- Time at cruise.
- Time at idle.
- Number of stops per kilometer of travel.
- Average acceleration.
- Average deceleration.
- Positive kinetic energy.

The drive cycle was constructed by connecting a number of micro-trips that were randomly selected from the database. The database contained a large number of real micro-trips extracted from the on-road collected speed data. Driving data were separated into micro-trips to determine the predominant patterns occurring within in the actual driving situations and parameters for each micro-trip were calculated. Micro-trips were then grouped based on their average velocities, and, for each velocity interval, every micro-trip was given an equal probability based on the number of micro trips within the interval. A computer program was then used to construct the drive cycle.

### *Motorcycle Drive Cycle*

Researchers in Taiwan worked to develop drive cycles for motorcycles in the city of Kaohsiun, Taiwan, where it is estimated that motorcycles comprised approximately 73 percent of all vehicles in 2002 (25). Four routes (two running north and south, and two running east and west) were selected for investigation. All routes selected connected the downtown area with rural areas and two of the roads separated passenger cars from motorcycles. The distances of the routes selected ranged from 3.5 to 4.6 km and the number of traffic signals on each route ranged from 18 to 30. Data were collected during the morning rush hour (7:00 a.m.–10:00 a.m.), the evening rush hour (4:00 p.m.–7:00 p.m.) and during the mid-day off peak (11:00 a.m.–3:00 p.m.). Each route and time period was tested twice.

The motorcycle used in this study was equipped with a frequency-voltage transducer and time-speed data acquisition system mounted to the front wheel. Five magnetic chips were affixed to the front wheel disk at equal intervals along with a magnetic sensor that was affixed to a hole in the outer hubcap of the front wheel. This magnetic sensor detected the movement of the magnets as the motorcycle progressed through traffic and the transducer would transmit the signal to the data



acquisition system. The driver of the motorcycle would randomly select a target motor to follow so as to establish the driving cycle. Data were recorded at 0.1-second intervals and was averaged to provide a 1-second data point. This served to “smooth” and “filter” the data, as it was time weighted, and only values within 5 percent of the mean were selected. The induction auto-logger would then transfer the speed signal data into digital data.

In an additional drive cycle development effort, motorcycles belonging to commuters in the Edinburgh area (in Scotland) were installed with data acquisition devices (26). Data were collected over five routes covering urban and rural areas. The devices used in this study were GPS-based and were installed beneath the seat of each participating motorcycle or in the driver’s bag. The device measured speed, local position, G-force, lap times, and split times of motorcycles at every 10 Hz. Data that the unit collected were then stored on a computer on a weekly basis. The researchers estimated that the devices, which were tested on a test track used for the calibration of speedometers, were accurate to within  $\pm 0.2$  percent. Data were collected between August and November 2007. Five volunteers each took 44 trips along designated routes that occurred during the morning rush hours, the afternoon off-peak, and the evening rush hour. Questionnaires provided additional information to researchers about vehicle usage and operating conditions.

After data were collected, these were divided into two categories based on the speed limits and classification of the roadways. Unique codes were assigned to describe various attributes such as route, engine type, travel time, day, month, and age of the driver. Input coded files were then created and exported to a computer program that generated a set of assessment parameters, which were then used to assess to what extent each driving cycle was representative. The driving cycle was then developed based on 12 sets of relative assessment parameters.

## **TEXAS-ORIENTED VEHICLE ACTIVITY DATA**

The research team investigated the available vehicle activity data that were collected in Texas. Since the development of drive schedules requires vehicle activity data at a frequency of 1 Hz or higher, only the sources with those frequencies are discussed here.

### **Heavy-Duty Freight Truck Data–ORNL**

ORNL used a complex data acquisition system to collect large-scale vehicle activity data for heavy-duty diesel trucks. The data acquisition system includes GPS receivers, wind speed and vehicle weight sensors, and ambient air and road surface temperature probes. These data were collected, archived, and analyzed, then a set of drive schedules was developed for HDDVs. The archived data set includes HDDV activity on part of east Texas.

### **Austin Heavy-Duty Drive Schedule Data–CTR**

The Center for Transportation Research (CTR) at The University of Texas at Austin collected a set of HDDV activity data as part of the RMC 0-5974 project for TxDOT. The data include GPS speed and location information from multiple runs on the I-35 corridor in Austin during different hours of the day. The CTR intends to develop a series of drive schedules for the evaluation of vehicle operation costs.

### **Drayage Activity at Port of Houston–ERG/EPA**

Under a contract for the EPA, the Eastern Research Group performed a series of emissions testing on drayage tractor-trailer trucks serving the Port of Houston. Vehicle activity data (GPS and engine data) were also collected for all the tested trucks. The research team requested access to these data and the ERG staff referred them to the sponsor (EPA). TTI is actively following up with EPA to receive the data. It is anticipated that these data will be very helpful in developing HDDV's non-highway drive schedules.

### **Light-Duty DMI Data for Houston–TTI**

TTI's Houston Office has an extensive archived data set. One portion of this data set includes data collected with a distance measuring instrument (DMI) on a total of 233 centerline-miles of freeway routes and 198 centerline-miles (319 km) of arterial routes. The speed and distance data from DMI-equipped passenger vehicles were collected on pre-determined routes in Houston at a frequency of approximately 0.5 seconds. The research team uses these data to complement the GPS data. DMI data require further processing to be converted into a format that is consistent with GPS readings.

## HDDV COLD START AND EXTENDED IDLE EMISSIONS

Extended idling and cold starts are significant sources of emissions from HDDVs. Extended idling by commercial trucks use a significant amount of petroleum resources (27, 28). Each year, heavy-duty diesel (long-haul) trucks consume over 800 million gallons of diesel fuel while idling overnight and emitting about 10 million tons of CO<sub>2</sub>, 50,000 tons of NO<sub>x</sub>, and 2,000 tons of PM (29). Currently, idling regulations have been set and are practiced in 29 states in the United States, with the American Transportation Research Institute (ATRI) providing information about these regulations (30). This includes states where at least one city or county has its own active idling regulation(s).

For cold start emissions, there is some information available in the literature, but almost all of the information is for gasoline vehicles with or without actual test results. For example:

- Baugh et al. observed higher emissions of THC, CO, NO<sub>x</sub>, and formaldehyde emissions at lower temperatures under idle operations in six gasoline-fueled light-duty vehicles (LDVs) (31).
- Nam et al. showed that PM increased exponentially with decreased temperature in gasoline-fueled LDVs (32).
- Cook et al. showed in simulation work that HC emissions and air toxics in LDVs and light-duty trucks (LDTs) are underestimated compared to those estimated by EPA's MOBILE 6.2 emissions model (33).

Recently, Gaines et al., Argonne National Laboratory (ANL), reported some cold start and idling testing results from diesel-fueled vehicles as well as gasoline-fueled vehicles (34). One interesting test result observed from the study showed that catalysts on the diesel vehicles may never actually warm up when idling from a cold start. However, the diesel vehicles tested in the study were for light-duty and not for heavy-duty trucks. There is little information on cold start emissions from heavy-duty diesel trucks (35).

Vehicular emissions are higher when the vehicle is not warmed up because catalysts such as a diesel oxidation catalyst (DOC) cannot remove pollutants effectively until the catalysts are warmed up—that is, until the temperature of the DOC reaches the desired operational temperature. The new EPA's emissions estimation model, MOVES, shows different emissions results with different temperature inputs. Choi et al. from an EPA study showed that diesel

vehicle cold-start emissions differ greatly depending upon temperature in a MOVES sensitivity analysis (36).

To estimate emissions from HDDVs, MOVES relies on emissions data from different sources, e.g., results from Consent Decree testing that the West Virginia University conducted using their Mobile Emissions Measurement System (MEMS) (37). However, cold start and extended idling emissions estimates in MOVES suffers from the following shortcomings (38):

- The sample of test vehicles for start emissions is very small: 21 HDDVs from model years 1988 to 2000 and one 2007 HDD engine to develop cold start emissions for this vehicle class.
- Different makes and model years are not adequately covered; especially, newer models are not represented properly in cold start and idling emissions data.
- The cold start conditions for different ambient temperatures are not addressed.
- Cold start PM<sub>2.5</sub> emissions for heavy-duty trucks have not been collected in any significance.

As described above, the current cold start and idling activity and emissions information in MOVES are based on a very limited number of observations. Therefore, it is anticipated that the accuracy of HDDV emissions estimation using MOVES can be improved when more cold start and idling emissions data are incorporated into MOVES.

### **Cold Start and Idling Test Procedures**

There are a few emissions standards and test procedures in the literature for cold start and idling; however, none are for HDDVs. Cold start tests are usually referred to as so-called cold FTP tests, during which a vehicle is started and operated on the FTP-75 drive schedule while the engine is not fully warmed up. For the cold FTP test, only one bag of emissions sample from a test vehicle is collected during 505 seconds of the first cold phase, which represents the cold start emissions. The result from the bag sample (total amount of emissions during the entire 505 test run) does not provide any detailed information of the cold start emissions (that is, no second-by-second emissions information that can be provided by the proposed Portable Emissions Measurement System [PEMS] testing) nor effects of actual cold temperature conditions on emissions because the tests are performed at an average ambient temperature of  $77^{\circ} \pm 9$  F. In addition, the cold FTP test is for light-duty vehicles.

LDVs, light-duty trucks, and medium-duty passenger vehicles (MDPVs) are also subject to:

- Meet cold temperature CO emission standards according to 40 Code of Federal Regulations (CFR) Part 40 Subpart S—CO emissions testing on the FTP at 20°F (−7°C) (39).
- Perform fuel economy tests on an Urban Dynamometer Driving Schedule (UDDS) test procedure at 20°F (−7°C) based on 40 CFR 86 Subpart C—Cold Temperature Test Procedures (40).

However, all emissions testing of HDDVs or heavy-duty diesel engines (HDDEs) are conducted at an average ambient temperature of 77°F ± 9. This has resulted in a lack of full understanding of the cold start HDDV emissions.

For idling testing, there are no emissions regulations for HDDVs, either. The idle test procedures, described in 40 CFR Part 86 Subpart P, are designed to determine the raw concentration (in percent) of CO emissions in the exhaust flow at idle (low- and high-idle conditions) for LDTs and HDDEs (41). The test procedures begin with the trucks/engines at normal operating temperature. For the certification, short test described in 40 CFR Part 86 Subpart O, raw CO and HC concentrations in the exhaust flow are also measured at idle mode as well as high-speed mode for LDVs/Ts (42). However, there are no specific idling emissions regulations for HDDVs.

## **TEXAS-ORIENTED MOVES-BASED EMISSIONS ANALYSIS EFFORTS**

EPA recommends using as much local information as possible for MOVES-based inventories (7). MOVES 2010 was developed to allow for the accommodation to local area conditions, so that state and local governmental agencies can more accurately satisfy legislative mandates for air quality and transportation planning. These features give MOVES considerable flexibility. As noted in a slightly different context, a first level would be to input local vehicle fleet and activity data such as vehicle age distribution, vehicle distance traveled, and vehicle population (37). Another level would involve developing vehicle emissions rates reflecting specific unique local road types or driving patterns.

TTI's Transportation Modeling Program has been aggressively working with the Texas Commission on Environmental Quality (TCEQ) and TxDOT on implementation of MOVES for its ongoing emissions estimation work. Most notably, TTI has developed an approach to adapt

link-level VMT data for use with MOVES under contracts with TCEQ and TxDOT. In an ongoing project with TCEQ, TTI is performing a comparison analysis of the emissions estimations using MOVES with previous emissions estimations using MOBILE6.2 for the Houston area. TTI's recently completed and documented MOVES-related work is summarized next.

In a 2010 TCEQ-sponsored study entitled *MOVES On-Road Inventory Production and Document Preparation*, researchers produced and documented hourly link-based mobile emissions inventory analyses for the eight Houston Galveston Area Council (HGAC) counties using the MOVES model for comparison with a previous MOBILE-based inventory for the same area and period. The relationship between MOVES and MOBILE was summarized, as well as the relationship between analysis year trends within each estimation package.

TTI initially developed a methodology to convert local data (e.g., vehicle classification counts and vehicle registrations) into the source use and fuel type categories that MOVES used. This source use type (SUT)/fuel type mix is the estimated distribution of on-road fleet VMT across the fuel-specific MOVES categories (43). The SUT/fuel type mix method also provided the framework for other MOVES fleet parameter estimation procedures (e.g., age distributions, fuel fractions, SUT populations) used in this analysis.

TTI further updated its link-based emissions estimation utilities for use with MOVES emissions factors (44) (refer to *Update of On-Road Inventory Development Methodologies for MOVES Model Compatibility*, TTI, August 2010). [Appendix B](#) describes these various emissions estimation utilities. Particular utilities were used to produce various MOVES model inputs to adjust MOVES model emissions rate output, and to calculate the emissions estimates by externally combining adjusted MOVES emissions rates with the appropriate activity estimates.

Initially implemented in the MOBILE6-to-MOVES link-level emissions comparative analysis of this task, this MOVES-based method is summarized below in contrast to the MOBILE6-based method. To show the impacts of MOVES as compared to MOBILE6 for link-based analyses, the process inputs/data sources were kept consistent between analyses (inputs and data sources from MOBILE6 analysis were applied in the MOVES analysis where possible). Rather than using available MOBILE6-to-MOVES input data converters (as described in EPA's April 2010 Technical Guidance), TTI's overall approach was to use methods and

procedures with original data sources to develop the MOVES emissions estimates for the comparison.

The MOVES analyses were developed for comparison to existing MOBILE6 analyses for the eight-county HGAC area. However, given this objective, and the relative newness of MOVES, the associated MOVES-based analysis is not an inventory. Rather, it is a link-based emissions estimate for comparison purposes. Given this caveat, along with the fundamental structural differences in the two procedures, the results are not directly comparable. Even the categorical definitions are not identical.

MOVES was found to generally estimate less CO than MOBILE, but greater NO<sub>x</sub> and VOC. This was true for 2006 as well as 2018. However, for 2018 the differences were themselves different. Specifically, the difference in NO<sub>x</sub> was greater and the difference in VOC was less.

In 2009 and 2010, TTI researchers completed a study entitled Improve Capabilities for Combining Vehicle Miles Traveled Activity Data Sets with Updated MOVES Model Emissions Rates for On-Road Mobile Inventory Development for TCEQ. For this study, researchers developed electronic utilities for combining VMT activity data sets from both travel demand model (TDM) and HPMS sources with on-road emissions rates from the EPA MOVES model.

The MOVES-based link-level emissions calculation utility, MOVESemscal, is used to produce link-based emissions estimates by county, year, and day type. The MOVESabcomb utility is subsequently applied to combine the results from individual county MOVESemscal runs into single, multi-county region tab-delimited files, containing individual county and region total activity and emissions summaries. The major inputs for each analysis year are:

- The regional, day type, SUT/fuel type VMT mix (by MOVES roadway type).
- The regional, day type, TDM-based hourly link VMT and speed estimates (links coded by county, TDM roadway, and area type).
- The county, SUT/fuel type population estimates.
- The MOVES-based emissions factors (VMT-based and vehicle-based) look-up tables by pollutant, process, hour, and SUT/fuel type.
- MOVES-based emissions factors for “on-network” activity by average speed and roadway type).
- TDM roadway/area type combinations-to-MOVES road types associations.

In 2008 and 2009, researchers completed a study for TCEQ entitled *Development of Methodologies for Conversion of Data Sets for MOVES Model Compatibility* that investigated methods for utilizing existing transportation data sets so as to be compatible with MOVES. MOVES categorizes the on-road fleet into nine fuel types and 13 SUTs. Recommendations were made for querying the vehicle registration database from TxDOT so that the final output can be compatible with the SUT age distribution format needed for MOVES. Recommendations were also made for using existing vehicle classification counts available from TxDOT for SUT allocation of VMT estimates.

As part of a 2009 and 2010 study for TxDOT entitled *Maintain, Update and Enhance Emissions Analysis Utilities as Needed*, researchers evaluated existing emissions estimation procedures and associated utilities, and provided incremental updates and enhancements as appropriate to support ongoing and anticipated analyses. Researchers also maintained and enhanced the suite of TTI-developed procedures and utilities used to perform conformity-related emissions analyses.

MOVESutl is a collection of emissions inventory estimation utilities that TTI developed. Each of these utilities was written in the Visual Basic programming language. Some of the utilities also use the version of MySQL provided with MOVES to access and process database tables. The individual utilities are accessed using MOVESutl, which is job control file (jcf)-driven code that selects the appropriate utility based on the utility in the jcf. MOVESutl allows the user to access any of the following utilities using a jcf style input file:

- MOVESactivityInputBuild.
- MOVESmetInputBuild.
- MOVESsutmixBuild.
- MOVESpopulationBuild.
- MOVESfleetInputBuild.
- MOVESratesAdj.
- MOVESemscal.
- MOVESlinkemssum.
- MOVESoutSummary.
- MOVESstabfiletotals.
- MOVESstabcomb.



## **INCORPORATING FINDINGS INTO TRANSPORTATION CONFORMITY**

The primary role of MOVES and the application of primary interest to TxDOT is to support conformity demonstration. Therefore, it is important to identify the suitable procedures of officially incorporating the findings of this study into the conformity analysis.

Transportation conformity is a Clean Air Act requirement that ensures federally supported highway and transit projects are consistent with state air quality implementation plans. Conformity helps protect public health through early consideration of the air quality impacts of transportation decisions in places where air quality does not currently meet federal standards or has not met them in the past.

Part 93 Title 40 (Protection of the Environment) of the Code of Federal Regulations describes transportation conformity requirements and the conditions under which a Metropolitan Planning Organization (MPO) must have a conformity determination completed. This same regulation requires TCEQ to publish procedures for Interagency Consultation. Those procedures are published in TAC Title 30 Rule 114.260. Part 93.105 of Title 40 CFR provides guidance for the consultation process.

### **Consultative Partners or Consultation Partners**

These terms are used interchangeably during the transportation conformity process. The term, in general, refers to representatives of EPA Region VI, Federal Highway Administration (FHWA)/Federal Transit Authority (FTA), TCEQ, and TxDOT. Note that this is only a portion of the agencies listed in TAC Title 30, Part 1, 114.260(d)(1)(A).

A major portion of the Transportation Conformity is the Interagency Consultation process. In general, this process is an ongoing, almost daily, process. There are many actions that can trigger the need for a conformity determination, such as project changes in the MPO Transportation Improvement Program (TIP), the MPO Metropolitan Transportation Plan (MTP), the Statewide Transportation Improvement Program (STIP), the National Ambient Air Quality Standard (NAAQS) for various pollutants, and similar items. While this ongoing process is facilitated by the Technical Working Group for Mobile Emissions Sources (TWG). The TWG does not have approval authority. The Consultative Partners must agree on specific actions or decisions.

## **Conformity Determination**

Part 93 of Title 40 CFR indicates that a transportation conformity determination consists of the MPO and the U.S. Department of Transportation (FHWA/FTA) agreeing that the proposed TIP, MTP, or project meets that applicable air quality laws. Therefore, the conformity determination is completed when the MPO receives a letter from the FHWA/FTA. As part of the review process, EPA must also agree that the portion of the SIP for the MPO is in compliance with the applicable laws.

## **CHAPTER 3: DATA COLLECTION PROTOCOL DEVELOPMENT**

This chapter covers the work conducted under Tasks 2, 3, and 4. The objective of Task 2 is to develop test protocols for different data collection elements of the study-drive schedule data collection and idle and cold start emissions testing of heavy-duty diesel vehicles. The developed protocols are outlined here and are based on related literature and the research team's previous experiences. Task 3 identifies and selects the study areas and the heavy-duty diesel truck model years for cold start and idling emissions testing (Phase II). Task 4 consists of recruiting vehicles for both Phases I and II.

Three categories of vehicles were selected for drive schedule data collection based on the findings of Task 1—light duty, medium duty, and heavy duty. Vehicles from these categories were identified, recruited, and equipped with data loggers according to the recommended procedure. In addition to drive schedule data collection, a sample of 10 HDDVs from different makes, models, and years were selected, recruited, and tested for idling and cold start emissions.

The data collection plan for developing local drive schedules (Phase 1) consists of the following major items:

- Vehicle sample sizes at each location and from each vehicle category.
- Data collection technology, methodology, and installation procedures.
- Number of required data collection days.
- Procedures for protecting participants' privacy.

The emissions testing protocol for the Phase 2 emissions testing covers items such as equipment required for HDDV emissions testing, environmental chamber settings, and emissions test procedures including soak time, engine load, test duration, and test equipment configurations.

### **PHASE I—DATA COLLECTION PROTOCOL FOR DRIVE SCHEDULES**

#### **Vehicle Sample Sizes**

During the project kickoff meeting on October 8, 2010, PMC members suggested that the project focus on the large urban areas of Texas: Houston, Dallas–Fort Worth, El Paso, Austin, and San Antonio. The rationale behind this recommendation was that these urban areas generate

high volumes of transportation activities and are also either in nonattainment or near nonattainment for one of the criteria pollutants. The research team therefore decided to focus on these urban areas for collecting vehicle activity data.

The literature review revealed that all drive cycles are divided into three major categories based on vehicle categories, i.e., light, medium, and heavy duty. Any of the 13 vehicle classes in the MOVES emissions estimation model are assigned to one of these categories and use the corresponding drive schedules. The research team recommended following the current categories in the MOVES model, with at least five vehicles from each vehicle category in each target area needed to provide the required data to cover the most prevalent vehicle activity modes required for developing Texas-specific drive schedules.

### **Protecting Participants' Privacy**

The data collection process included pinpointing the exact location of the recruited vehicle at any given time to identify the type of road facility being traveled. Because these data revealed an individual's exact location, the data collection process required procedures to ensure that participants' identity and location information are properly protected per instructions of Title 45 Code of Federal Regulations (CFR) Part 46. The research team prepared and implemented data collection and analysis procedures following The Texas A&M University System's (TAMUS) Institutional Review Board (IRB) procedures and obtained the necessary approvals from the IRB to conduct this project.

Following are the main items in the IRB-approved procedures.

- **Obtain participants' consent** and make sure they understand the risks and benefits. The research team required acquiring the signed consent form from each individual participant before the data collection began. The consent form is found in [Appendix A](#). For fleet vehicles (i.e., organizations and corporations), an overall approval of the owner or fleet manager was obtained; however, a signed consent form from each driver was not required.
- **Data labeling and storage procedures** to protect the collected data and ensure that the data are used only for the stated purpose and are accessible only by authorized TTI staff. The authorized staff was required to have completed CITI (Collaborative

Institutional Training Initiative) training before accessing the data. Following are the procedures for accessing the data:

- Data download and labeling: all data files were labeled according to following format: dataLoggerUnitNumber\_DownloadDate\_VehicleType.csv (or .xlsx), e.g. “TTI\_10\_02102011\_PC.xlsx.”
- Data were downloaded using TTI computers on a secure folder that is accessible only to the authorized TTI staff.
- The information of the participants and logger units assigned to them was recorded in a log table, which is accessible only to authorized TTI staff with CITI credentials.
- All the files are backed up on a TTI server. TTI has established a secure folder on its server to host these data.

### **Data Collection Technologies**

The literature review findings revealed that Global Positioning System technology is the best candidate for collecting speed and location data required for this study. GPS data were already used to develop MOVES’ default drive schedules.

The research team focused on identifying the GPS data logger that meets the requirements of this study. After a careful review of the available GPS technology, it was concluded that new off-the-shelf GPS loggers are capable of providing the speed and location data at the desired accuracy level. Additionally, since the participants were scattered in different regions of the state, it was decided that the technology should be a standalone unit (i.e., no connection to the vehicle required) and be easy to install.

The majority of current high sensitivity GPS units are based on chipsets manufactured by SiRF Technology™ (SiRF III™ chipset series) or MediaTek Incorporation™ (MTK II™ chipset series). The research team obtained and field tested a few commercially available GPS units based on these technologies. The following factors were considered in the assessment of the units:

- Accuracy of readings (desired—unit sensitivity of  $-165$  dbm or higher).
- Memory size (desired-external SD card).
- Battery capacity and whether it can be extended.

- Ease of installation (desired-no external antenna).
- Accompanied software.
- Other options such as motion activation, etc.

No single unit met all the desired specifications. The research team selected the QStarz BT-Q1000eX Xtreme Recorder based on its overall performance and specifications (45). Figure 4 shows the QStarz BT-Q1000eX unit. The Xtreme Recorder is based on MTK II chipset with a sensitivity of  $-165$  dbm, which exceeds the desired sensitivity threshold. The unit has the capability of recording speed and position data on a second-by-second basis (1 Hz) as well as 5 Hz and has a memory capacity for 64 hours of observation on the 1-Hz mode.



**Figure 4. QStarz BT-Q1000eX Unit and Its Extended Battery Pack.**

The QStarz unit is equipped with a vibration detector that enables the option of deactivating the unit if no motion is detected for 10 consecutive minutes. This option is crucial to conserve battery power by deactivating the recorder when no activity is detected. A rechargeable lithium-ion battery—similar to ones that Nokia cell phones use and that are capable of powering the unit for one week under normal urban driving conditions—provides the power for the data logger. The original battery life is extended by soldering an additional battery pack onto the original unit, in expectation that about two weeks of passenger vehicle data need to be recorded for driving on typical urban trip patterns.

A limited sample of engine data including vehicle speed, engine speed, and throttle position was collected using CarChip Pro OBD-II data logger. These data are intended to be used for quality control to specifically validate algorithms that identify acceleration and deceleration events. A comparison with the corresponding GPS data showed the engine data lack the

precision needed for this study, i.e., speed is recorded with no decimal digits and records are slightly different from the 1 Hz frequency needed. The manufacturer indicated that they cannot fix any of these problems because these are either out of their control (exact sampling rate depends on the engine) or a fix is not planned for the near future (the loggers' firmware need to be updated to record decimal digits for vehicle speed). Therefore, the research team does not recommend using this data logger for any purpose beyond quality control of algorithms.

### **Duration of Data Collection**

The battery capacity and data logger's memory size are the main limiting factors for the duration of data collection. The research team performed a limited number of beta testing with the selected data loggers to determine the optimal duration for each category of vehicles. The results of this beta testing suggested that a two-week period provides the necessary amount of data. This estimated time might be lower for long-haul vehicles since they tend to drive more in a short period of time.

### **Data Collection Methodology**

The data collection process included two parallel efforts:

- Planned data collection on pre-defined routes.
- Normal vehicle activity, which was the main data collection effort for this study.

The first data collection effort consisted of a TTI staff member driving a GPS-equipped vehicle on a predefined route in the target area during a set period of time. This included driving during peak and off-peak periods. A minimum of two days of data collection is recommended for this effort. This data collection is intended to address the possible gaps in the data from the main data collection effort and therefore was a limited effort performed after the main data collection.

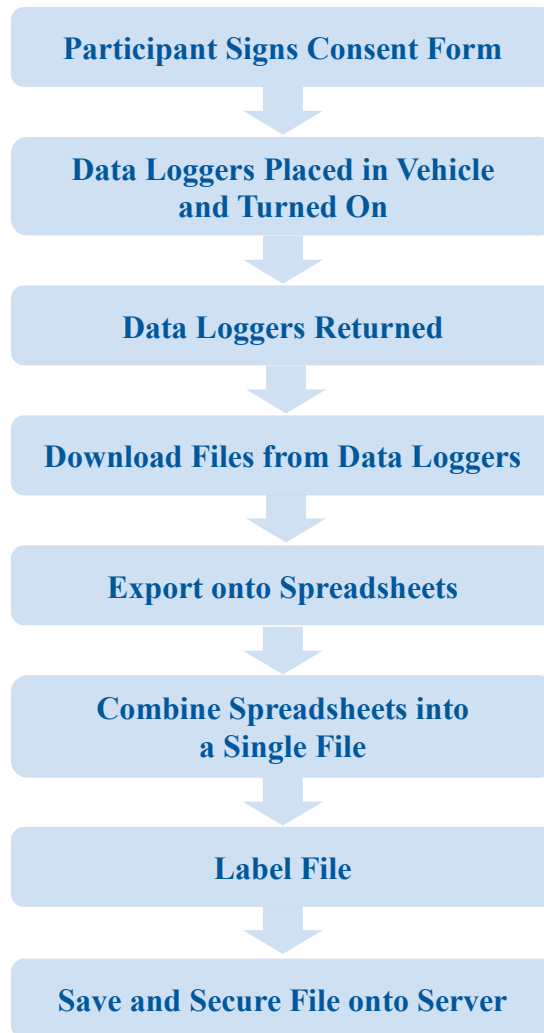
The main data collection effort consisted of requiring individual and fleet vehicles to record their normal activity during an extended period of time. The research team developed a standardized methodology for gathering and storing personally identifiable information collected using GPS data loggers that monitor second-by-second movement. [Figure 5](#) shows an overall outline of the data collection methodology.

After assembling a pool of potential candidates, the first step was to have the participant review and sign a consent form detailing the research being conducted and how their information

would be used in the study. Participants also filled out a form giving information about the vehicle make, model, year, fuel type, number of cylinders, and engine size.

Three GPS data loggers were sent through the mail or hand-delivered to the participants. Installing three units as opposed to one unit in each vehicle helped to ensure accuracy in case that one unit malfunctioned or provided erroneous data. A set of instructions accompanied the devices providing instructions on how to place and activate the data loggers (see [Appendix A](#)). Typically, the devices were set in the driver-side storage compartment (as shown in the figure in [Appendix A](#)) to ensure that the vibration detector started recording whenever the vehicle door was opened, which was usually at the beginning of a trip. If the vehicle did not have a driver-side storage compartment, the loggers were placed in the vehicle's glove box or another secure location inside the cabin. The data loggers were returned after two weeks when the power supply for the unit was expected to be completely drained. For some participants, payment was issued after the units were safely returned.





**Figure 5. Data Collection Process Flowchart.**

Information from each of the three data loggers was downloaded onto a central server and given a unique identifier that would not trace the data back to the original participant. The spreadsheets from each of the three devices were merged into one document that was labeled with variables describing unit number, date of initial activation, and type of vehicle observed. Only researchers assigned to the project were given access to the secure files on the server. Data encryption was used as a means to protect all data files.

### **Vehicle Recruiting for Drive Schedules**

A total of 245 vehicles were recruited for GPS data collection. As documented in [Chapter 2](#), the research team focused on the following large urban areas of Texas:

- Houston.

- Dallas–Fort Worth.
- El Paso.
- Austin.
- San Antonio.

Per TAMU’s Institutional Review Board requirement, a signed consent form was obtained from each individual participant as part of the recruiting effort. Fleet vehicles are not subject to this requirement. The following documents the recruiting effort for each of these vehicle types.

For light-duty vehicles, the research group recruited mostly TTI staff from TTI urban offices at the target urban areas who volunteered to participate in the data collection. A few outside individuals, who were compensated \$75 for their participation, were also included in this effort. Private fleets and public works maintenance crews (including regional TxDOT offices) mostly composed the participants for medium- and heavy-duty vehicles.

### **Vehicle Sample Sizes**

A goal of seven to 10 vehicles per vehicle category—light-, medium-, and heavy-duty—was set for each region. The region was defined as being the locality where the original GPS assembly placement had occurred. Vehicles in the study were known to travel across multiple regions within a single observation period. Light-duty vehicles were passenger cars and small trucks less than 10,000 in gross vehicular weight (GVW), medium-duty vehicles ranged from 10,000 to 30,000 pounds, and heavy-duty vehicles were trucks that weighed more than 30,000 pounds. Each vehicle was observed for a period of one to two weeks, depending on the level of driving activity. [Table 5](#) shows the distribution of vehicles observed by weight classification and region. The research team recruited 245 individual vehicles for drive cycle data collection (Phase 1). In addition, TTI performed 30 vehicle-days of drive cycle data collection on predetermined routes for medium-duty trucks and a total of 650 miles of data for electric vehicles.

**Table 5. Recruited Vehicles by Weight Class and Region.**

<b>Vehicle Type   Area</b>	<b>Austin</b>	<b>Dallas–Fort Worth</b>	<b>El Paso</b>	<b>Houston</b>	<b>San Antonio</b>	<b>Total</b>
Light Duty	31	11	26	7	8	83
Medium Duty	7	15	3	18	7	50
Heavy Duty	14	20	34	23	21	112
<b>Total</b>	<b>52</b>	<b>46</b>	<b>63</b>	<b>48</b>	<b>36</b>	<b>245</b>

According to MOVES documentation, the majority of light-duty vehicles can be categorized as the following three vehicle types:

- Passenger Cars.
- Passenger Trucks including minivans, SUVs, and pickup trucks.
- Light Commercial trucks.

As mentioned above, the majority of the recruited drivers for light-duty vehicles were TTI staff who volunteered to participate in the data collection. For each urban region, an e-mail message was sent to all of the TTI staff who worked out of an office in a particular region. Interested volunteers contacted the main coordinator (in Austin) who distributed consent forms electronically; which had to be signed and returned. The TTI El Paso office recruited a few individual participants by using its personal contacts.

### **Heavy- and Medium-Duty Vehicles**

Heavy-duty vehicles were defined as vehicles with a gross vehicle weight ratio (GVWR) of more than 30,000 pounds. Prospective fleet managers of heavy-duty vehicle fleets were recruited through a variety of methods, including in-person contact, phone conversations, and e-mail messages. In-person contact was tried for a few operators because a TTI staffer could physically show the unit to the fleet manager, hoping to gain their trust and confidence to participate in the study. Phone and business directories were gathered to help compile a list of potential contacts. The Office of Vehicle Management from the Texas State Comptroller’s Office was contacted for a list of fleet managers who worked with state agencies. The NAFA Fleet Management Association, a national trade group representing fleet managers, had a database of individual phone and e-mail contacts that was also useful. Over 200 fleet managers were recruited as volunteers for this study.

A sample script was used in the body of messages that was first sent out to fleet managers to describe the research study, detail what was required, and formally ask them to volunteer. The

text of the sample script is shown in [Appendix B](#). Pictures of the device were distributed to give managers an idea about the size of the assembly and how it operated.

The script was useful in communicating a coherent summary of the research project; however, most managers declined because they felt that participation would not directly benefit the day-to-day operation of their respective business. Most managers have explicitly stated that financial incentives would not have changed their perceptions about participating in the research. Overall, the success rate for participation versus total contact was less than 5 percent. A significant majority of managers contacted did not return any messages or phone calls. A successful strategy that did work was to use individual contacts from freight companies that volunteered for prior TTI research. For example, TTI had maintained a list of stakeholder contacts from trucking fleets while conducting research about use of the SH 130 Toll Road.

The majority of medium-duty vehicles were classified as commercial trucks with GVWR of more than 10,000 lb, but not greater than 30,000 lb. Typically, these included pickup delivery trucks, utility service trucks, and flatbed trucks. The recruitment process for vehicles within the medium-duty classification was similar to recruiting fleets that mostly had heavy-duty vehicles. It was a challenge to recruit medium-duty vehicles because not many fleet managers were willing to participate. Highway maintenance fleets from local TxDOT districts were recruited to help increase the sample size of medium-duty vehicle activities within each region. Within the sample from TxDOT, activities were monitored from vehicles that handled sign installation and repair.

TxDOT fleets were recruited by contacting the main fleet coordinator, based in Austin, who contacted a local person within each region. After TxDOT made initial contact with the local person, the fleet coordinator gave the contact information to the TTI researcher, who followed up with the local individual and scheduled the date and location of the installation. For vehicles in the TxDOT fleet, a TTI researcher personally did all vehicle installation.

The major reasons that fleet managers who declined to participate in the study gave were:

- Time taken to participate in the study would take effort away from running the business.
- Boss would not condone monitoring activities from an outside group.
- Managers felt that employee morale would dampen if devices were placed in their vehicles without their consent.

Fleet operators who volunteered for the project met with TTI researchers at the site of their vehicle storage yards and coordinated the placement of GPS devices in selected vehicles. The TTI researcher responsible for installation would, in addition to other vehicle characteristics, record the visible ID number that the fleet operator gave (usually displayed on the side of the door) as a way to track which vehicles were equipped with GPS devices when time came to retrieve the devices. Individuals who drove personal vehicles were required to sign and return a consent form that followed ethical protocol for conducting human subject research from the Institutional Review Board of the Texas A&M University System. The GPS assemblies for personal vehicles were distributed in person or through the mail directly to the volunteers, who then placed the assemblies in the vehicles themselves.

### **In-House Data Collection for Medium-Duty Vehicles**

Because of the difficulties of recruiting medium-duty vehicles, it was determined that there was not enough data for this vehicle category in some urban areas. The research team designed a series of data collection efforts using rental trucks, i.e., 24- or 26-foot moving truck in the following urban areas:

- Austin (two trucks).
- El Paso (one truck).
- Dallas–Fort Worth (two trucks).
- San Antonio (one truck).

Each truck was assigned a driving schedule covering different times of day (peak and off-peak) as well as different road types (freeway and non-freeway). The same TTI staffer drove each truck for the entire duration of the data collection. This effort consisted of a total of 30 vehicle-days of data collection on predetermined routes in the urban areas previously mentioned.

### **PHASE II–COLD START AND IDLING EMISSIONS TESTING PROTOCOL**

The purpose of this task was to develop a cold start and extended idling testing protocol to examine HDDV exhaust emissions while the vehicles are cold-started and idling in an environmental chamber, where testing conditions (such as temperature and humidity) can be easily controlled and maintained. A total of 10 HDDVs were tested according to the following protocol.

## Test Procedures

As discussed in the Task 1 technical memorandum, there is no specific cold start and idling emissions regulation for HDDVs. Only a very few studies provide information for idling emissions testing of HDDVs (46, 47). The idling testing protocol from an EPA-sponsored TTI study is based on national testing standards such as Society of Automotive Engineers (SAE), Technology and Maintenance Council (TMC), and CFR. Using the information from these studies, TTI researchers developed a test protocol to examine HDDV extended idling and cold start emissions for this study.

Not all the idling speed, temperature, and load combinations are sensible and the table below shows a summary of the proposed testing combinations based on the expected condition for Texas. Table 6 shows a test condition matrix developed based on the test protocol.

**Table 6. Test Condition Matrix.**

Test ID	Temperature	Relative Humidity
Hot	100°F (37.8°C)	70%
Cold	30°F (-1.1°C)	N/A

HDDV extended idling occurs mainly to provide air conditioning on hot days and heat on cold days, so that temperature conditions for a hot test (100°F or 37.8°C) and a cold test (30°F or -1.1°C) are proposed for the emissions testing in this study.

In the TxDOT-sponsored TTI study 0-6237, the temperature for cold (or heating system) testing was set at 0°F (-17.8°C) to cover the entire continental United States including cold winter conditions in northern U.S. regions (44, 48). Based on recent data from the National Oceanic and Atmospheric Administration (NOAA), average winter season (December and January) temperatures in Texas average in the range of 45°–50°F, which are about 15°F higher than national averages, and the lowest average temperatures do not usually fall below 20°F (49).

To represent the winter conditions that affect a large number of trucks in Texas, the research team selected the Dallas–Fort Worth (DFW) area as the largest transportation activity center in the northern part of the state. Temperature data from 2000 to 2010 were obtained and analyzed. These data showed that the average lowest temperature for the coldest month of year

(January) in the DFW area was approximately 30°F. TTI researchers therefore propose to use 30°F (−1.1°C), instead of 0°F (−17.8°C) from the previous TTI study and the proposed TMC practice (48) to represent Texas-specific conditions. For the hot weather condition, TTI researchers propose to set the temperature at 100 F (37.8°C) (the same from the EPA study and the practice) and a relative humidity of 70 percent (instead of 50 percent from the EPA study and the practice) to consider hot, humid summer days in Texas such as in Houston areas in July and August. Additionally, based on previous study experience, 120 watts of continuous electricity loading is proposed for both the cold and hot tests to simulate the use of small appliances such as laptops, small televisions, and microwave ovens.

To perform a statistical analysis, the research team performed three runs for each test condition in each HDDV test. Based on the team's past experience, it was estimated that 30 minutes of measurement was needed for each test condition for each truck. For each test condition, the first test contained only the cold start emissions data—one cold start emissions test for each condition for each truck. Due to limited time and budget, additional cold start emissions testing was not performed. The test fuel, regular Texas low-emission diesel (TxLED) with a sulfur content of 15 ppm or less, was used because MOVES does not specify any detailed fuel types for emissions estimation.

### **Testing Equipment**

The research team proposed that a portable emissions-measuring system and a particulate matter (PM) mass monitoring system be used simultaneously during the emissions testing in the environmental chamber that was proposed for this study. The PEMS unit collected oxides of nitrogen (NO<sub>x</sub>), hydrocarbon (HC), carbon monoxide (CO), and carbon dioxide (CO<sub>2</sub>) gaseous emissions while the PM mass monitoring system collected PM mass emissions. It was also proposed to use TTI's SEMTECH-DS unit along with TTI's electronic vehicle exhaust flow meters (EFMs) for the gaseous emissions and to use TTI's Dekati Mass Monitor (DMM) system to measure the PM mass emissions.

For the PM and other toxics characterization, the research team collected integrated samples from TTI's dilution system while the HDDVs were subjected to various idling modes. The PM mass in these tests were measured using the DMM. Collected filter and cartridge samples were sent to the Oak Ridge National Laboratory for PM and other mobile source air toxics (MSAT)

chemical analysis including organic carbon (OC)/elemental carbon (EC) analysis. The following briefly describes the SEMTECH PEMS unit, DMM, and microdilution sampling system (MSS). The details of the emission testing equipment are discussed in [Chapter 6](#).

### **Selection of HDDV Model Years**

To determine what vehicle model years would be selected for testing, the research team looked at the current registration data from the Texas Department of Motor Vehicles, as well as the EPA emission standards for on-road heavy-duty diesel vehicles; data were then used in the MOVES model. [Table 7](#) shows the breakdown of the data compiled to select the model years to be tested. The data show that the biggest gap in data occurs in vehicles from model years 2007–2012. These are also the model years that count for a total of over 41 percent of all HDDVs registered in Texas. By looking at these numbers, the research team recommended to test the following model year vehicles from different manufacturers and engine sizes.

- MY 2012 to MY 2013—three vehicles.
- MY 2010 to 2012—six vehicles.
- MY 2007 to 2009—four vehicles.
- MY 2004 to 2006—two vehicles.



**Table 7. Summary of Vehicle Data.**

MOVES Model Year	% of Registered HDDVs in Texas (50)	# of Vehicles Tested to Date by TTI	Vehicles Tested for MOVES2009 (36)	
			Running and Idling Emissions	Cold Start Idle Emissions
Pre-1985	0.76	0	18	25
1985–1987	0.70	0		
1988–1989	0.81	0		
1990	0.58	0		
1991–1993	2.1	1	184	
1994–1997	5.39	3		
1998	2.01	0		
1999–2002	16.11	0		
2003–2006	30.69	15		
2007–2009	27.32	0	0	
2010–2012	13.77	2	0	

**Testing Protocol**

Each test vehicle was tested under two different scenarios, normal idling as well as a “high idle” test. As described above, each of these tests was conducted under two conditions, shown in Table 8 below, selected to represent the winter and summer conditions in Texas. To represent the winter conditions that affect a large number of trucks in Texas, the research team selected the Dallas–Fort Worth (DFW) area as the largest transportation activity center in the northern part of the state. Temperature data from 2000 to 2010 were obtained and analyzed. These data showed that the average lowest temperature for the coldest month of year (January) in the DFW area was approximately 30°F. TTI researchers therefore proposed to use 30°F (–1.1°C) for the cold test. The research team also proposed to set the temperature at 100°F (37.8°C). A relative humidity of 70 percent was adopted to consider hot and humid summer days in Houston in July and August.

**Table 8. Test Conditions.**

Test ID	Temperature	Relative Humidity
Hot	100°F (37°C)	70%
Cold	30°F (–1.1°C)	N/A

Initially, the research team proposed to include 120 watts of continuous electricity loading to simulate the use of small appliances such as laptops, small televisions, and microwave

ovens. The team did a preliminary investigation and found that the impact of this load was not detectable, so the electric load was not included in the final test protocol.

The normal idling testing was done for a set of three different soak times, with one soak time being greater than 720 minutes, representing cold start idling. The team determined the other soak times by testing the first test truck under different soak times to find the appropriate soak times for the remaining trucks (see Table 9). Based on the testing of the first truck the team determined that the other soak times would be 5 minutes (Bin 101) and 15 minutes (Bin 102). Budget and timeline limitations were among the key determining factors in this decision; using soak times from any of the other operating mode bins would have required that the truck be tested on multiple days for each condition, therefore almost doubling the required budget and testing time.

**Table 9. MOVES Operating Mode Bins for Start Emissions (as Function of Soak Time).**

<b>Operating Mode Bin</b>	<b>MOVES Operating Mode Bin Description</b>
101	Soak Time < 6 minutes
102	6 minutes ≤ Soak Time < 30 minutes
103	30 minutes ≤ Soak Time < 60 minutes
104	60 minutes ≤ Soak Time < 90 minutes
105	90 minutes ≤ Soak Time < 120 minutes
106	120 minutes ≤ Soak Time < 360 minutes
107	360 minutes ≤ Soak Time < 720 minutes
108	720 minutes ≤ Soak Time

When a vehicle is ready to be tested, it is parked overnight inside the test chamber. This allows it to be off for the required amount of time for a cold start. The following day, the vehicle is turned on and idled, for a minimum time period of one hour for the cold soak testing and 45 minutes for all other soak times. Following the first test, the vehicle is turned off for the required soak time as determined from testing the first vehicle. After the vehicle has soaked for that time, it is turned on and idled for 45 minutes. This process is repeated for the final soak time.

In addition to the testing under all three recommended soak times, each truck is tested for “high idle” conditions, if applicable.<sup>1</sup> The “high idle” test is conducted by increasing the idle speed of the vehicle to 1000–1100 RPMs. In addition, the A/C/heating is turned on, depending

<sup>1</sup> If the truck is capable of idling at a higher RPM, it is tested for the “high idle” condition.

on the temperature condition of the test. The load represents the trucker's running of appliances. The truck is then idled, for a minimum of 45 minutes, to complete the "high idle" testing. The "high idle" testing is not done for the cold soak testing, but is done for the other soak times if applicable.

### **Vehicle Recruiting for Emissions Testing**

The research team recruited and tested a total of 15 trucks as proposed for this project. The details of these trucks are discussed in [Chapter 6](#). The trucks were obtained from three different sources: TTI owned one (Truck 1), and the others were rented from two separate leasing companies.

Five trucks were rented from *Longhorn Idealease*, a rental company with locations throughout Texas. Most of the trucks from this test came from the Austin area. The contact at Longhorn was Greg Keogel, the rental manager for the company. In addition to the trucks, the company provided drivers, so the trucks would be delivered two at a time to TTI's EERF test facility. Once the testing was complete, the rental company would bring two more trucks, and return the two that had already been tested.

After testing the sixth truck, the research team decided to look for another rental company from which to acquire the remaining trucks. This was done to give a better variety of truck and engine manufacturers in the test group. A second company, *Bruckner Leasing Company*, located in the Dallas area, was found and provided the necessary trucks for the remaining tests. The contact for this company was Jon Hunt. However, Bruckner Leasing did not employ drivers that could deliver the trucks to the test facility. To keep the testing moving, a local driver was hired who would transport the trucks, one at a time, to and from the rental location to the test facility in Bryan.

The main obstacle in the testing of the vehicles was the logistics of getting vehicles to and from the test facility in a timely manner. To meet the project schedule as well as the task budget, the trucks did not stay at the facility longer than necessary. With the length of the testing (approximately 12 hours per test), one extra day of rental was necessary for each truck. This allowed the trucks to be prepped and tested in three days.

The final three trucks were rented from *Bruckner Leasing Company*, the same company that the 7th–12th trucks were rented from. At this time Bruckner Leasing had a driver available

to deliver the trucks to College Station. The driver brought each vehicle to College Station the day before testing began, then would pick these up the following day and returned the trucks to Bruckner's yard.

## **CHAPTER 4: DRIVE SCHEDULE DATA COLLECTION**

As reported in [Chapter 3](#), the research team recruited 245 individual vehicles for drive cycle data collection (Phase 1). In addition, TTI performed 30 day-vehicles of drive cycle data collection on pre-determined routes for medium-duty trucks and a total of 650 miles of data for electric vehicles.

For the light-duty vehicles, the research team recruited mostly TTI staff from TTI urban offices at the target urban areas who volunteered to participate in the data collection. A few outside individuals, who were compensated \$75 for their efforts, were also included in this portion of data collection. Private fleets and public works maintenance crews (including regional TxDOT offices) made up most of the participants for medium- and heavy-duty vehicles.

Data collection included a mix of supervised and unsupervised procedures. The majority of data were collected via the unsupervised data collection effort in which drivers were instructed to follow their normal driving activities for a certain period of time. The drivers were provided with instruction materials and contact information of the research team in case of any unforeseen problems during the data collection period. An average of two weeks of data collection was used for the unsupervised data collection. The supervised procedure was used to collect data from medium-duty vehicles and electric vehicles. The process involved assigning a vehicle to a series of predetermined routes throughout the study areas at different hours of the day.

Individual vehicle owners selected to participate in the study were instructed to meet TTI researchers at a predetermined location, usually a local TTI office. At this location TTI staff performed the following tasks:

- Explained the purpose of the study and how data are collected.
- Obtained the written consent of the participants per IRB requirements.
- Verified that the vehicle meets the selection criteria established in Task 2 (Data Collection Protocol Development).
- Installed the data collecting equipment in the owners' vehicles.
- Recorded the detailed information of the vehicles.

After a predetermined data collection period, the owners returned with their vehicles, and TTI researchers removed the data collecting equipment and paid the owners for their

participation (when they were eligible for compensation as TTI policy determined). After this step, the GPS data were downloaded onto a TTI computer, verified, and labeled properly for data processing and analysis.

The following results were achieved through this task:

- A database of second-by-second speed for all participating vehicles.
- A database of engine parameters data for a sample of two light duty vehicles.

## GPS ASSEMBLY VEHICLE INSTALLATION

As shown in [Figure 6](#), each GPS assembly consists of three high accuracy GPS logger units. The GPS assemblies were placed in a secure location within the passenger cabin for vehicles in the medium- and heavy-duty classes. Usually, the assembly was placed in either the driver-side front door pocket or around the seat belt mount on the right side of the driver seat. [Figure 7](#) shows the placement of a GPS assembly inside a heavy-duty vehicle. For light-duty passenger vehicles, the assembly was placed in the driver-side map pocket.



**Figure 6. GPS Assembly Used in Data Collection.**

The assemblies were placed near the driver seat as a way to maximize the chance for each GPS unit to self-actuate after detecting vibrations from the physical movement of entering and leaving the vehicle. The actuation sensor was turned on for each device as a mechanism to save power when the vehicle is not moving. A zip tie physically secured the GPS assembly to prevent units from becoming lost during the observation period. The vehicle make, model, GVWR,

engine displacement, fuel type, and VIN were recorded on-site for each vehicle on a log sheet and were saved to be inputted onto the master installation log sheet stored on the central server.

The GPS assemblies were left in place within the vehicle cabin for an observation period of approximately two weeks. The driver of the vehicle was instructed to not disturb the device during this period; after the two weeks, a TTI researcher would retrieve the assembly.



**Figure 7. GPS Data Logger Placement inside a Heavy-Duty Vehicle.**

An Excel<sup>®</sup> spreadsheet was used as an installation log to monitor when the devices were installed, the region of initial placement, and other variables specific to individual vehicles. A record of each GPS assembly placement was made in the table. The spreadsheet was used as a tracking tool to know the location and potential availability of the GPS assemblies across the state. The list of variables noted on the table was:

- Installation Number: an index that matched individual installations to signed IRB forms that participants filled out.
- Participant Name.
- Participant Contact Information: Mail Address, Phone Number, E-mail.
- Data Logger Assembly Number, e.g., TTI-03.
- Date of Installation.

- Date of Downloading Data from Device.
- Current Status: “In Office” or “In Progress.”
- Vehicle Location: e.g., AUS for Austin Region.
- Vehicle Identification Number (VIN)—only for medium and heavy-duty vehicles.
- GVWR: in pounds, only for medium- and heavy-duty vehicles.
- Vehicle Make and Model.
- Model Year.
- Fuel Type.
- Number of Cylinders.
- Engine Size.

## **DATA TRANSFERRING AND LABELING**

Data were transferred from each individual GPS unit to a secured central server using the QSport<sup>®</sup> software; a proprietary software that came with the QStarz<sup>®</sup> BT-Q1000EX GPS unit. After connecting the GPS data logger to a computer with a USB connection, the QSports software program was opened and the import function was selected to begin the direct download. All the files were then saved into a single Excel workbook with specific spreadsheets that were labeled as A, B, or C depending on which device was the source of data for that GPS assembly. The complete filename was a concatenation of GPS assembly number (e.g., TTI-03), download date (i.e., listing the number series 08302012 for August 30, 2012), and vehicle type (e.g., listing CT for combination truck). An example of a filename using this formatting would be “TTI\_03\_08302012\_CT.”

It was important to label each file distinctly so vehicle record sets could be matched to corresponding vehicle characteristics, e.g., GVWR, engine displacement size, recorded on the installation log. Detailed information about study participants and their associated vehicles from the installation log were not directly connected to the GPS files as an assurance to protect confidentiality of the information. Only authorized researchers who had a valid IRB training had access to both data sources.



## **CHAPTER 5: DEVELOPMENT OF TEXAS-SPECIFIC DRIVE SCHEDULES**

The data used for the drive schedule development were all collected in Task 5 using the data collection methodology that the research team had developed ([Chapter 2](#)). The team examined the other sources of data including the data set from Oak Ridge National Laboratory and previous TTI studies. This investigation showed that that these data do not meet the quality and quantity required for this task. Specifically, ORNL’s heavy-duty vehicle data had only a few observations within Texas, which were mostly rural driving. The GPS units used for the data collection are of higher quality and sensitivity than those used in other available data sets. Furthermore, three GPS units were used on each vehicle to increase the precision and fidelity of the data, as the project director had approved.

The data processing and analysis of this task were conducted according to the following general steps:

1. Quality control and validation of raw data—This step involved examining the speed and location data from the GPS units to determine their validity, and identify errors and outliers in the data. The faulty information was filtered out and a database of verified unprocessed data was established. Multiple error detection criteria were developed for this step.
2. Data processing—This step consisted of merging information from the three GPS units in each assembly, extracting micro-trips, and categorizing them by the target area, road classification (highway/freeway or arterial/local), average speed bin, and type of area (urban or rural).
3. Data analysis and drive schedule development—The processed data were analyzed according to a drive schedule selection algorithm that the research team developed based on EPA’s procedures for MOBILE and MOVES models.
4. Comparison to MOVES default drive schedules—The developed drive schedules were compared to the default drive schedules of MOVES in terms of their corresponding distribution of modal operating bins.

The following sections cover these steps and the developed local drive schedules.

## QUALITY CONTROL AND VALIDATION OF RAW DATA

After downloading the data from the GPS units, the quality of data was checked to detect errors in speed data and missing speed values. This process was performed separately for all three data loggers of the same assembly.

The major step in this exercise was checking the speed differences between each two consecutive observations, i.e., instantaneous acceleration or deceleration rates. Two factors—friction coefficient between the pavement and vehicle tires, and the available power from the engine—mechanically limit the maximum attainable acceleration rate of a vehicle under a certain driving condition or load. Friction coefficient is the dominant factor in lower speeds while the engine power is the limiting factor at higher speeds. The MOVES model's documentation suggests the following thresholds for the acceleration/deceleration values:

- An upper limit of 14 mph/s for acceleration.
- A lower limit of -10mph/s for deceleration.

While these two criteria filter out the most extreme outliers, they are not sufficient to detect and eliminate all the errors in the data; specifically, the ones with high acceleration rates at higher speeds. As mentioned above, the upper limit of the attainable acceleration drops as the speed of the vehicle goes up, i.e., an observation with a high acceleration rate at a high speed is not possible for regular vehicles even though the acceleration rate values stay within the above limits. On the other hand, the deceleration maneuver is made by braking, which is only governed by the effective friction coefficient between tires and the pavement. However, a high deceleration rate is usually associated with near crash or very aggressive driving, which are not the desired driving conditions for a representative drive cycle. To partially address these concerns, the EPA used the following two additional criteria for light duty vehicles established based on the VPS values for each second of speed observations:

- An upper limit of 62.5 kW/Mg for positive VSP values.
- A lower limit of kW/Mg for negative VSP values (deceleration).

The research team examined the collected data based on these criteria, and found that these thresholds are not sufficient to detect all suspected data for heavy- and medium-duty vehicles. Researchers then developed a method based on the accumulative distribution of the positive accelerations. Different percentiles were calculated for positive acceleration observations grouped by their speed values. A 99 percentile value was found to provide

satisfactory results with regard to filtering out suspected high accelerations. Therefore, the acceleration rate corresponding to the 99 percentile was chosen as the upper limit of valid acceleration values used in this study. All the observations with an acceleration value higher than these limits were dropped from the database. [Table 10](#) shows the upper threshold (99 percentile value) resulted from this approach.

After applying the above criteria to the light-duty vehicles, the research team noted that there are still speed observation points with marginally high acceleration values. Since these suspicious observations are technically valid, it was decided to treat these as noisy valid data points. A data smoothing method was applied to these observation points to cancel the noise. This noise cancellation was applied to observations with an acceleration rate higher than 8 mph/s at speeds over 15 mph. A simple 3-point average was used for this purpose. [Table C.1 \(Appendix C\)](#) demonstrates the other processes used in the data quality control.

**Table 10. Upper Threshold of Accelerations for Medium- and Heavy-Duty Vehicles.**

Vehicle Type/Area/Area Type	0–25 mph	25–50 mph	>50 mph
	Maximum Acceleration Rate (mph/s)		
Medium Duty/Texas State-Wide/Rural	4.6	3.1	1.9
Medium Duty/Texas State-Wide/Rural	4.4	3.0	2.0
Heavy Duty/Texas State-Wide/Rural	3.4	3.2	2.4
Heavy Duty/Austin/Urban	3.8	3.0	2.3
Heavy Duty/Dallas–Fort Worth/Urban	3.8	2.8	2.2
Heavy Duty/San Antonio/Urban	3.8	2.8	2.2
Heavy Duty/El Paso/Urban	3.8	2.7	2.3
Heavy Duty/Houston/Urban	3.8	2.7	2.3

## DATA PROCESSING

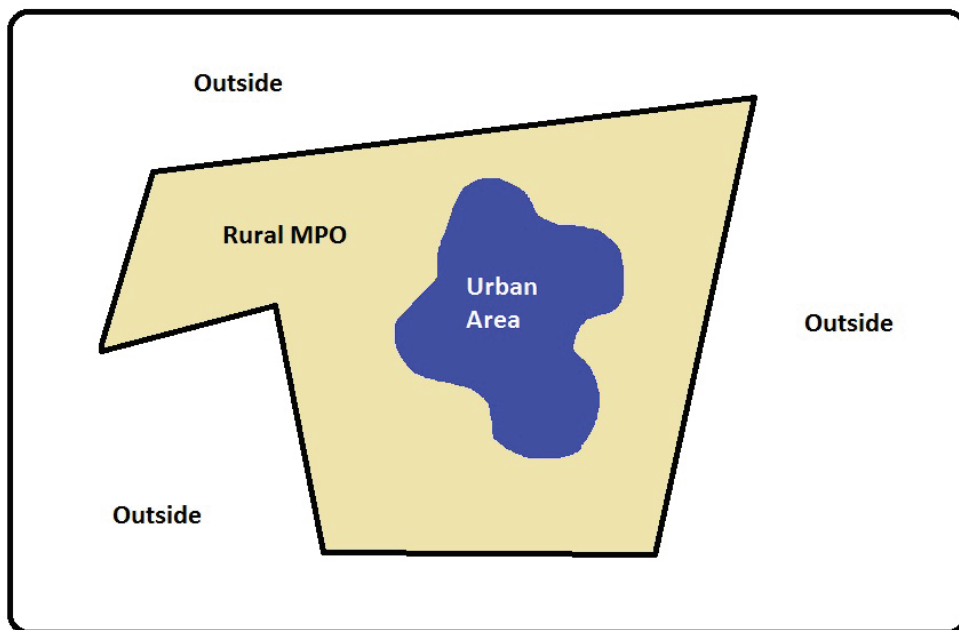
Data processing consisted of the following processes:

1. Merge data from the three GPS units of an assembly.
2. Perform quality control and validation on the merged data.
3. Determine the locations and road type.
4. Extract and label micro-trip.

Each participating vehicle was equipped with an assembly of three GPS units named A, B, and C. Information from each of the three data loggers was downloaded into a separate file. To merge this information to create a single data set for each vehicle, the researchers averaged the speed and coordinates information for each second of data set for the three separate files. [Table C.2 \(Appendix C\)](#) contains the details of this process.

After merging the information and creating a single data file for each vehicle, a quality control was performed on the observations to detect and correct any error that may have resulted from the merging process. The criteria used for this purpose were generally the same as the ones used in the validation step process above. As the result, a new data file is created that contains the validated data. The details of this process are covered in [Table C.3 \(Appendix C\)](#).

The goal of this study is to develop local drive schedules for each of the target areas according to MOVES road types (rural and urban arterials and freeways/highways). Therefore, the location information of each second of the data needs to have study area and road type information assigned. The research team processed the validated data file from the previous step in a GIS environment. [Figure 8](#) shows an example of the polygons used to determine location and area type in GIS. The details of this process are covered in [Table C.4 \(Appendix C\)](#).



**Figure 8. Basic Diagram of the Shapes to Determine Location and Area Type.**

The approach used for development of the drive schedules is based on the methodology that ERG used to develop MOVES' default drive cycles (51). The research team made necessary modifications to the ERG's methodology based on the characteristics of the data set. The approach is based on a process of building up cycles from individual micro-trips extracted from the GPS data; i.e., the GPS data for all vehicles are broken down into micro-trips.

The extraction of micro-trips was performed using a two-step process: First, observations in the data file were divided into *trips*, i.e., a more than 150 seconds of continuous data with no data gap. Each trip was then assigned a unique Trip Index showing information about the vehicle and target area. Table C.5 (Appendix C) demonstrates the process of extracting trips from the observation data set.

The second step of the process involved extracting micro-trips from the trip data set using a set of criteria. These criteria were developed based on ones that ERG used to develop drive schedules for MOVES. Necessary modifications were made to reflect the characteristics of the data set. The criteria for extracting micro trips are:

1. The first micro-trip starts at the beginning of a trip and ends when:
  - a. There is more than 30 seconds of consecutive zero speed observations.
  - b. The end of the trip.
  - c. The length of the micro-trip is more than 2 miles.
2. The other micro-trips start at the end of the previous micro-trip and end according to the criteria of step 1.
3. A micro-trip must have a minimum duration of 20 seconds of consecutive observations.
4. Micro-trips with an average speed of less than 1 mph are considered idling and are not included in the analysis.
5. If there is an idling period (speed = 0) with a duration of more than 35 seconds, the micro-trip starts at 5 seconds before the non-0 speed.
6. Freeway/highway micro-trips are identified based on the road classification of the starting point or if they are 2 miles in length without any 0 speed observation. They were assigned the "FWY" code to indicate their road type. Non-freeway/ highway roads were assigned the "ART" code.

All micro-trips were assigned a unique micro-trip identification number and their time index for the starting point was set to 0, i.e., all micro-trips starting at 0 second. The micro-trip identification number indicates the type of vehicle and a number showing the order they were extracted regardless of their location. The following shows the format for micro-trip ID numbers:

- Light-duty: L + micro-trip order number – L00256.
- Medium-duty: M + micro-trip order number – M04257.
- Heavy-duty: H + micro-trip order number – H03652.

A summary table was created containing the following information for all valid micro-trips:

- Micro-trip ID.
- Average speed (mph). Duration (second).
- Distance travelled (miles).
- Location.
- Road classification (FWY or ART).
- Area type (Rural or Urban).

The extracted micro-trips were grouped together in separate data files based on the following parameters:

- Area—5 metro areas + the statewide rural.
- Area type—urban or rural.
- Average speed bin as shown in [Table 11](#).

**Table 11. Speed Bin Definitions for Grouping Micro-Trips.**

<b>Roadway Types</b>	<b>Cases</b>	<b>Average Speed Bin (mph)</b>	<b>Speed Bin Definition (mph)</b>
<b>Non-Freeway</b>	A_5*	5	0 ≤ & <7.5
	A_10	10	7.5 ≤ & <12.5
	A_15	15	12.5 ≤ & <17.5
	A_20	20	17.5 ≤ & <22.5
	A_25	25	22.5 ≤ & <27.5
	A_30	30	27.5 ≤ & <35
	A_40	40	35 ≤ & <45
	A_50	50	45 ≤ & <55
	A_60	60	>55
<b>Freeway</b>	F_0**	2.5	0 ≤ & <5
	F_10	10	5 ≤ & <15
	F_20	20	15 ≤ & <25
	F_30	30	25 ≤ & <35
	F_40	40	35 ≤ & <45
	F_50	50	45 ≤ & <55
	F_60	60	55 ≤ & <65
	F_70	70	>65

\* “A\_x” refers to arterial/non-highway roadways at an average speed of “x” mph.

\*\* “F\_x” refers to freeway/highway roadways at an average speed of “x” mph.

## **DATA ANALYSIS AND DRIVE SCHEDULE DEVELOPMENT**

Drive schedules provides the information of a sequence of second-by-second activity of the vehicle such as instantaneous acceleration and speed for a moving vehicle. The MOVES model converts this information to a time distribution of activity unit bins called operating modes (opMode) and then applies appropriate emissions rates to this distribution.

An ideal drive schedule for a given driving condition is the one that has the maximum amount of information regarding that condition; i.e., in the context of this study, the one that has all the observations corresponding to that driving condition. However, using an entire database of second-by-second speed data is impractical in reality because of the high number of calculations that needs to be done for each link and the technical difficulties with coding discontinuous micro-trips in MOVES. Therefore, a sub-ideal solution will be a continuous short drive-schedule constructed from a limited number of micro-trips, which will closely represent

the ideal solution. This sub-optimal solution is easy to implement and is currently used in MOVES in the form of default drive schedules.

In addition to second-by-second speed data, MOVES let the user to input vehicle activity information in terms of the equivalent operating mode distribution. The current implementation of this method is not as straightforward as the drive schedules and therefore most users do not use it in their analysis. Despite this limitation, this method provides an opportunity to implement the ideal solution (i.e., all observations) in a practical way. The research team analyzed the data and developed both ideal and sub-ideal solutions. For a specific speed bin, the ideal solution is the opMode distribution of the entire database for that bin, while the sub-ideal solution is a relatively short continuous speed profile representing that average speed bin.

Constructing a sub-ideal solution from a micro-trip database requires a methodology to examine the representativeness of each micro-trip. ERG used a speed/acceleration/vehicle-specific-power (VSP) comparison for this purpose. The research team decided to use a modified version of this approach based on opMode distribution as MOVES' basic unit of activity. The main benefit of this approach is direct consistency with MOVES internal calculations. The proposed methodology first calculates the operating modes distribution for the entire target database (desired speed bin, area, area type, vehicle type, road class). This distribution is called target. The opMode distribution of the micro-trips is then compared to this target. However, both of the comparisons will be made during the cycle evaluation. The following section covers the general methodology.

## **GENERAL METHODOLOGY OF DRIVE-SCHEDULE DEVELOPMENT**

The operating mode is the term to describe the vehicle's moving behavior based on the speed, acceleration and VSP<sup>2</sup> or STP.<sup>3</sup> Table 12 shows the operating modes definition used in the MOVES model and adopted for this research project. The calculation of VSP and STP values are based on MOVES' defaults for vehicle parameters as shown in Table 13. For each vehicle type, a representative MOVES source type was selected for the calculations, i.e., light-duty–source type 21, medium-duty–source type 52, and heavy-duty–source type 61. These selected source types are the ones with the highest expected traffic in an urban area for that vehicle type.

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<sup>2</sup> For light-duty vehicles.

<sup>3</sup> Scaled Tractive Power is a modified version of VSP used for medium- and heavy-duty vehicles.



First, all the second-by-second observations are binned to the operating mode bins and a time distribution is developed for the target database. This normalized count of each opMode forms the target operating mode distribution vector, i.e., vector T. Table 14 shows an example of a target vector. Similarly, the opMode distribution for micro-trip number  $i$  is calculated and named  $M_i$ . The sub-optimal solution, called cycle in this study, will also have a corresponding opMode distribution vector, called vector C. The drive schedule building process consists of combining selected micro-trips together while minimizing the value of T-C. The T-C function used in this project is the sum of squared differences.

**Table 12. Operating Mode Bin Definitions for Running Emissions.**

<b>Braking (Bin 0)</b>			
<b>Idle (Bin 1)</b>			
<b>VSP / Instantaneous Speed</b>	<b>0-25 mph</b>	<b>25-50 mph</b>	<b>&gt; 50 mph</b>
< 0 kW /tonne	Bin 11	Bin 21	
0 to 3	Bin 12	Bin 22	
3 to 6	Bin 13	Bin 23	
6 to 9	Bin 14	Bin 24	
9 to 12	Bin 15	Bin 25	
12 and greater	Bin 16		
12 to 18		Bin 27	Bin 37
18 to 24		Bin 28	Bin 38
24 to 30		Bin 29	Bin 39
30 and greater		Bin 30	Bin 40
60 to 12			Bin 35
< 6			Bin 33

**Table 13. MOVES Parameters Used in VSP and STP Calculations.**

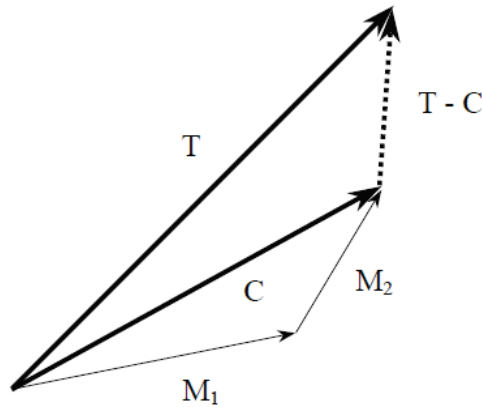
<b>Source Type ID</b>	<b>Source Type Definition</b>	<b>Rolling Term A</b>	<b>Rotating Term B</b>	<b>Drag Term C</b>	<b>Source Mass</b>	<b>Fixed Mass Factor</b>
21	Passenger Car	0.156461	0.002002	0.000493	1.4788	1.4788
52	Single Unit Short-Haul Truck	0.561933	0	0.001603	7.64159	17.1
61	Combination Short-Haul Truck	1.96354	0	0.004031	29.3275	17.1

**Table 14. Target Vector of Case “A\_30” in Austin Rural Area.**

<b>Operating Mode</b>	<b>Count</b>	<b>Target Vector</b>
0	1444	0.119834
1	505	0.041909
11	401	0.033278
12	611	0.050705
13	243	0.020166
14	196	0.016266
15	158	0.013112
16	166	0.013776
21	1617	0.134191
22	1284	0.106556
23	1617	0.134191
24	1316	0.109212
25	774	0.064232
27	823	0.068299
28	269	0.022324
29	53	0.004398
30	6	0.000498
33	158	0.013112
35	240	0.019917
37	130	0.010788
38	36	0.002988
39	2	0.000166
40	1	8.3E-05

**T-C** indicates the representativeness of the sub-ideal (cycle), i.e., how similar it is to the ideal solution (target). The goal of the drive schedule building process is to get a **C** vector from the micro-trips ( $M_i$ ) that is close enough to **T**. The following explains the steps of this process, which is also showed graphically in [Figure 9](#):

1. Select the micro-trip that has the closest **T-M** value as the first candidate micro-trip vector  $M_1$ , now  $C = M_1$ .
2. Select the micro-trip with the closet **T-M** value among the rest of the micro-trips as the second vector  $M_2$ , now  $C = M_1 + M_2$ .
3. Repeat step 2 until the **T-C** value is acceptable, and  $C = \sum M_i$ .



**Figure 9. Drive Schedule Building Process.**

One of the main requirements for using a drive schedule in MOVES is that it needs to be continuous, i.e., no gaps in the speed profile. Since micro-trips in the trip data files do not start and end at the same speed, a process is required to address this requirement through the micro-trip selection process. In this study, this was done through adopting a maximum acceptable gap between the end of a micro-trip and the next one. A value of 2 mph of maximum gap was found to provide satisfactory results for all the vehicle types.

To terminate the drive schedule building process for a certain case, T-C value should be “small enough.” ERG stopped the process after 25 micro-trips were added to the cycle. The research team followed this approach; however, it is found that this criterion may not always result in a small enough value of T-C, specifically when the numbers of micro-trips in the trip data set are relatively low for some cases. Therefore, the researchers used a target value of 0.05 for the T-C in addition to the 25 rounds of drive schedule creation.

The research team evaluated the cycles resulted from the above process, and found that using only the T-C value does not always guarantee the best representative cycle. [Figure 10](#) shows an example of highlighting this issue. The T-C value for this example is less than 0.05; however, there is a significant mismatch between the target and cycle for operating modes above 30, which make the representativeness of the resulted cycle questionable. Such a cycle would not have high speed operations that are usually associated with higher emissions rates.

To address this issue, the research team performed a visual evaluation of opMode distribution ([Figure 10](#)) and speed-acceleration profile ([Figure 11](#)) of all the cycles and identified the areas of major discrepancies between T and C for each case. The cycles were redeveloped

again using more micro-trips from the trip set while keeping the T-C below the target value of 0.05. These new micro-trips were selected carefully to provide observations needed to fill the gaps. Figure 12 shows a comparison of the opMode distribution for the example shown in Figure 10 after the visual inspection and correction. As Figure 12 shows, the new cycle has a similar opMode distribution to the target vector. These new cycles are the final drive schedules. Appendix E shows a summary of the developed target opMode distribution and drive schedules.

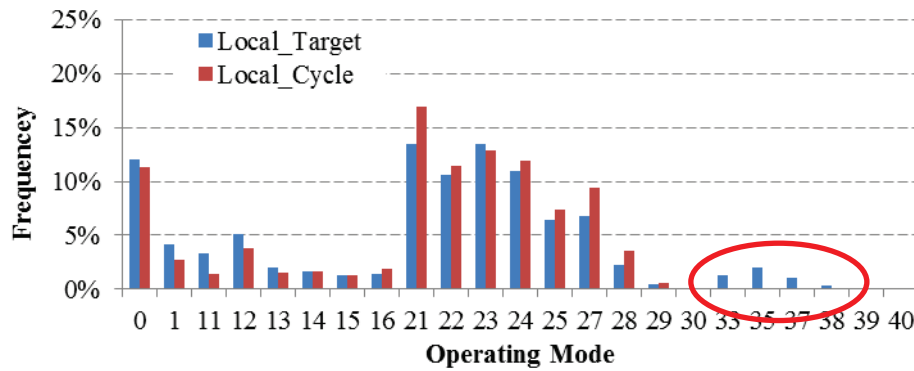


Figure 10. Comparisons of T and C Vectors before Visual Evaluation.

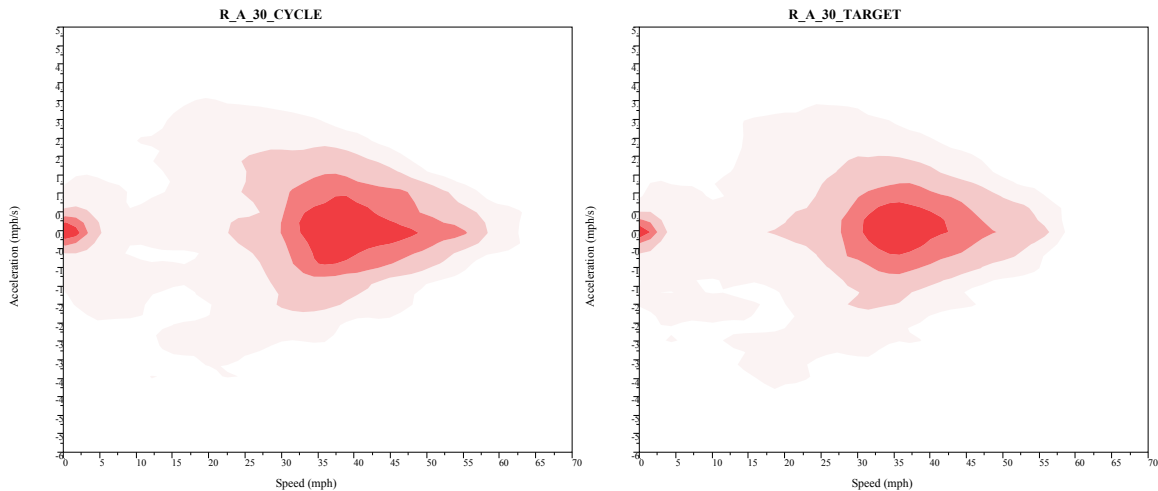
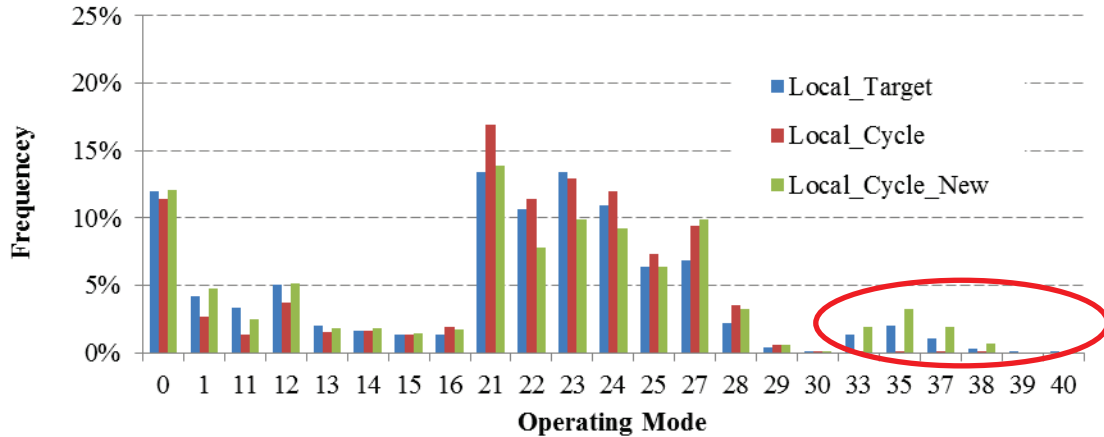


Figure 11. Example of Speed-Acceleration Profile Comparison.



**Figure 12. Comparisons of T and C Vectors after Visual Evaluation and Correction.**

These final drive schedules and target opMode distributions have been submitted to TxDOT in a database format. By providing both these information, the users can pick the solution that fits their specific applications best. While the target opMode distribution is considered the ideal solution, however, it is now easy to implement for simple analyses. On the other hand, the developed drive schedules (i.e., cycle) are sub-ideal but easy to implement in most cases.

### COMPARISON TO MOVES DEFAULT DRIVE SCHEDULES

The resulted target opMode distributions (i.e., T vectors) and drive schedules (i.e., cycles) were compared to the default drive schedules of MOVES in terms of their corresponding distribution of modal operating bins and emissions. A single analysis year of 2012 was used for this purpose. The comparison process consists of the following steps:

Establish Target opMode distribution (Target):

- Input the target opMode distribution along with it corresponding average speed into MOVES.
- For all the other parameters use the default values for the target area and vehicle type.
- Run MOVES in project level mode to estimate emissions rates for CO<sub>2</sub>, NO<sub>x</sub>, CO, THC, and PM<sub>10</sub>.

### Develop drive schedules (Cycle)

- Calculate opMode distribution for the cycle (for opMode comparison purpose only).
- Input the drive schedule (speed profile) into MOVES.
- For all the other parameters use the default values for the target area and vehicle type.
- Run MOVES in project level mode to estimate emissions rates for CO<sub>2</sub>, NO<sub>x</sub>, CO, THC, and PM10.

### Compare with MOVES defaults drive schedules

- Extract the MOVES default drive schedule that is closest to the target and cycle and calculate its opMode distribution (for opMode comparison purpose only).
- Input the average speeds of the target and cycle into MOVES.
- For all the other parameters use the default values for the target area and vehicle type.
- Run MOVES in national level mode to estimate emissions rates for CO<sub>2</sub>, NO<sub>x</sub>, CO, THC, and PM10.

Figure 13 through Figure 15 show an example of the results of this comparison effort.

Figure 13 demonstrates the percentage difference of cycle and target emission rates from the MOVES default emission rates (baseline) for all speed bins. The results in the figure belong to the NO<sub>x</sub> emissions from heavy-duty vehicles in the urban Austin area. Figure 14 and Figure 15 show opMode distributions for the 50 mph speed bin on arterial/local and freeway/highway of the same scenario, i.e., NO<sub>x</sub> emissions from heavy-duty vehicles in the urban Austin area.

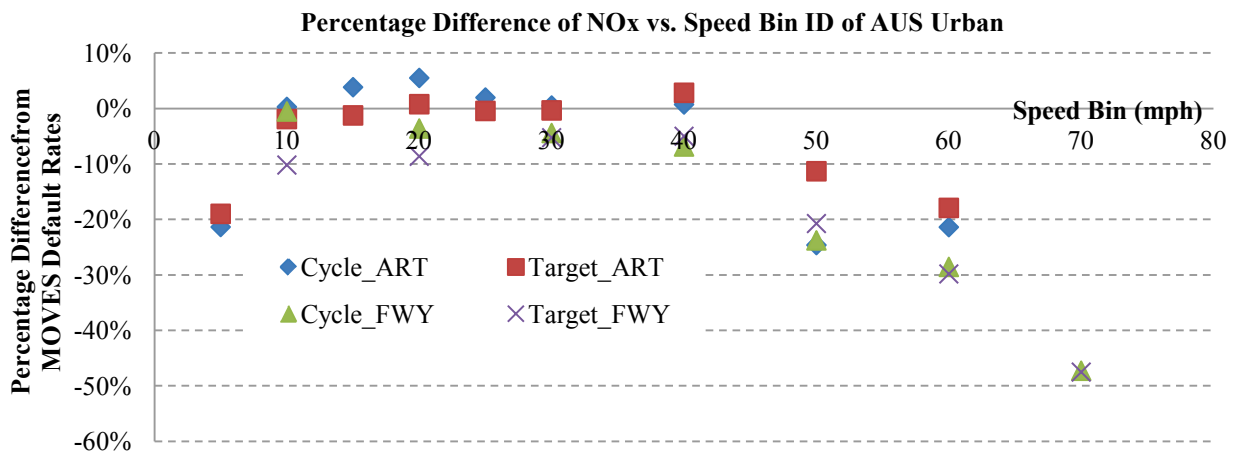
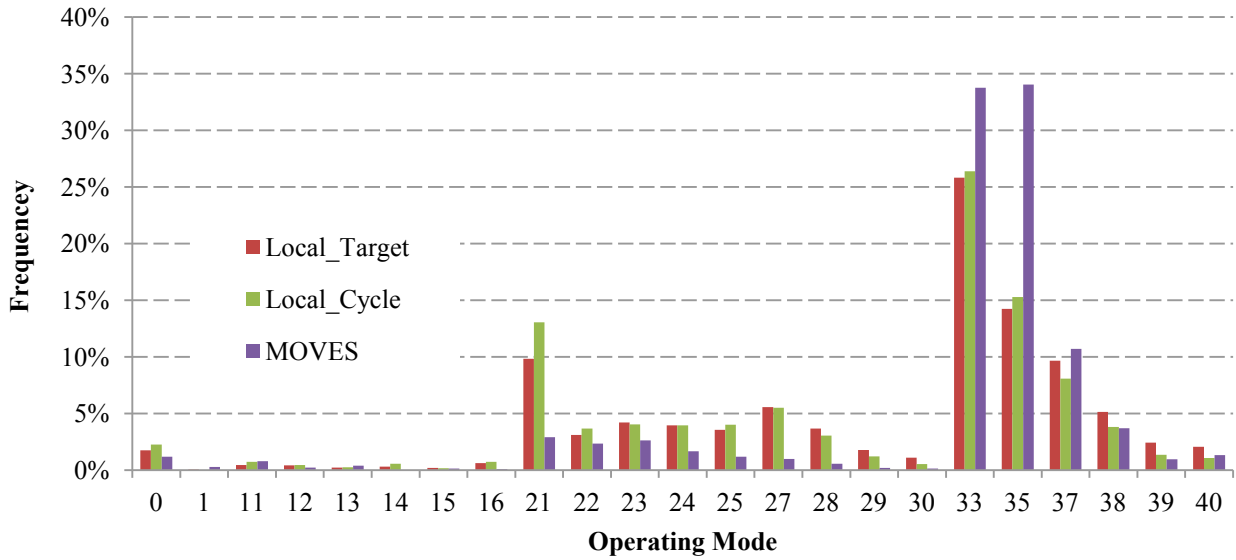
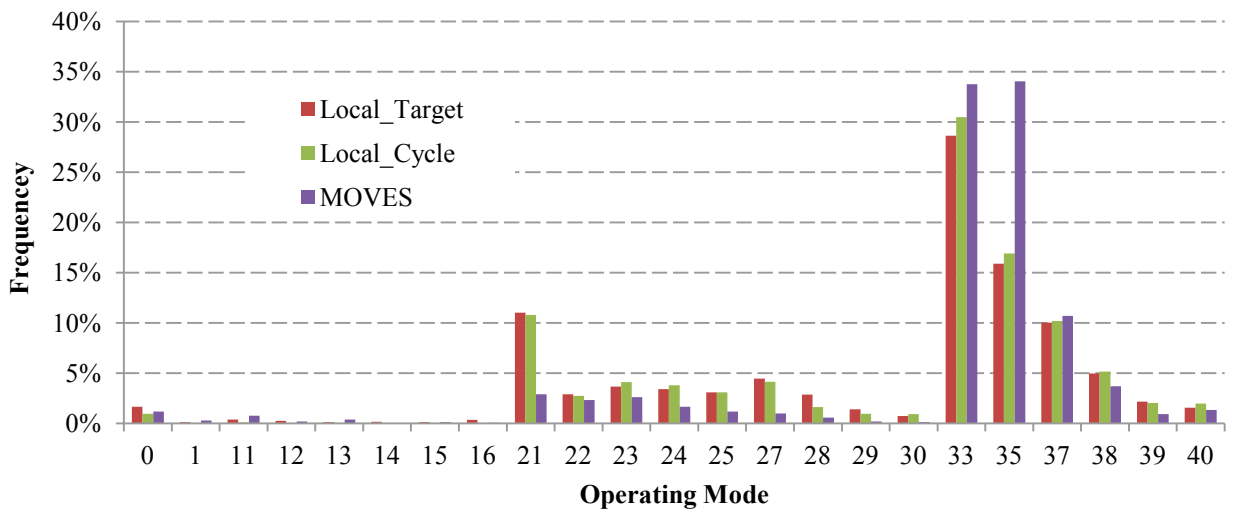


Figure 13. NO<sub>x</sub> Emissions Comparisons for Heavy-Duty Vehicles in Austin.



**Figure 14. OpMode Distribution Comparisons for Heavy-Duty Vehicles, Arterial, Austin, Speed Bin 50 mph.**



**Figure 15. OpMode Distribution Comparisons for Heavy-Duty Vehicles, Freeway/Highway, Austin, Speed Bin 50 mph.**





## **CHAPTER 6: COLD-START AND IDLING EMISSIONS MEASUREMENT AND ANALYSIS**

This chapter characterizes HDDVs' cold-start and idling emissions rates in Texas. For characterization of cold-start and idling emissions, the research team used existing data as well as data from testing the 15 HDDVs selected in Task 4 in a controlled environment, i.e., an environmental chamber where temperature and humidity are controlled precisely.

The data from available sources were also compiled and compared to the observations related in this chapter. It is anticipated that the compiled data and measured data through this study will play a key role in establishing accurate emission estimations for HDDVs, especially in Texas, and can be an important data source for future revision of MOVES. See [Chapter 7](#) for a comparison of a sample of these data to MOVES results.

### **TEST METHODOLOGY**

Cold-start and idle emission tests were performed on the 15 vehicles; 12 vehicles were tested in FY2012 and the other three vehicles in FY2013. The testing methodology was built on the research team's extensive experience with testing HDDVs and input from experts from EPA and ORNL as well as feedback from TxDOT PMC. The research team conducted idling emissions testing inside an environmental chamber at TTI's Environmental and Emissions Research Facility, where temperature and relative humidity were controlled precisely.

In this section, the followings are described in detail:

- Test Vehicles.
- Test Conditions.
- Testing Equipment.

#### **Test Vehicles**

As described in [Chapter 3](#), the research team investigated Texas HDDV registration data, the EPA emission standards for on-road heavy-duty diesel vehicles, and vehicle data used in the MOVES model. Based on the investigation, the research team recommended testing the

following model year vehicles, which covered more than 40 percent of all HDDVs registered in Texas, and the PMC approved for the recommended model year selections:

- MY 2012 to MY 2013—three vehicles.
- MY 2010 to 2012—six vehicles.
- MY 2007 to 2009—four vehicles.
- MY 2004 to 2006—two vehicles.

Based on the approved vehicle selection recommendation, the research team recruited 15 HDDVs and performed cold-start and idling emissions measurement on them. The specifications for the 15 vehicles are shown in [Table 15](#). More details for the vehicle selection can be found in [Chapter 3](#). [Figure 16](#) shows pictures of a test truck. The trucks were assigned numbers in the order of their model years (MYs) and, for the same MY, in which they were tested.

**Table 15. Test Vehicle Specifications.**

Truck Number	Make	Model	MY	Engine Make	Engine Model	Horsepower @ Governed Engine Speed (RPM)	Displacement	Odometer
#1	Freightliner	Colombia	2006	Caterpillar	C15	466 @ 1800 RPM	15.2 L	484550
#2	International	94001 SBA 6×4	2007	Cummins	ISX 450	450@2000 RPM	15 L	505964
#3	International	Prostar	2008	Cummins	ISX 450ST	450 @ 1800 RPM	15 L	406740
#4	Peterbilt	N/A*	2008	Cummins	ISM 425V	425 @ 1800 RPM	11 L	353945
#5	Mack	CHU 613	2009	Mack	MP8-415C	415 @ 1500 RPM	12.8 L	96409
#6	Mack	CHU 613	2010	Mack	MP8-415C	415 @ 1500 RPM	12.8 L	89469
#7	International	Prostar+ 122 6×4	2011	MaxxForce	GDT430B	430 @ 1700 RPM	12.4 L	73030
#8	Navistar	8600 SBA 6×4	2011	MaxxForce	A410	410 @ 1700 RPM	12.4 L	57814
#9	International	ProStar+ 122 6×4	2011	MaxxForce	A475	475 @ 1700 RPM	12.4 L	10724
#10	Mack	CHU 613	2011	Mack	MP8-445C	445 @ 1500 RPM	12.8 L	95169
#11	Mack	CHU 613	2012	Mack	MP8-415C	338 @ 2100 RPM	12.8 L	82976
#12	Volvo	N/A*	2012	Volvo	VE-D12-465	465 @ 1800 RPM	12.13	640341
#13	Mack	CXU 613	2013	Mack	MP8-445C	445 @ 1500 RPM	12.8 L	6056
#14	Mack	CXU 613	2013	Mack	MP8-445C	445 @ 1500 RPM	12.8 L	11989
#15	Mack	CXU 613	2013	Mack	MP8-445C	445 @ 1500 RPM	12.8 L	25148

\* N/A—Certain specifications of some vehicles were not available.



**Figure 16. Test Vehicle (Left) and Sampling Lines Installed on a Test Vehicle (Right).**

### Test Conditions

When possible, each of the 15 test vehicles was tested under two different scenarios: normal idling at their low engine speeds, and high idling at about 400 rpm higher than normal idling. Also, as described in [Chapter 3](#), each test was conducted under hot and cold test conditions (see [Table 16](#)). The temperature conditions were selected to represent the normal ambient conditions in the Dallas–Fort Worth (DFW) area in winter and in the Houston area in summer. More details for the vehicle selection can be found in [Chapter 3](#).

**Table 16. Test Conditions.**

Test ID	Temperature	Relative Humidity
Hot	100°F (37.8°C)	70%
Cold	30°F (–1.1°C)	N/A

The research team also added a set of another test conditions based on soak time, i.e., the time at which the engine is turned off before being restarted. Engine soak time is a factor affecting starting emissions and used in the MOVES model for characterizing start emissions.

Table 17 shows a summary of the soak time categories that are implemented in MOVES with their corresponding operating mode bin numbers.

**Table 17. MOVES Operating Mode Binds for Start Emissions (as Function of Soak Time).**

<b>Operating Mode Bin</b>	<b>MOVES Operating Mode Bin Description</b>
101	Soak Time < 6 minutes
102	6 minutes ≤ Soak Time < 30 minutes
103	30 minutes ≤ Soak Time < 60 minutes
104	60 minutes ≤ Soak Time < 90 minutes
105	90 minutes ≤ Soak Time < 120 minutes
106	120 minutes ≤ Soak Time < 360 minutes
107	360 minutes ≤ Soak Time < 720 minutes
108	720 minutes ≤ Soak Time

Three different soak times were included in the normal idling testing with one soak time being greater than 720 minutes representing *cold-start* idling. The decision on the number of tests was based on technical as well as budgetary and timeline constraints. The other soak times were determined by testing the first test truck under different soak times to find the appropriate soak times for the remaining trucks. Based on the testing of the first truck, the team determined that 5 minutes (Bin 101 in) and 15 minutes (Bin 102) can effectively capture the changes in emissions as a function of soak time.

After a test vehicle was prepared for testing, it would be parked overnight inside the test chamber. This allowed for the engine to be turned off for the required period of time for a cold-start testing, i.e., longer than 12 hours. The vehicle would be turned on the following morning and left idling for a minimum time period of one hour for the cold star testing, and a minimum of 45 minutes of data was collected for the other two soak times. Following the cold start test, the engine was turned off. After the vehicle had soaked for the required soak time period, the engine was turned on again and idled. This process was then repeated for the final soak time.

After the completion of the normal idling, the test truck was tested for *high idle* conditions, when applicable.<sup>1</sup> The high idle tests were conducted by increasing the idle speed of the vehicle to the range of 1000–1100 RPMs. High idle testing included two soak times, 5 minutes and 15 minutes. In summary, each of the hot and cold test conditions consists of five different test conditions/scenarios:

- Cold-start normal idle (called cold-start).
- Normal idle after 5-minute soak time (called 5-min. soak).
- Normal idle after 15-minute soak time (called 15-min. soak).
- High idle after 5-minute soak time (called 5-min. soak high).
- High idle after 15-minute soak time (called 15-min. soak high).

The research team also performed additional idling emissions testing for an extended period of time to obtain stabilized idling emissions. The extended idling emissions testing was combined with a cold-start test by measuring idling emissions continuously after the cold-start idling began until the measured idling emissions were stabilized. The measured “stabilized” emissions were then considered as the baseline emissions, and were used to compare with the measured emissions during the different five test conditions above.

Additionally, the air conditioning (A/C) or heating system of the test truck was turned on, depending on the temperature condition of the test. The load represented actual operation of the A/C or heating system as truck drivers would do during their normal idling at the tested temperature conditions.

## **Testing Equipment**

The research team conducted idling emissions testing inside an environmental chamber at TTI’s Environmental and Emissions Research Facility, where temperature and relative humidity were controlled precisely. For emissions measurements, a portable emissions measurement system—SEMTECH-DS, a PM, and an MSAT sampling system along with dilution systems were used. Details are described in the following subsections.

### *TTI Environmental and Emissions Research Facility (EERF)*

The idling emission testing was conducted in TTI’s EERF, which is located at Texas A&M University’s Riverside Campus in Bryan, Texas. The EERF includes an environmentally controlled test chamber with dimensions of 75 ft long × 23 ft wide × 22 ft high where the test vehicles were placed one at a time for the idling testing. The chamber can control both temperature (from −40°F to 131°F) and humidity. [Figure 17](#) shows the test chamber.



**Figure 17. TTI's EERF Test Chamber.**

### *SEMTECH-DS*

The SEMTECH-DS is a portable emissions measurement system, which complies with the EPA's Code of Federal Regulations (CFR) Title 40 Part 1065 (40 CFR 1065) emissions testing instrument requirements<sup>4</sup> and is used for emissions testing during the idling tests. It consists of a set of gas analyzers to measure gaseous emissions of NO<sub>x</sub> (both nitrogen oxide [NO] and nitrogen dioxide [NO<sub>2</sub>]), hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and oxygen (O<sub>2</sub>) in the exhaust. The SEMTECH-DS is used in conjunction with the SEMTECH electronic flow meter (EFM), which measures the vehicle exhaust flow rate. This allows for the calculation of exhaust mass emissions from all measured gasses. [Figure 18](#) shows the SEMTECH-DS and EFM installed on a HDDV during the testing.

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<sup>4</sup> The system is approved as a lab-grade emissions measurement system and can be used for both in-lab and real-world testing.



**Figure 18. SEMTECH-DS (Left) and EFM Installed on a Test Truck (Right).**

### *PM Filter and MSAT Sampling Systems with Dilution Systems*

The research team used its partial flow dilution (PFD) systems to sample PM filters and MSAT cartridges. A 40 CFR 1065-compliance PFD dilution system, BG-3, is shown in [Figure 19](#). The exhaust from test vehicles is sampled from a probe in the outlet of the SEMTECH EFM and transferred through a heated line to the BG-3 where the exhaust is diluted. The diluted exhaust passes PM filter and MSAT cartridge sampling systems to collect PM and MSAT from the diluted exhaust on a PM filter and MSAT cartridges, respectively. The collected cartridges and most of the filters were sent to Oak Ridge National Laboratory for MSAT and PM mass analysis. TTI recently acquired a high accuracy weighing chamber and therefore analyzed some PM filters inhouse. MSAT compounds that were analyzed are formaldehyde (HCHO), acetaldehyde (CH<sub>3</sub>CHO), and acrolein.



**Figure 19. BG-3 System.**

*Dekati Mass Monitor (DMM)*

The research team also used DMM for PM emission data quality control and quality assurance (QC/QA) (see [Figure 20](#)). The DMM 230-A is a real-time PM measuring instrument for vehicular emissions testing. The DMM was used in conjunction with the PFD systems. The DMM provides second-by-second analysis of the PM concentrations from the vehicle exhaust, providing both total mass measurements and the size of the particles up to 1.5  $\mu\text{m}$  in six size bins. MOVES estimates, with which comparisons of the test results is the main goal of this project, provide emissions of PM with sizes up to 2.5 or 10  $\mu\text{m}$ , known as  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ , respectively. Therefore, DMM results cannot be directly compared with MOVES estimates, so that the DMM results were used for PM data QC/QA purpose only.





**Figure 20. Dekati Mass Monitor (DMM).**

## **COLD-START AND IDLING EMISSION TEST RESULTS AND DISCUSSIONS**

Fifteen heavy duty diesel vehicles were tested in this task. For each vehicle, researchers measured exhaust emissions while the test vehicle was idling inside TTI's environmental chamber under different combinations of engine speed (rpm) and soak time for hot and cold test conditions.

To characterize and examine HDDV idling emissions, the collected emissions data were analyzed for NO<sub>x</sub>, CO, HC (as total HC [THC]), CO<sub>2</sub>, PM, and MSAT in the following aspects:

- Test vehicle model year and other characteristics.
- Temperature conditions (hot or cold).
- Idling conditions (normal or high idling with different soak times).

For MSAT, formaldehyde, acetaldehyde, and acrolein were collected and analyzed for cold-start and Stabilized Tests only. Among the three compounds, concentrations of collected acrolein were all under the detection limit, so that no acrolein data are reported here.

### **Stabilized Idling Emissions**

Stabilized, i.e., continuous steady-state, emissions were measured for comparison with idling emissions under the different idling and soak time conditions. [Table 18](#) and [Table 19](#) show the stabilized emissions rates (grams per hour [g/h]) of CO<sub>2</sub>, CO, NO<sub>x</sub>, THC, PM, and MSAT (formaldehyde and acetaldehyde) for each test vehicle for the hot and cold test conditions, respectively. These results are shown graphically in [Figure 21](#) and [Figure 22](#).

Due to a malfunction of the THC analyzer, no readings were made for test vehicles # 5, 10, 12, (hot and cold) and 6 (cold only). The research team investigated options to repair the analyzer, but found that the entire PEMS would need to be sent to the manufacturer for repair.

The researchers attempted repairs onsite with assistance from the manufacturer, but were unsuccessful for some time. Due to the availability of the test trucks, the research team decided not to send the PEMS out for repair in FY12 until the testing of the first 12 vehicles (Truck #1 through #12) was finished. The PEMS unit was sent out for repairs and no malfunction happened for FY13 testing of Trucks # 13, 14, and 15. The THC emissions are not significant for HDDVs as shown in [Table 18](#) and [Table 19](#).

**Table 18. Stabilized Idling Emissions Results for the Hot Test Condition.**

Truck number	MY	Emissions Rate (g/h)					Emissions Rate (µg/h)	
		CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	Formaldehyde	Acetaldehyde
		#1	2006	7565	52.1	105	13.9	0.309
#2	2007	8385	31.7	151	13.0	0.509	0.6	0.2
#3	2008	9017	31.1	19.3	5.97	0.165	434.9	393.8
#4	2008	5741	66.7	5.25	13.6	0.011	0.0**	0.0**
#5	2009	6960	57.6	251	N/A*	0.041	8.5	46.1
#6	2010	6656	35.0	21.3	N/A*	0.050	18.7	0.2
#7	2011	6717	12.9	64.2	5.44	0.046	0.0	0.0
#8	2011	6029	13.2	57.1	5.22	0.029	46.0	212.6
#9	2011	7226	17.8	25.6	5.40	0.039	35.6	95.8
#10	2011	8459	50.1	78.5	N/A*	0.009	0.0	0.0
#11	2012	6110	74.7	199	10.2	0.142	283.8	260.2
#12	2012	7385	33.5	94.1	N/A*	0.169	86.1	0.6
#13	2013	6589	21.7	19.1	1.33	0.001	0.0**	0.0**
#14	2013	4972	60.4	32.8	2.84	0.001	0.0**	0.0**
#15	2013	6859	27.7	23.9	1.33	0.009	0.0**	0.0**

\* N/A: Not available due to malfunctioning of the HC measurement instrument.

\*\* Less than the detection limit.

**Table 19. Stabilized Idling Emissions Results for the Cold Test Condition.**

Truck Number	MY	Emissions Rate (g/h)					Emissions Rate (µg/h)	
		CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	Formaldehyde	Acetaldehyde
#1	2006	8360	51.8	115	10.5	0.165	0.5	0.2
#2	2007	8236	47.2	137	8.57	0.230	282.0	304.6
#3	2008	8205	33.3	33.4	5.45	0.078	0.5	23.2
#4	2008	5008	46.1	23.0	6.94	0.022	0.0**	0.0**
#5	2009	7762	155	129	N/A*	0.019	327.1	44.8
#6	2010	8282	56.5	47.2	2.02	0.008	0.0**	0.0**
#7	2011	6094	18.1	25.4	4.07	0.103	0.0**	0.0**
#8	2011	11610	17.4	73.1	2.57	0.060	134.4	195.4
#9	2011	5647	14.8	16.6	3.61	0.018	13.0	32.6
#10	2011	7532	52.0	99.8	N/A*	0.028	0.0	0.0
#11	2012	7697	127	189	9.98	0.119	148.1	570.9
#12	2012	5767	34.7	90.1	N/A*	0.125	0.0**	0.0**
#13	2013	8224	26.2	58.2	1.16	0.010	0.0**	0.0**
#14	2013	16925	43.5	106	0.36	0.002	0.0**	0.0**
#15	2013	5921	54.5	24.2	1.81	0.006	0.0**	0.0**

\* N/A: Not available due to malfunctioning of the HC measurement instrument.

\*\* Less than the detection limit.

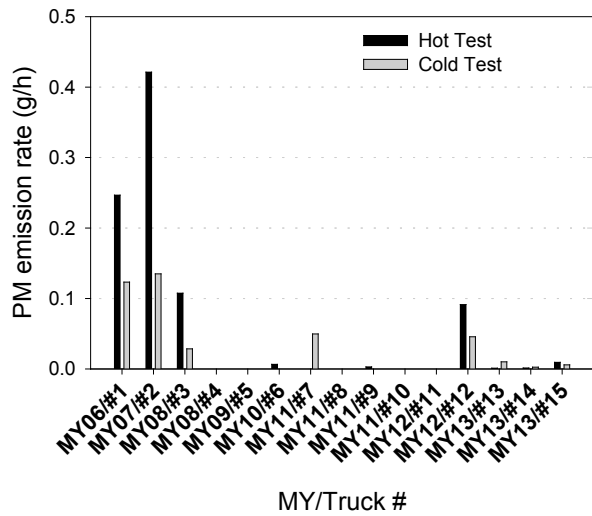
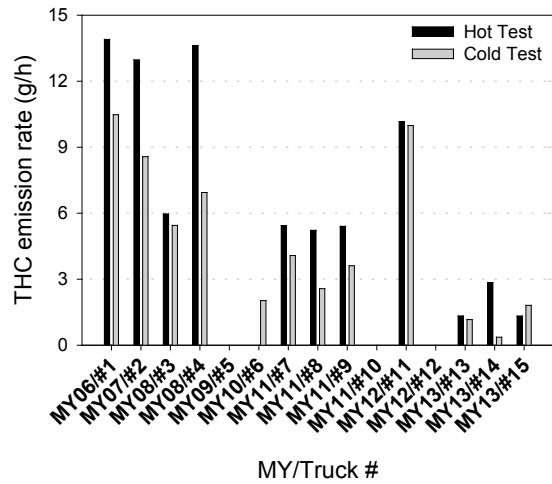
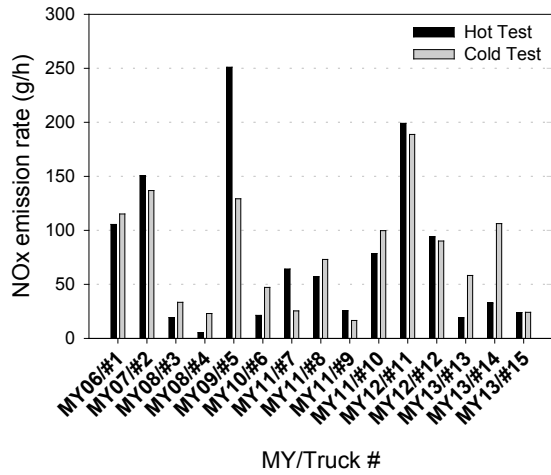
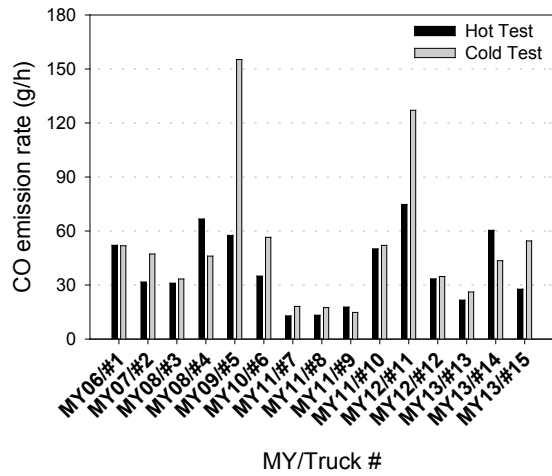
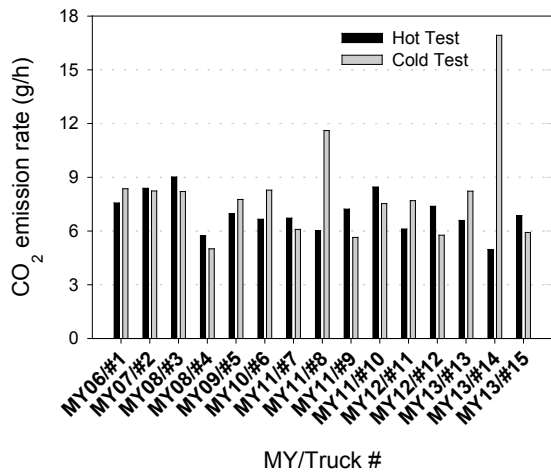
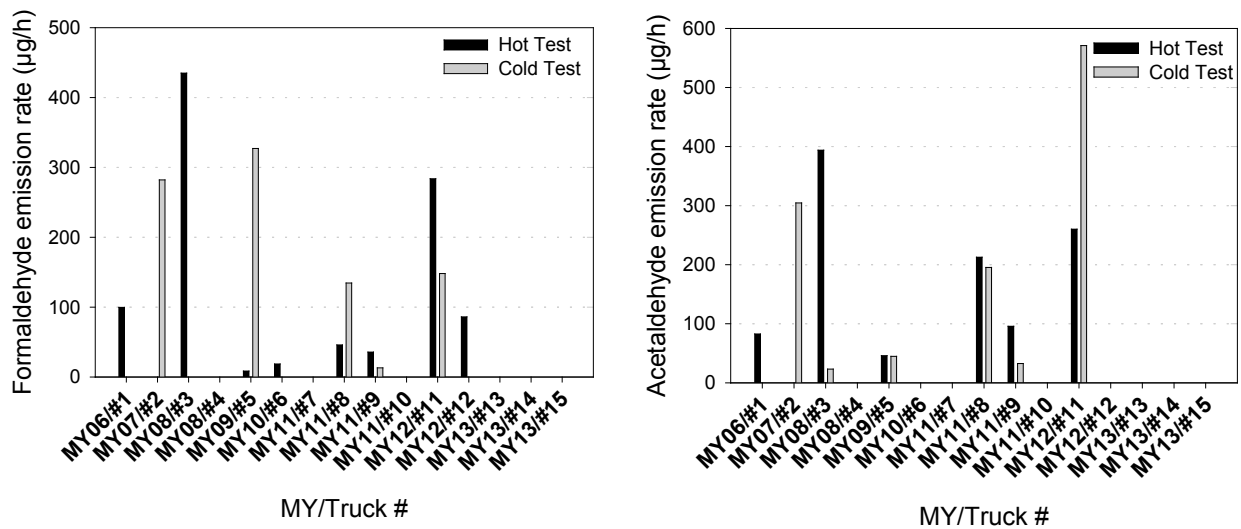


Figure 21. Stabilized Idling Emissions Results.



**Figure 22. Stabilized MSAT Emissions Results.**

The research team was expecting to observe that newer trucks to produce lower idling emissions for all the measured pollutants. Contrary to this expectation, mixed results were observed with regard to vehicle age as shown in Table 18, Table 19, and Figure 21. For example:

- The MY 2008 trucks produced both the highest (Truck #3) and the second lowest (Truck #4) CO<sub>2</sub> emissions for hot tests (the Stabilized CO<sub>2</sub> emissions rate for Truck #3 was 57 percent more than the rate for Truck #4).
- One of the newer MY (2012) trucks, Truck #11, produced the highest CO emissions for hot tests; the emissions rate was 4.8 times higher than the lowest truck, Truck #7, which was the (relatively) older truck (MY 2011).
- Truck #14 (MY 2013) produced the lowest THC emissions for the cold test condition while the truck’s CO<sub>2</sub> emissions were the highest, but its CO<sub>2</sub> emissions were the lowest for the hot test condition.

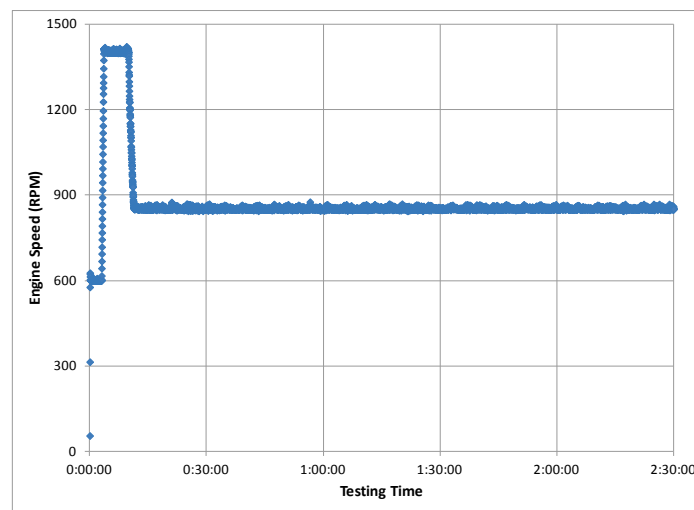
The main suspect for causing these mixed results is the fact that newer HDDVs like the ones tested in this study use different engine and emissions control technologies. Recent model year engines have complex systems with different emission control devices such as diesel particulate filters (DPFs), selective catalytic reduction (SCR) systems, and exhaust gas recirculation (EGR). Engine manufacturers also use different strategies to warm up their engines and emission control devices fast and to meet advanced combustion requirements, e.g., EGR

manipulation, additional fuel injection, and engine speed increases. In addition, some newer vehicles have features for cold ambient protection (CAP) to safeguard engines from damage caused by prolonged idle at no load during cold weather by increasing engine speed (rpm).

Such features usually include engine speed increases and automatic engine shutoff. For example, Truck #8 increased its engine speed (Figure 23) to preset values when ambient air temperature was below 50°F and coolant temperature was below 167°F. The engine continued to increase or decrease its rpm automatically to maintain a coolant temperature between 158°F and 176°F until the following occurred:

- Acceleration pedal engaged.
- Engine load increased over 45 percent.
- Temperature sensor malfunctioning, etc. (52).

As shown in Figure 23, the engine speed went up to about 1400 rpm from 600 rpm (normal) at about 3 minutes after the cold-start test started. Then, about 7 minutes later, it went down to approximately 850 rpm, not to the initial engine speed of 600 rpm, and stayed there until the cold test was finished. That is, after the engine speed went up from its low speed at the beginning for the cold test, it never went down to the low idle speed for the two-and-a-half-hour testing period. However, the engine speed was 600 rpm for the hot test during the entire test time. This resulted in the CO<sub>2</sub> emission rate of Truck #8 for cold test being almost twice as much as that for the hot test (see Table 18, Table 19, and Figure 21).



**Figure 23. Engine Speed Profile during the Cold-Start and Following Stabilized Idling Testing for the Cold Condition (Truck # 8).**

TTI researchers observed such engine and emissions control strategies and CAP features for some other trucks during their tests, but the parameters such as EGR ratios, preprogrammed engine speeds, and preset temperature and idling time seemed to be different among vehicles and test conditions, and the various parameters seemed to affect idling emissions differently. Investigations of the control strategies, CAP features, parameters, and their emissions impacts will facilitate this study in covering all aspects of idling emissions of newer HDDVs. However, such investigations require resources that are beyond the scope of this project.

Some trucks had auto-shutdown features that would turn off the engine after a set period of low idling while the acceleration pedal was not engaged. TTI researchers worked around this feature by applying a little weight to engage acceleration pedals or simply stepping on them when necessary for such trucks. However, for all other features such as engine speed changes and EGR manipulations, the researchers did not change nor stop those features because such features would operate during actual idling in the real world.

Texas Administrative Code (TAC) Title 30 Part 1 Chapter 114 Subchapter J Division 2 Rule §114.517, states that a 2008 or subsequent model year heavy-duty diesel engine that the EPA or another state environmental agency such as California Air Resources Board (CARB) have certified to not emit more than 30 grams of NO<sub>x</sub> per hour when idling is exempted from local idling restriction rules (53). Therefore, such a vehicle can idle indefinitely unless it is located in the idling restricted areas. Among the test vehicles, Truck # 4, 6, 7, 8, 9, 10, 13, 14, and 15 were California (CA) clean idle certified (see Table 20). However, the test results show that only Truck #4, 9, and 15 meet the required NO<sub>x</sub> idling emissions threshold of 30 g/h for both hot and cold test conditions.

**Table 20. NO<sub>x</sub> Idling Emissions from the Test Vehicles that CA Clean Idle Certified and/or Produced Their Emissions under 30g/h during the Tests.**

Truck ID		#3*	#4	#6	#7	#8	#9	#10	#13	#14	#15
MY		2008	2008	2010	2011	2011	2011	2011	2013	2013	2013
CA Clean Idle Certified		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
NO <sub>x</sub> Emissions (g/h)	Hot Test	19.3	5.3	21.3	<u>64.2*</u>	<u>57.1*</u>	25.6	<u>78.5*</u>	19.1	<u>32.8*</u>	23.9
	Cold Test	<u>33.4*</u>	23.0	<u>47.2*</u>	25.4	<u>73.1*</u>	16.6	<u>99.8*</u>	<u>58.2*</u>	<u>106.2*</u>	24.2

\* Underlined emission results are greater than 30 g/h

For other certified trucks (Truck # 6, 7, 8, 10, 13, and 14), either their NO<sub>x</sub> emissions for hot tests or cold tests, or their emissions for both conditions were over 30 g/h (in the range of 32.8 ~ 106.2). The engine and emissions control strategies and CAP features described earlier in this subsection, which would not be observed during the certification tests, could be accounted for the higher emissions. For example, for both hot and cold tests, engine speeds of Truck #10 went up to about 875 rpm and maintained at that speed till the end of the tests. Investigations of the exact causes could be explained through additional analyses with detailed investigations of emissions reduction devices, engine and emission control strategies, and idling control strategies along with all the parameters. However, such analyses are again beyond the scope of this task.

Other possible reasons for the higher numbers can be test methodologies and parameters:

- Temperature condition: For the certification tests, truck engines are tested on engine dynamometers at room temperature, so that the control strategies or CAP features that were observed during the real world (simulated) test conditions with using tractors instead of engines only would not be observed during these test conditions.
- Operations of A/C or heating systems: During the tests, A/C or heating systems were operated depending on test conditions of cold or hot, which added loads (not exactly applied during the certification tests) that would increase the emissions.

To find the relationships between the certification tests and the tests performed this study, one should:

- Identify engines tested for certification.
- Find the engines (now in tractors).
- Test those tractors based on the test protocol in this study.
- Compare the certification results with the tractor test results with the test protocol.

However, it is beyond the scope of this project to perform such tests with tractors assembled with certified engines.

Although Truck #3 is not a CA clean idle certified vehicle, its idling emissions were under the threshold for the hot test and near the limit for the cold test, 19.3 and 33.4 g/h, respectively. In conclusion, the test results suggest that CA-certified trucks do not always meet the NO<sub>x</sub> idling emissions limit of 30 g/h under real world conditions, while non-CA-certified trucks may still emit less NO<sub>x</sub> than the threshold while idling.



## Model Year Comparisons

The research team observed mixed results with regard to model years regardless of soak time, engine speed, and pollutants. [Figure 24](#) through [Figure 29](#) show the average emission rates with respect to MY. [Appendix F](#) includes the data for these figures in tabular format. Note that for model years 2006, 2007, 2009, and 2010, only one test vehicle for each model year was tested. To examine the differences in MYs with respect to emissions standards changes, the research team performed a statistical analysis (t-test) to determine if the differences are statistically significant between the tested HDDVs meeting the most recent emissions standards<sup>5</sup> and vehicles complying with previous standards. The t-test results showed that at the 95 percent confidence level (i.e.,  $\alpha=0.05$ ) no statistically significant differences were observed for both NO<sub>x</sub> and PM for all scenarios<sup>6</sup> and test conditions.

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<sup>5</sup> 2010 standard for NO<sub>x</sub>, 0.20g/bhp-hr, and 2007 standard for PM, 0.01 g/bhp-hr.

<sup>6</sup> Including Stabilized and cold-start, 5-min. soak, 15-min. soak, 5-min. soak high, and 15-min. soak high.

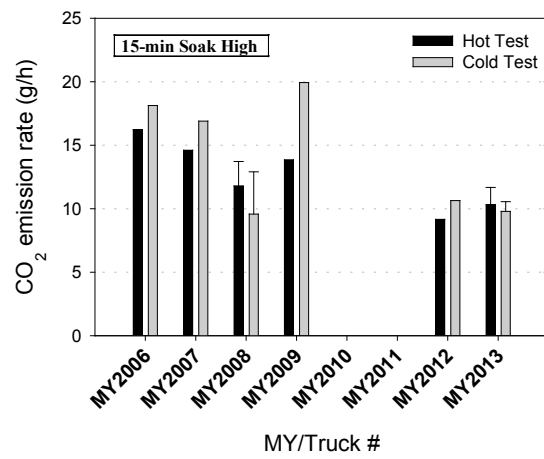
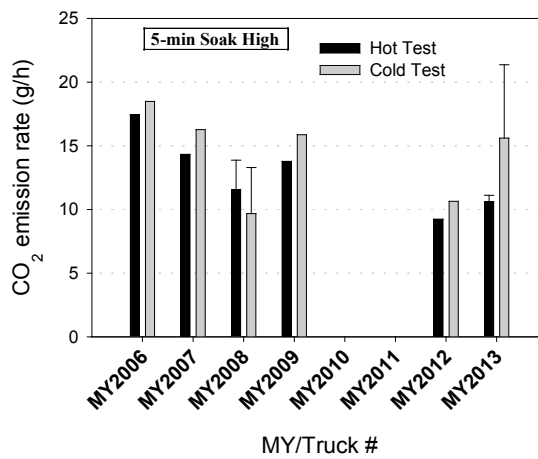
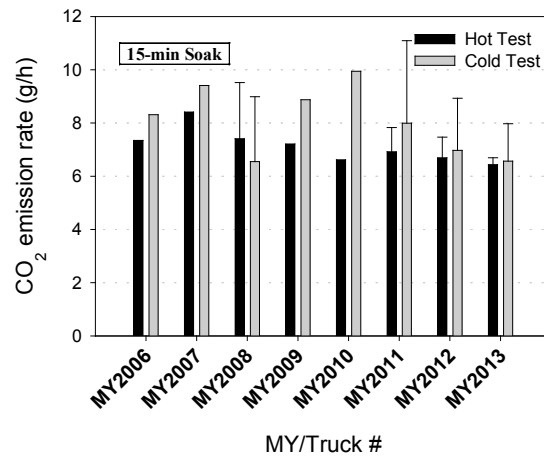
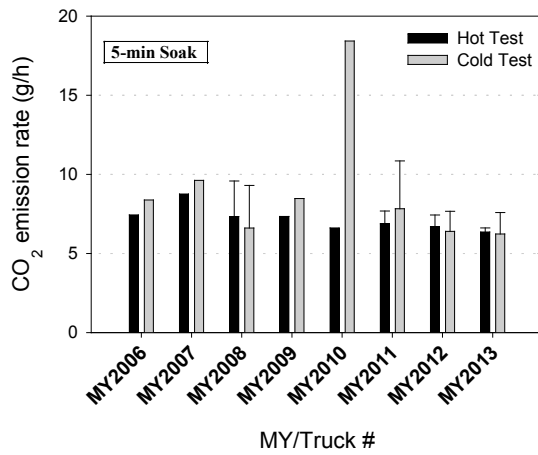
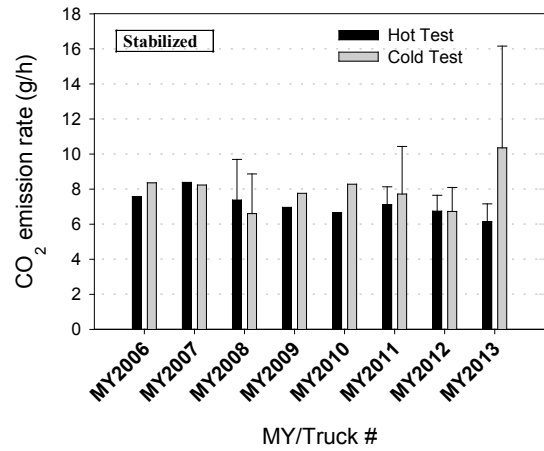
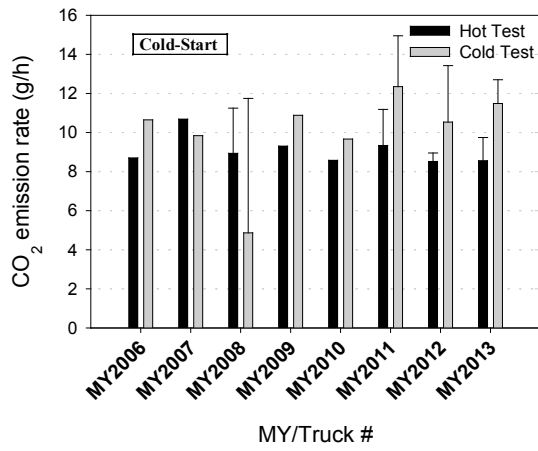


Figure 24. CO<sub>2</sub> Idling Emissions Results by MY.

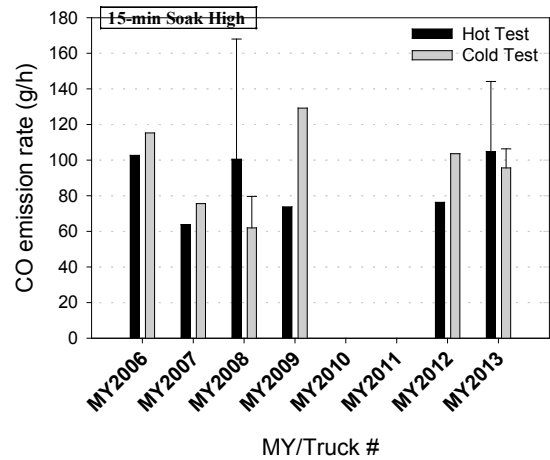
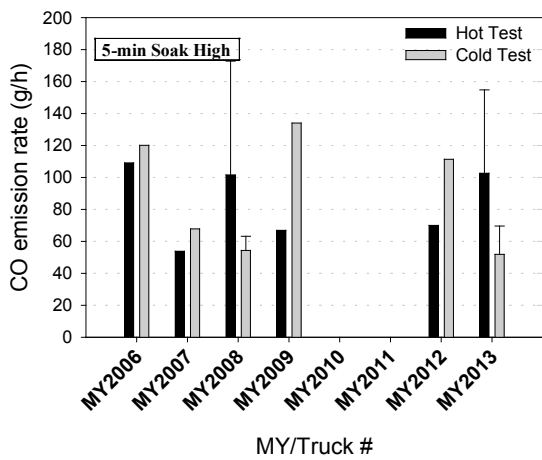
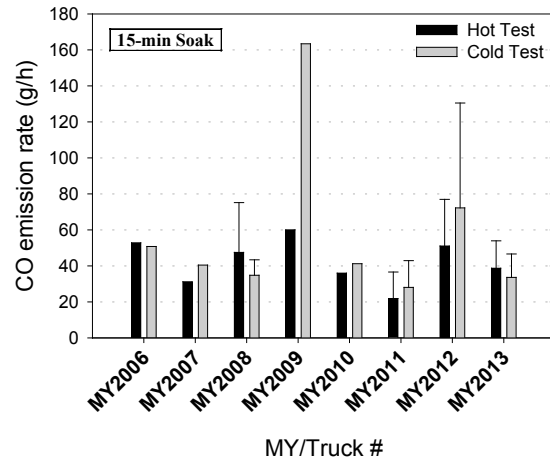
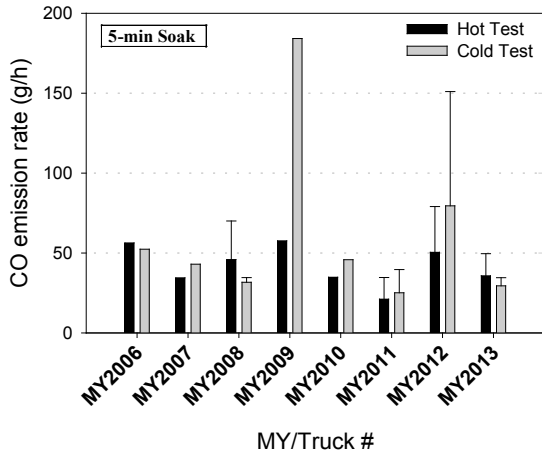
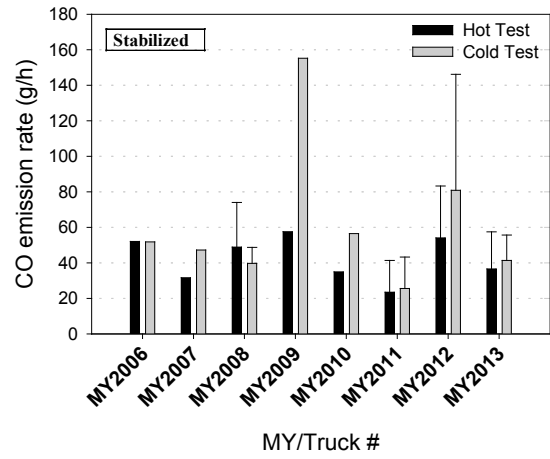
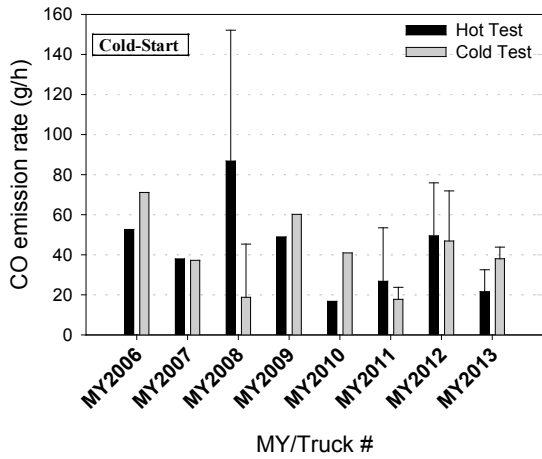


Figure 25. CO Idling Emissions Results by MY.

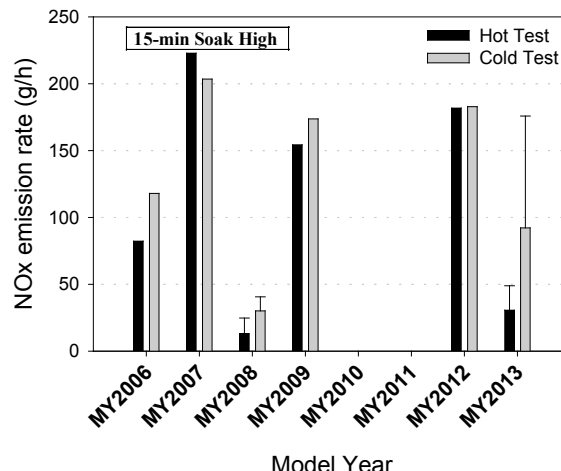
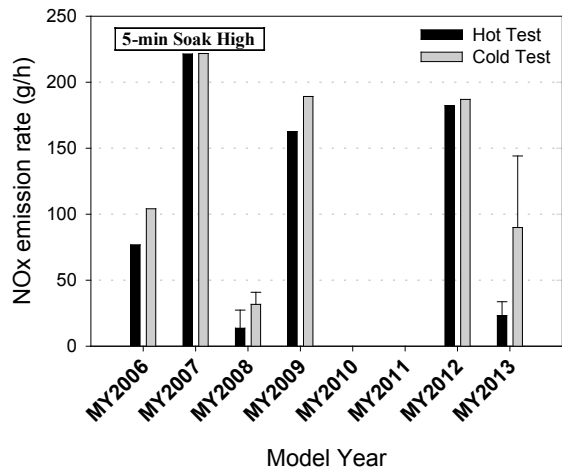
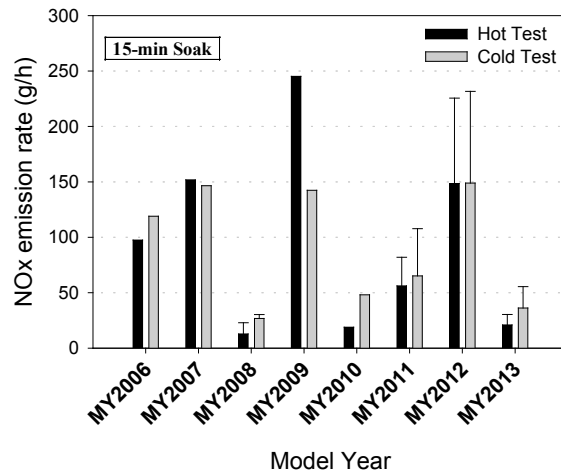
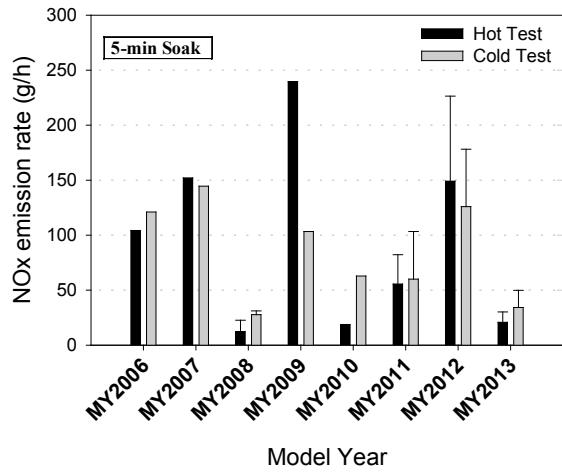
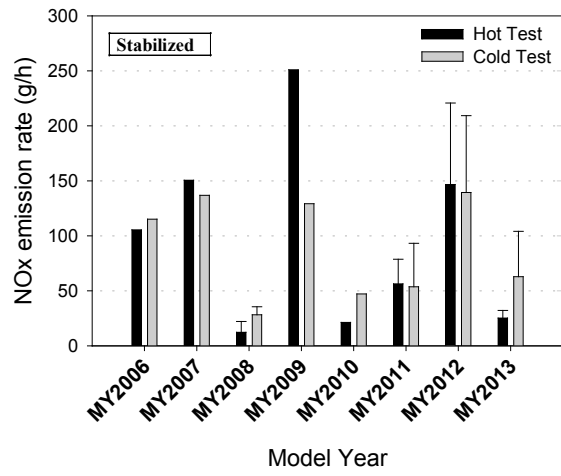
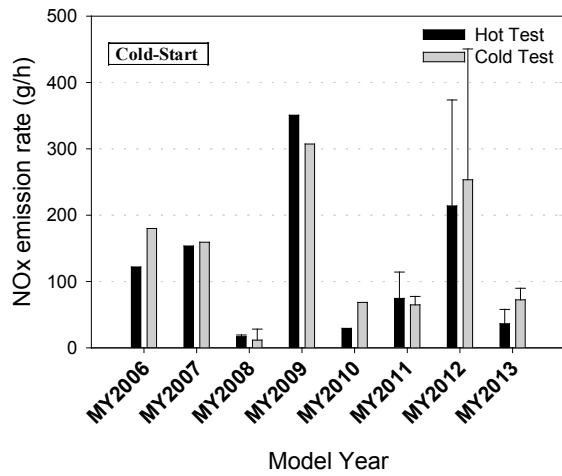


Figure 26. NO<sub>x</sub> Idling Emissions Results by MY.

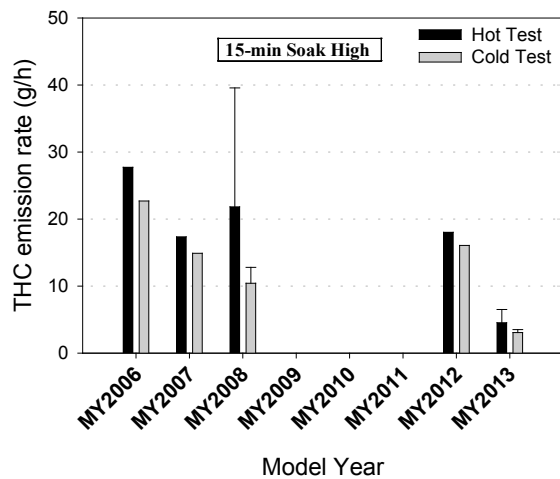
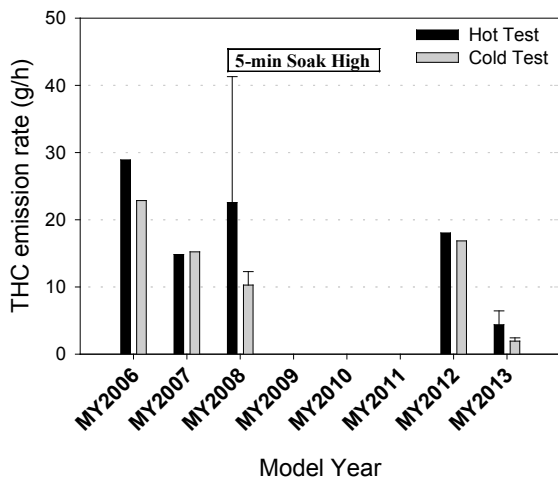
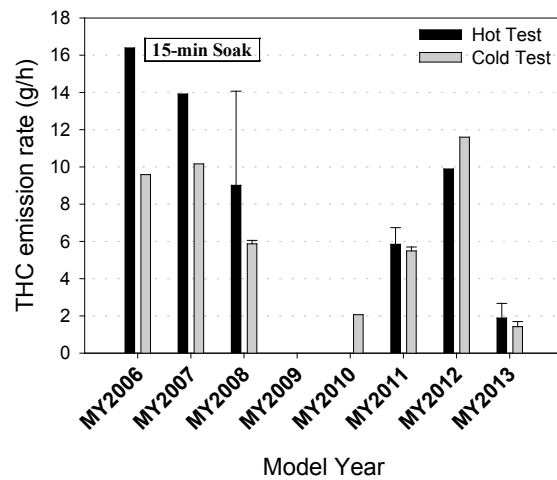
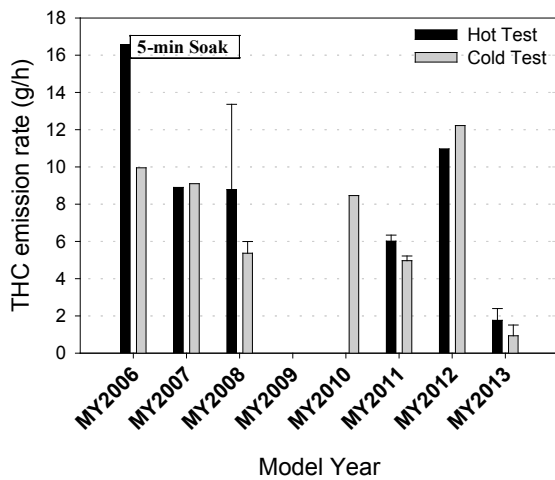
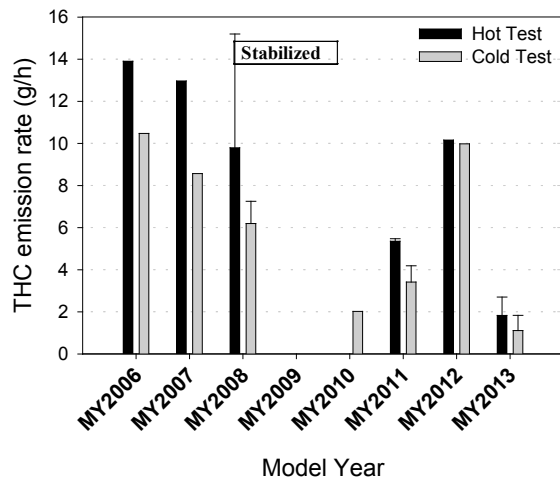
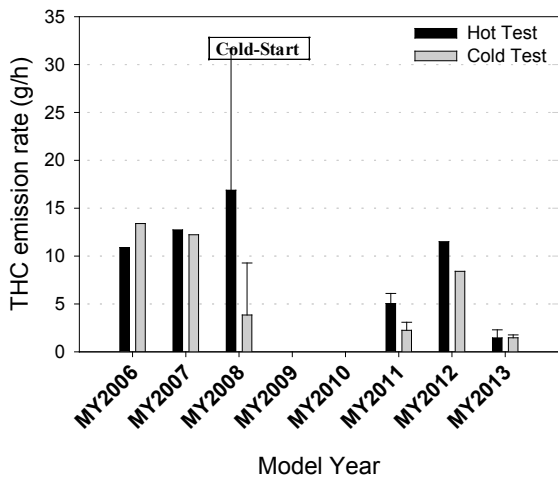
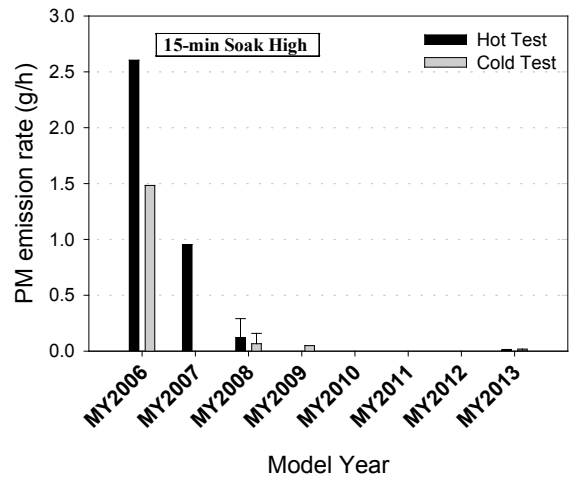
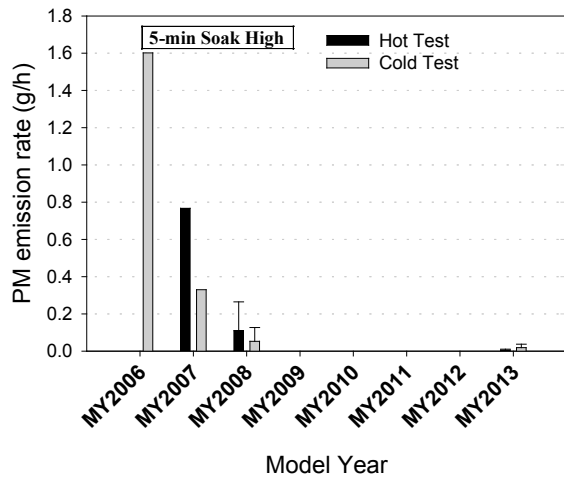
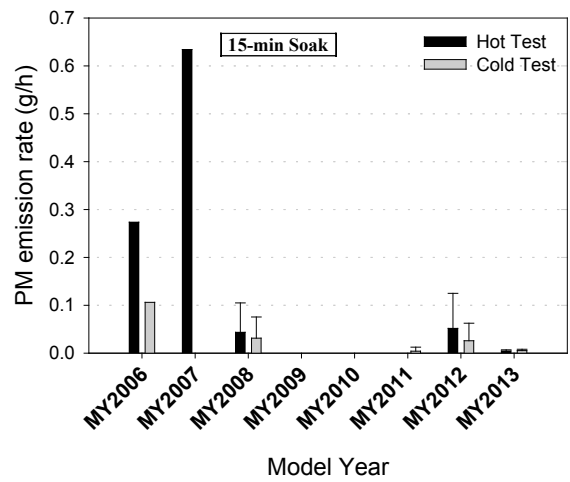
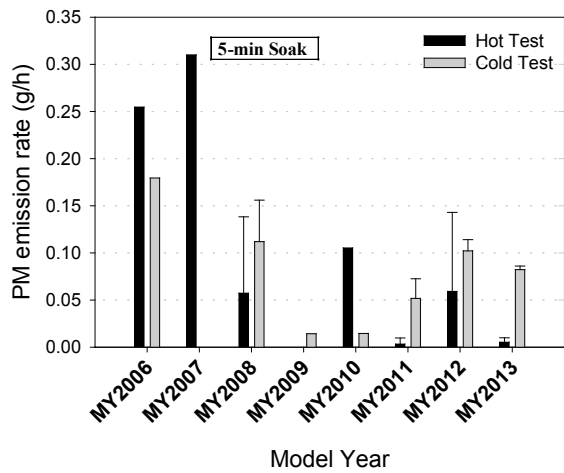
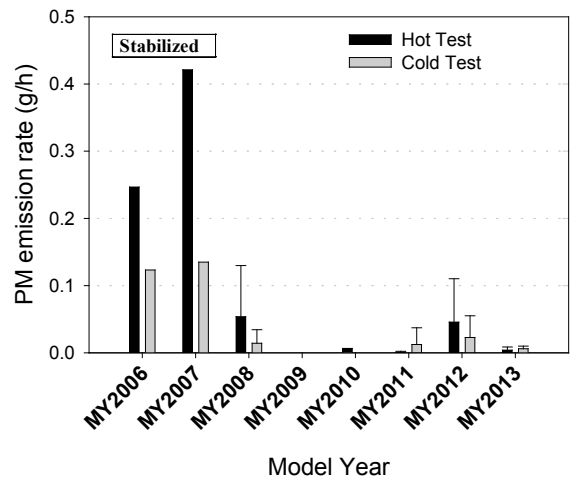
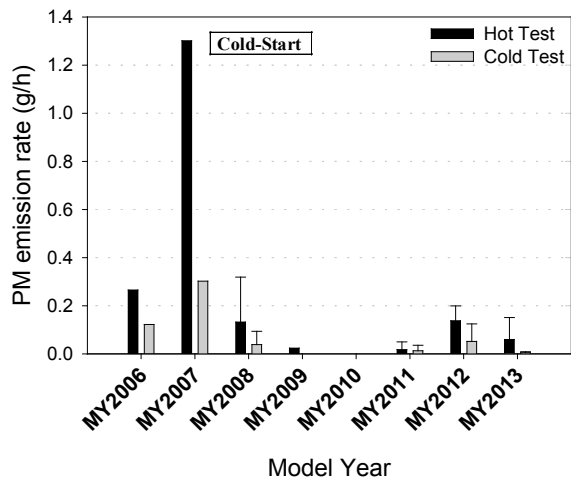
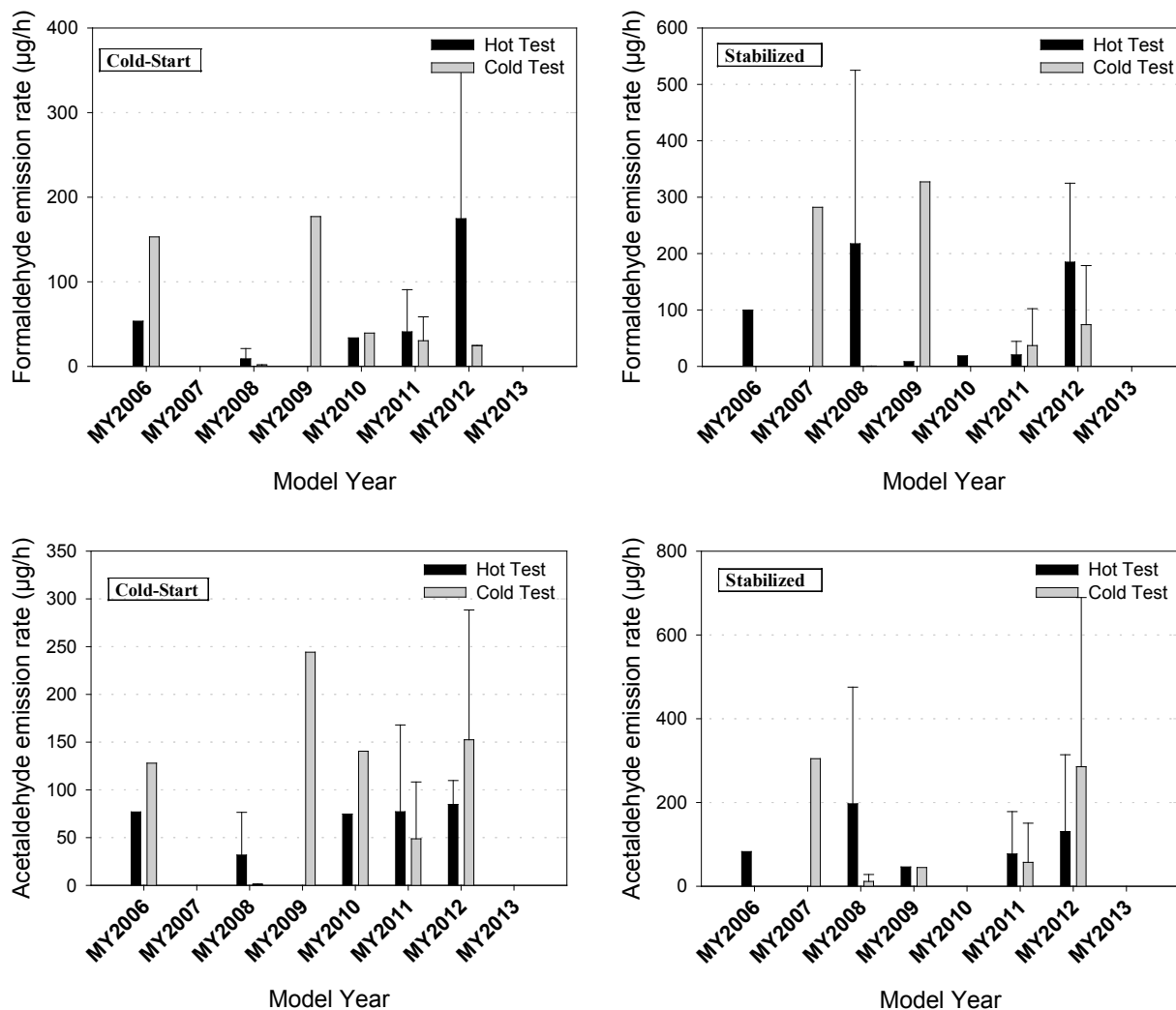


Figure 27. THC Idling Emissions Results by MY.



**Figure 28. PM Idling Emissions Results by MY.**



**Figure 29. MSAT Idling Emissions Results by MY.**

### Emissions of Cold-Start Idling and Idling during Other Test Conditions

As described in the earlier sections, the trucks were tested for other test conditions, soak times (including cold-start) and/or engine speeds (normal and high idle). The test results for those conditions are shown in Figure 30 through Figure 35. These results also show a mixed trend similar to those discussed in previous sections.

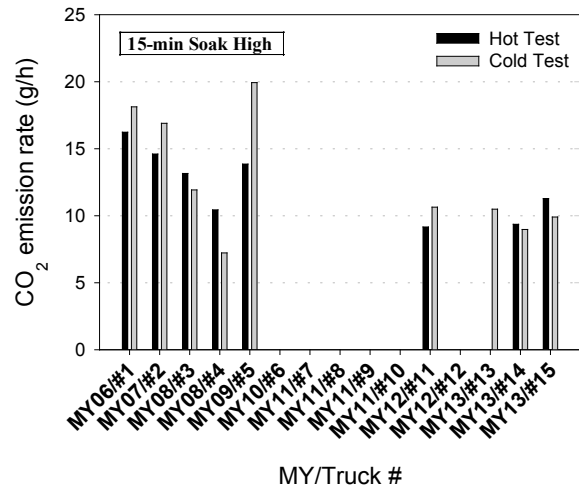
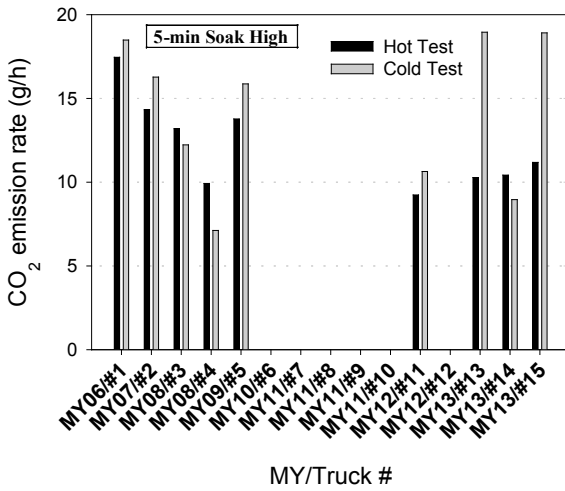
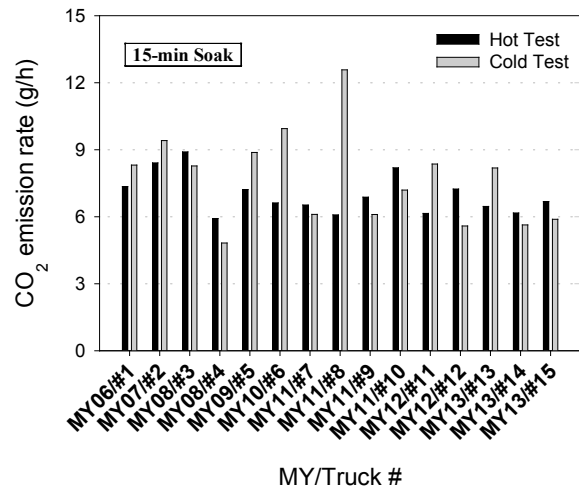
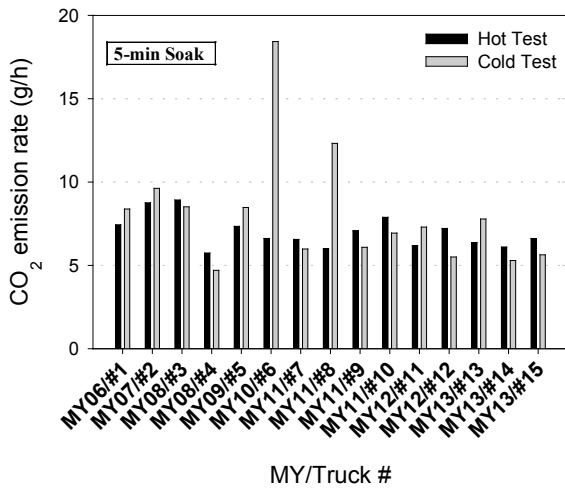
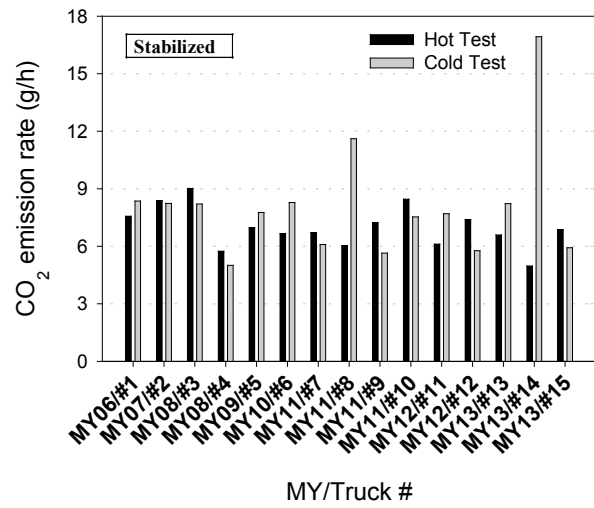
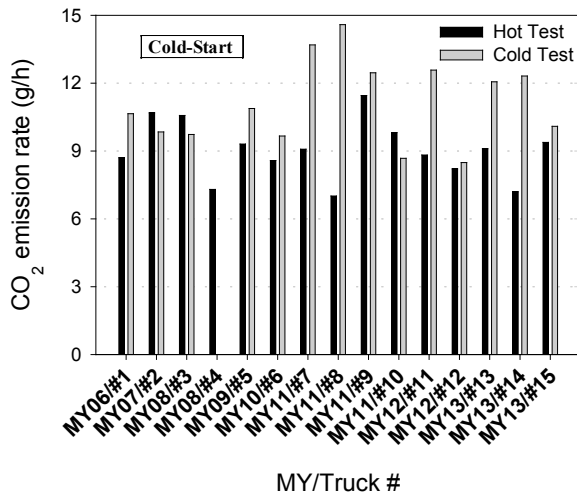


Figure 30. CO<sub>2</sub> Idling Emissions Results of CO<sub>2</sub> for Different Conditions.



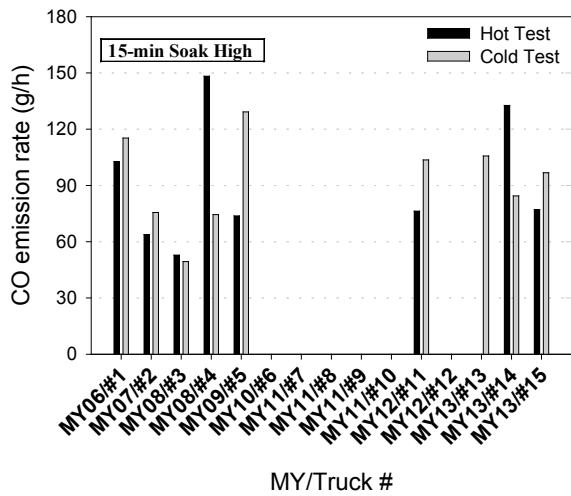
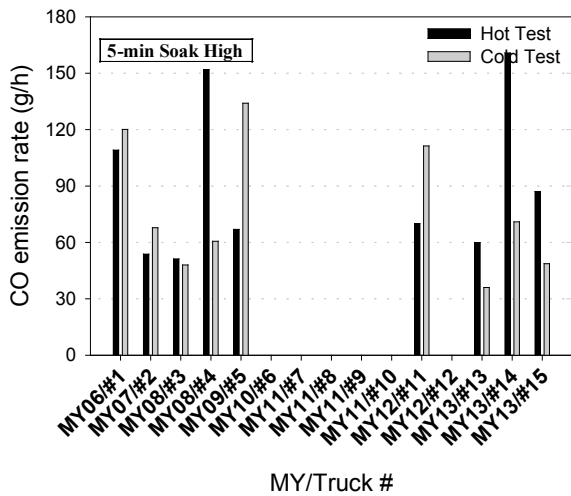
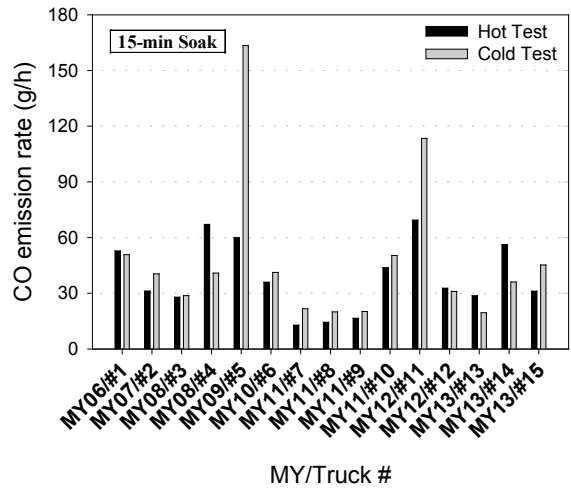
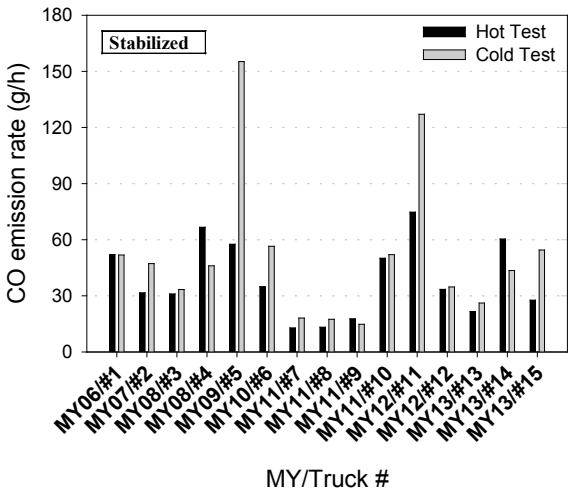
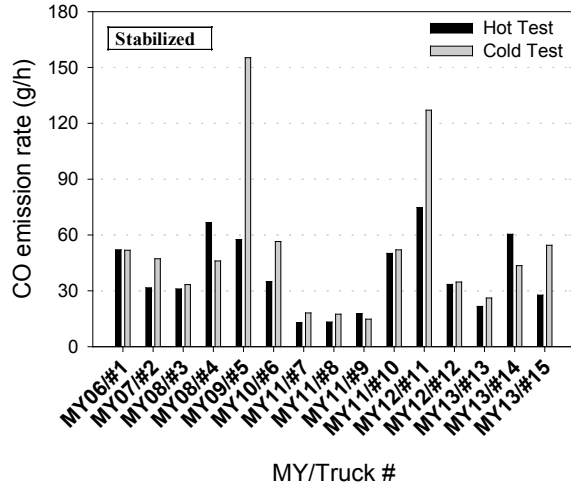
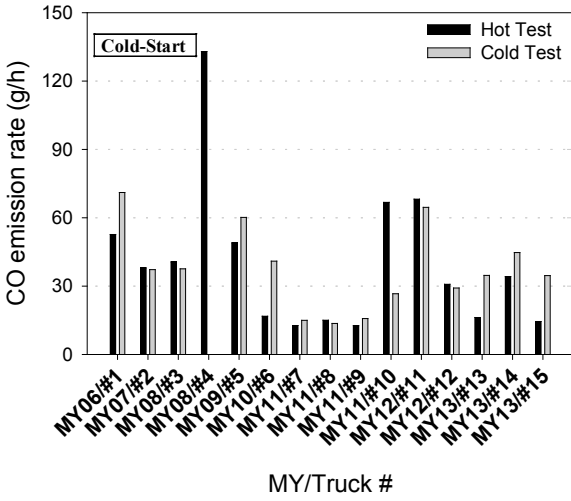


Figure 31. CO Idling Emissions Results for Different Conditions.

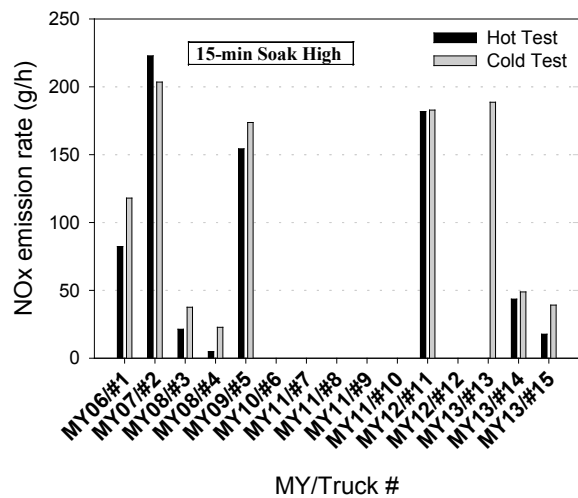
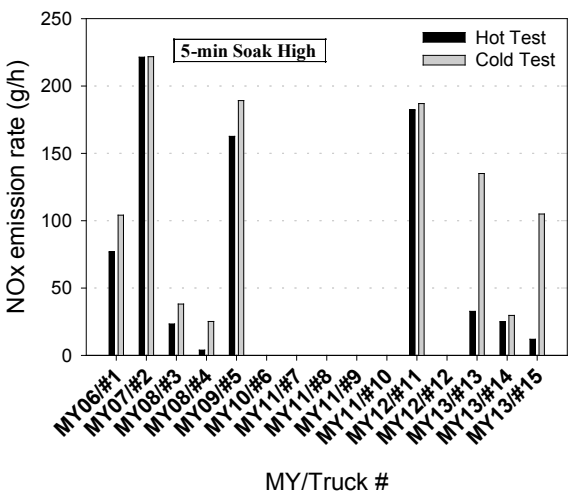
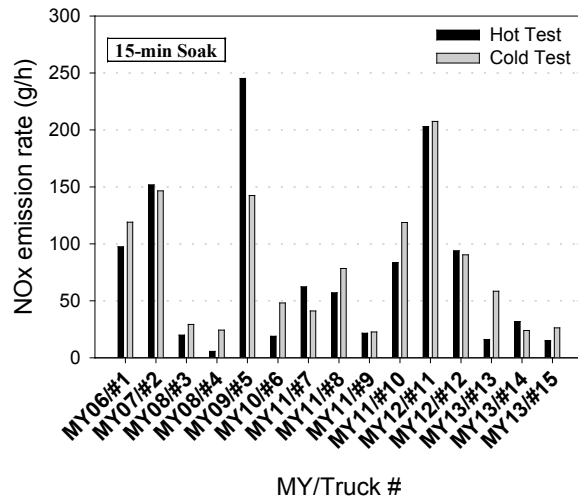
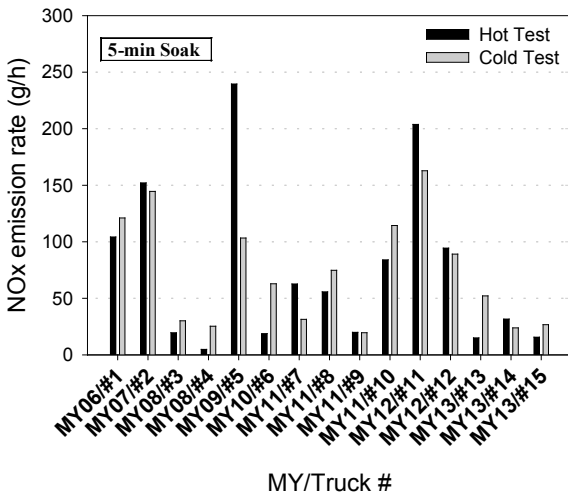
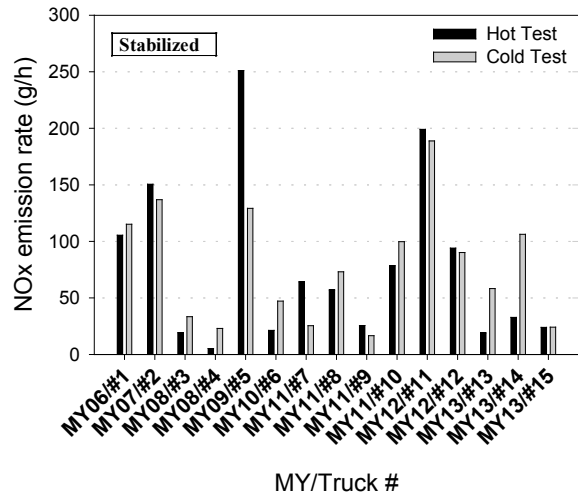
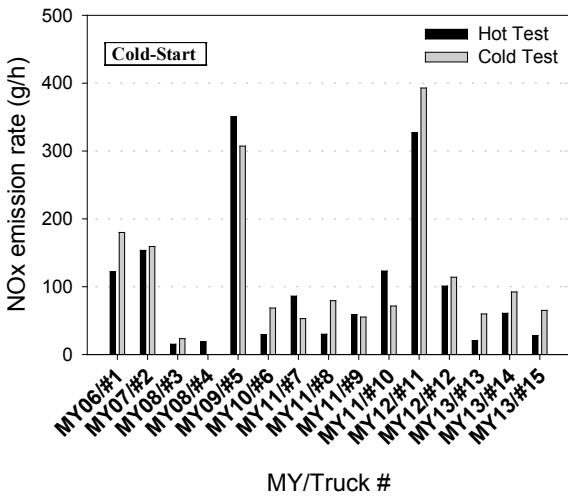


Figure 32. NO<sub>x</sub> Idling Emissions Results for Different Conditions.

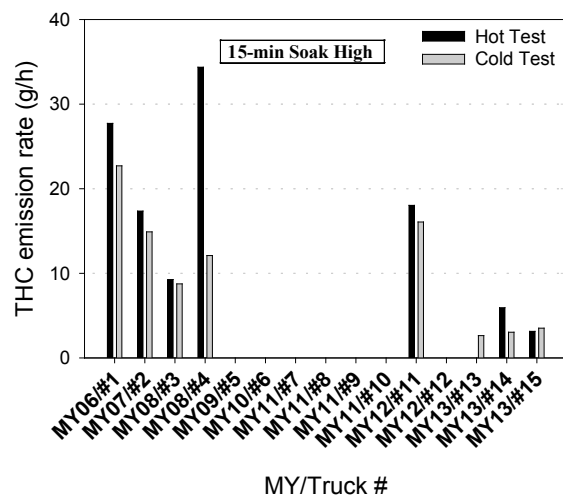
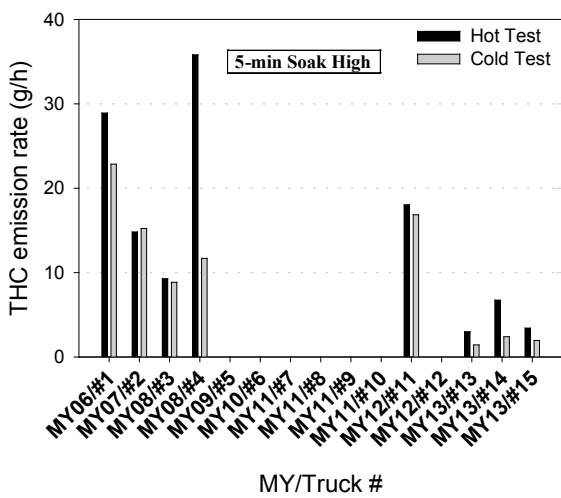
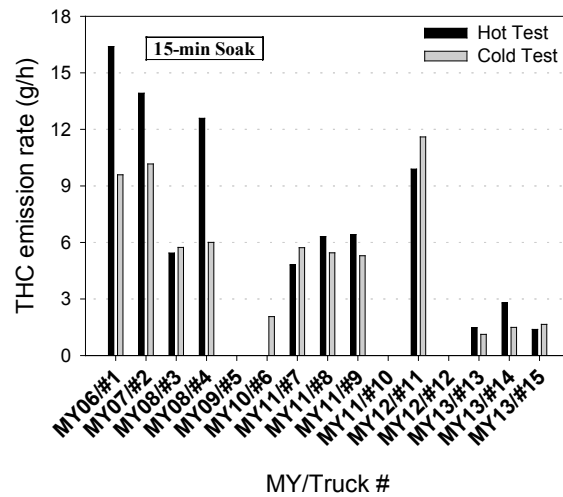
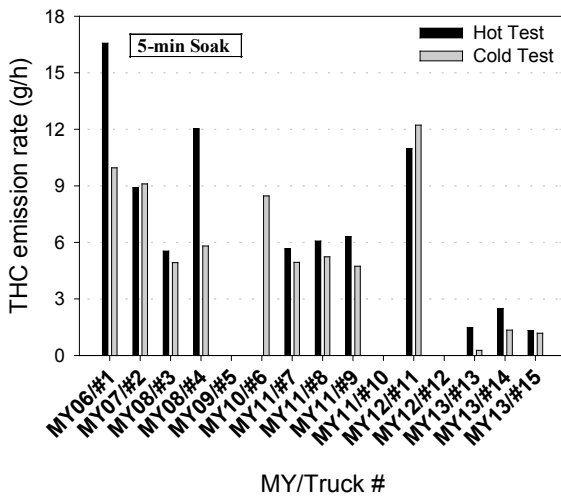
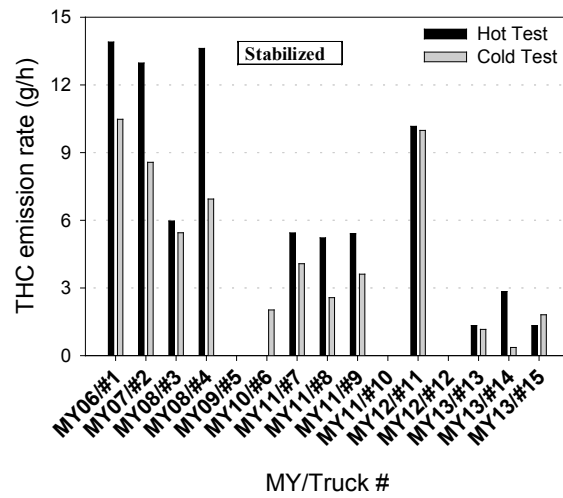
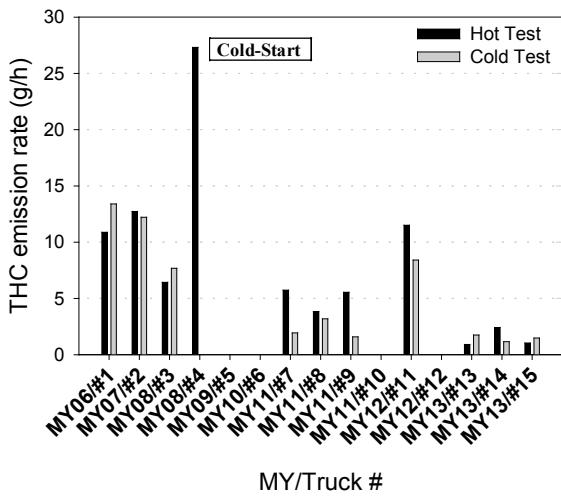


Figure 33. THC Idling Emissions Results for Different Conditions.

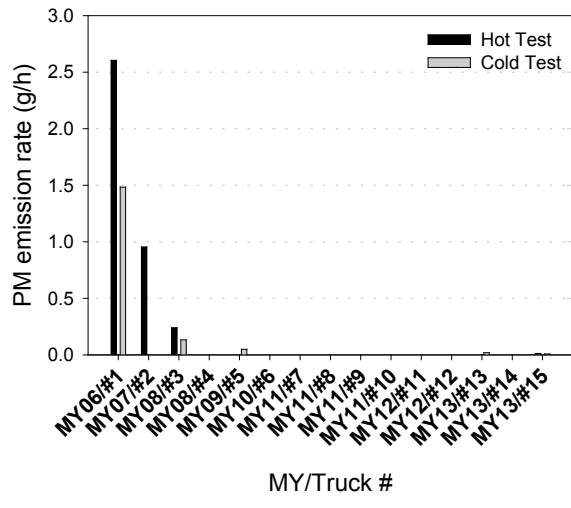
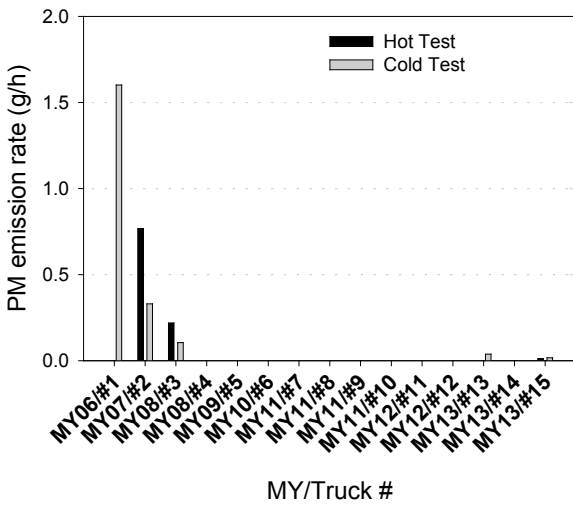
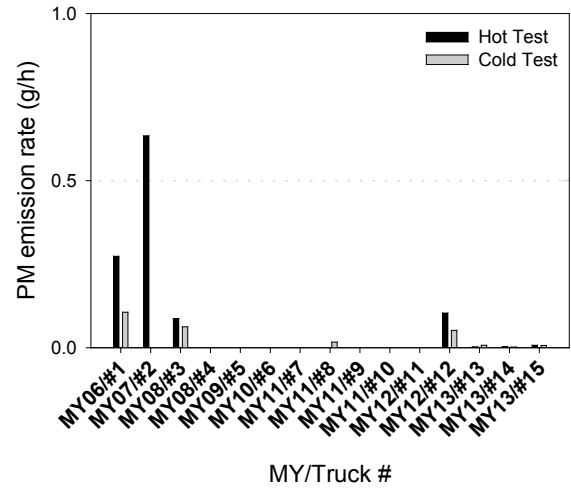
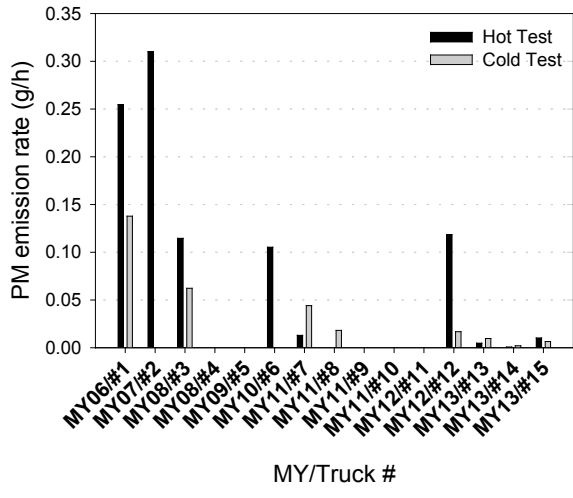
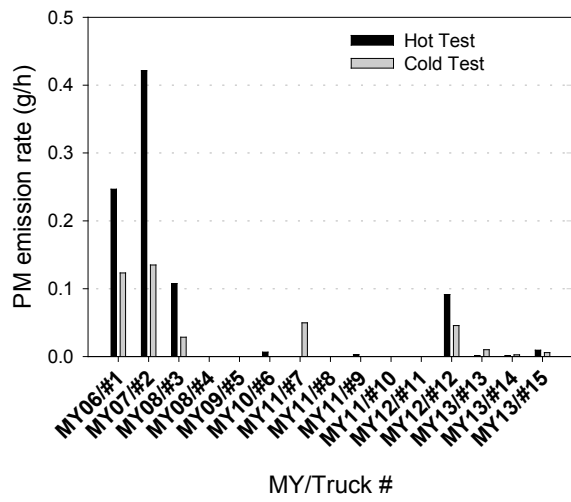
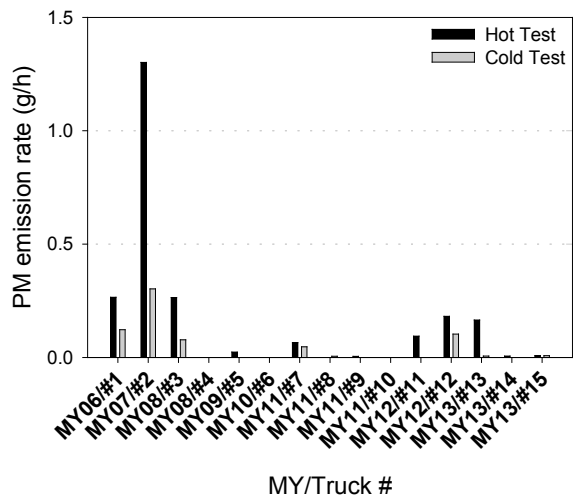
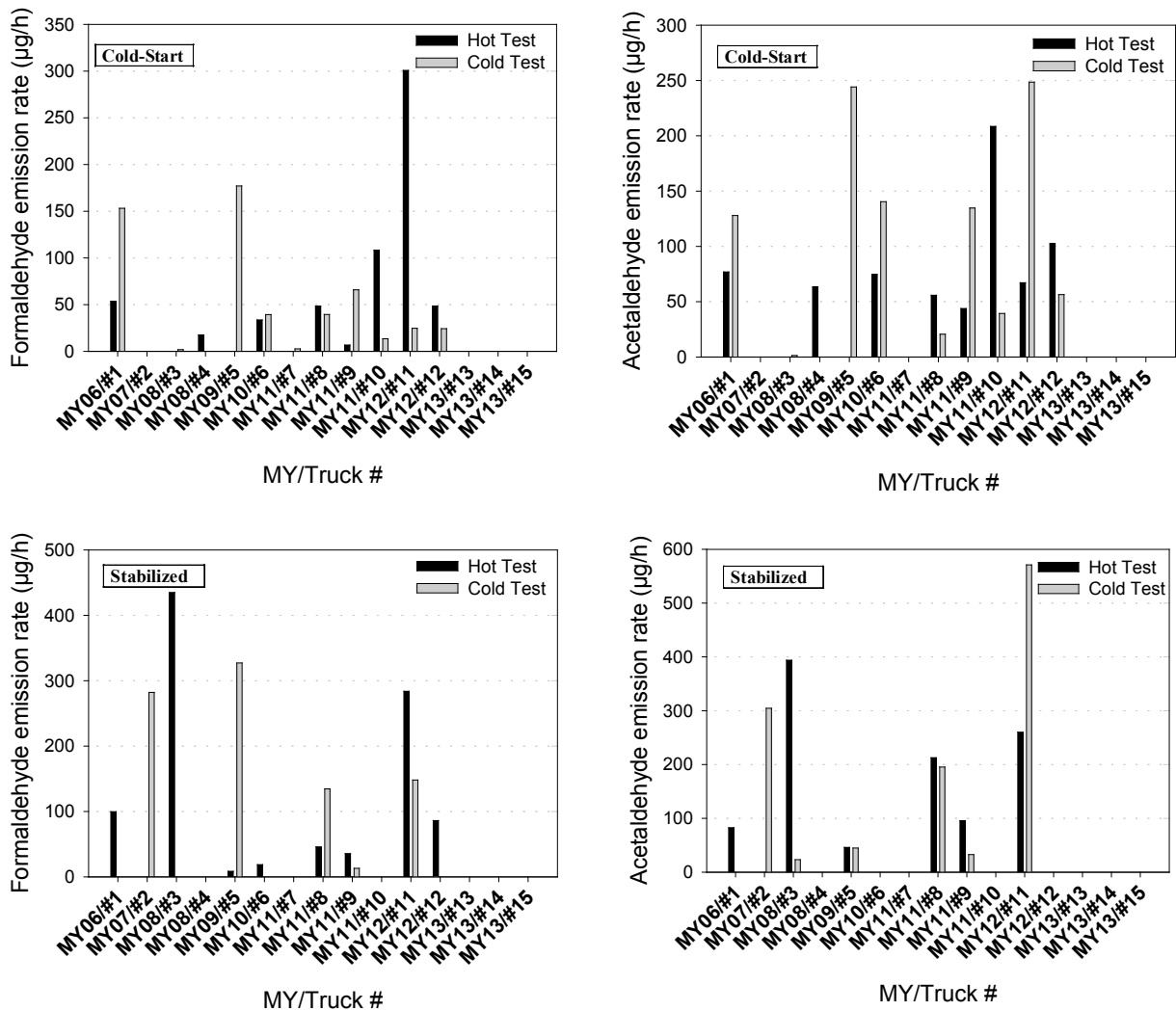


Figure 34. PM Idling Emissions Results for Different Conditions.



**Figure 35. MSAT (Formaldehyde and Acetaldehyde) Idling Emissions Results for Cold-Start and Stabilized Testing.**

The followings general and on-average trends were observed while acknowledging the high variability of the results:

- In general, cold-start emissions were higher than those of Stabilized and 5- and 15-min. soak idle tests.
- In general, emissions of 5- and 15-min. soak high idle tests were higher than those of Stabilized and 5- and 15-min. soak idle tests.

- Cold-start emissions were higher than or similar to the Stabilized emissions except those of HCHO (36 percent less, on average) for hot tests and of CO (15 percent less, on average) for cold tests, as shown in [Table 21](#).
- 5-min. soak emissions were similar to the Stabilized emissions except those of PM (191 percent more, on average) for hot tests and of HC (53 percent more, on average) for cold tests, as shown in [Table 22](#).
- 15-min. soak emissions were similar to the Stabilized emissions except those of PM (12 percent more, on average) for hot tests and of HC (43 percent more, on average) and PM (15 percent less, on average) for cold tests, as shown in [Table 23](#).
- 5-min. and 15-min. soak high emissions were higher than the Stabilized emissions for all but those of NO<sub>x</sub>, which were similar to the Stabilized for hot tests, respectively, as shown in [Table 24](#) and [Table 25](#).

The following sections provide some details on comparisons with the stabilized emissions.

#### *Cold-Start vs. Stabilized Normal Idling*

As the research team expected, emissions from cold-start tests were higher or, at least, similar to the Stabilized emissions (shown in [Table 18](#), [Table 19](#), [Figure 21](#), and [Figure 22](#)) for most test results, on average, as shown in [Table 21](#):

- For CO<sub>2</sub>, all reported cold-start emissions were higher (in the range of 11–125 percent higher) than the Stabilized, except for Truck #14 for cold test (27 percent less).
- For NO<sub>x</sub> and HC, cold-start emissions were, on average, higher than or similar to the Stabilized for both hot and cold tests (46, 1, 60, and 15 percent higher, on average, for NO<sub>x</sub> and HC for hot tests; and for NO<sub>x</sub> and HC for cold tests, respectively) with high variability, in the range from –100 percent (that is, no emissions detected) to 256 percent (about 2.5 times more emissions).
- For CO, cold-start emissions were, on average, similar (2 percent less on average) for hot tests or slightly less (15 percent less on average) for cold tests to the Stabilized with high variability, in the range from –61 percent (that is, 61 percent less) to 99 percent more.

- For PM, cold-start emissions were higher than the Stabilized (on average, 1737 percent for hot tests and 41 percent for cold tests) with much greater variability from –100 percent (i.e., no emissions detected) to 14,854 percent (about 150 times higher, for Truck #13 for hot test) or, excluding the Truck #13 data, to 359 percent (still more than 3.5 times higher).
- For MSAT, the variability was even greater than that of PM, from –100 percent (that is, no emissions detected) to 70,425 percent (about 700 times higher CH<sub>3</sub>CHO, for Truck #1 for cold test).

As discussed previously, these mixed results along with high variability are ascribed to the different engine, emission controls, and CAP features. For example, more than double of CO<sub>2</sub> emissions for Truck #7 and 9 for cold test are suspected to be due to automatic engine speed increases (850 rpm instead of regular 600 rpm) for more than 30 minutes in the beginning of tests, i.e., during the cold-start tests.

**Table 21. Comparisons between Emission Rates during the Cold-Start Tests and for Stabilized Emissions.**

Truck Number	Difference in Emission Rates during the Cold-Start Compared to the Stabilized Emission Rates for Hot Tests (%)										Difference in Emission Rates during the Cold-Start Compared to the Stabilized Emission Rates for Cold Tests (%)										
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO
#1	15	1	16	-22	8	-46	-7	27	37	56	28	-1	28421	70425	27	37	56	28	-1	28421	70425
#2	27	20	2	-2	209	-50	-36	19	-21	16	43	124	-100	-100	19	-21	16	43	124	-100	-100
#3	17	31	-21	8	146	-100	-100	19	13	-30	41	172	-	-94	19	13	-30	41	172	271	-
#4	27	99	256	101	-	-	-	N/A*	N/A*	N/A*	N/A*	N/A*	-	-	N/A*	N/A*	N/A*	N/A*	N/A*	-	-
#5	34	-15	40	N/A*	-	-94	-100	40	-61	138	N/A*	-	-46	445	40	-61	138	N/A*	-	-46	445
#6	29	-52	38	N/A*	-100	80	31762	17	-28	45	-100	-	-	-	17	-28	45	-100	-	-	-
#7	35	-1	34	5	-	-	-	125	-17	108	-52	-5	-	-	125	-17	108	-52	-5	-	-
#8	16	14	-48	-27	-	5	-74	26	-22	9	24	-	-71	-89	26	-22	9	24	-	-71	-89
#9	59	-29	130	3	71	-81	-54	121	6	232	-56	-	406	313	121	6	232	-56	-	406	313
#10	16	33	57	N/A*	-	-	-	15	-49	-28	N/A*	-	-	-	15	-49	-28	N/A*	-	-	-
#11	44	-9	64	13	-	6	-74	63	-49	108	-16	-	-83	-56	63	-49	108	-16	-	-83	-56
#12	11	-8	7	N/A*	99	-44	16479	47	-16	27	N/A*	126	-	-	47	-16	27	N/A*	126	-	-
#13	38	-25	7	-31	14854	-	-	47	33	3	51	-38	-	-	47	33	3	51	-38	-	-
#14	45	-43	86	-15	359	-	-	-27	3	-13	219	-86	-	-	-27	3	-13	219	-86	-	-
#15	37	-48	17	-22	-16	-	-	70	-37	169	-18	38	-	-	70	-37	169	-18	38	-	-
<b>Average</b>	<b>30</b>	<b>-2</b>	<b>46</b>	<b>1</b>	<b>1737</b>	<b>-36</b>	<b>5311</b>	<b>43</b>	<b>-15</b>	<b>60</b>	<b>15</b>	<b>41</b>	<b>4114</b>	<b>10120</b>	<b>43</b>	<b>-15</b>	<b>60</b>	<b>15</b>	<b>41</b>	<b>4114</b>	<b>10120</b>

\* N/A: Not available or applicable due to malfunctioning of the corresponding emission measurement instrument during either for cold-start or Stabilized condition, or both.

\*\* -: Results are not applicable because the Stabilized data for the comparisons were 0, i.e., denominator = 0.



**Table 22. Comparisons between Emission Rates during the 5-Min. Soak Tests and for Stabilized Emissions.**

Truck Number	Difference in Emission Rates during the 5-Min. Soak to the Stabilized Emission Rates for Hot Tests (%)					Difference in Emission Rates during the 5-Min Soak to the Stabilized Emission Rates for Cold Tests (%)				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
#1	-2	8	-1	19	3	0	1	5	-5	12
#2	4	9	1	-31	-26	17	-9	6	6	N/A*
#3	-1	-7	2	-7	7	4	-11	-10	-10	118
#4	0	-6	-8	-12	**	-6	-27	10	-16	**
#5	5	0	-5	N/A*	**	9	19	-20	N/A*	**
#6	-1	0	-12	N/A*	1514	123	-19	33	318	**
#7	-2	-4	-2	4	**	-2	-6	23	21	-11
#8	-1	5	-2	16	**	6	8	2	104	**
#9	-2	-4	-22	17	-100	8	20	18	31	**
#10	-7	-18	7	N/A*	**	-8	-10	15	N/A*	**
#11	1	-5	2	8	**	-5	2	-14	22	**
#12	-2	-10	0	N/A*	30	-5	-16	-1	N/A*	-63
#13	-3	29	-21	11	326	-5	-9	-10	-77	-4
#14	23	-14	-3	-12	-43	-69	-29	-78	271	-15
#15	-4	0	-34	-1	9	-5	-38	10	-35	11
<b>Average</b>	<b>1</b>	<b>-1</b>	<b>-7</b>	<b>1</b>	<b>191</b>	<b>4</b>	<b>-8</b>	<b>-1</b>	<b>53</b>	<b>7</b>

\* N/A: Not available or applicable due to malfunctioning of the corresponding emission measurement instrument during either for cold-start or Stabilized condition, or both.

\*\* -: Results are not applicable because the Stabilized data for the comparisons were 0, i.e., denominator = 0.

**Table 23. Comparisons between Emission Rates during the 15-Min. Soak Tests and for Stabilized Emissions.**

Truck Number	Difference in Emission Rates during the 15-Min. Soak to the Stabilized Emission Rates for Hot Tests (%)					Difference in Emission Rates during the 15-Min. Soak to the Stabilized Emission Rates for Cold Tests (%)				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
#1	-3	1	-8	18	11	-1	-2	3	-8	-14
#2	0	-1	1	7	51	14	-14	7	19	-100
#3	-1	-10	4	-9	-19	1	-14	-12	5	120
#4	3	1	7	-8	-**	-4	-11	6	-14	-**
#5	4	4	-2	N/A*	-**	14	5	10	N/A*	-**
#6	-1	3	-11	N/A*	-100	20	-27	2	2	-**
#7	-3	0	-3	-12	-**	0	20	61	40	-100
#8	1	9	0	21	-**	8	15	7	112	-**
#9	-5	-7	-16	19	-100	8	36	37	47	-**
#10	-3	-12	7	N/A*	-**	-4	-3	19	N/A*	-**
#11	1	-7	2	-3	-**	9	-11	10	16	-**
#12	-2	-2	0	N/A*	13	-3	-11	0	N/A*	13
#13	-2	33	-16	11	145	0	-25	0	-3	-28
#14	24	-7	-3	-2	131	-67	-17	-77	311	-28
#15	-3	12	-37	4	-22	-1	-17	9	-9	15
<b>Average</b>	<b>1</b>	<b>1</b>	<b>-5</b>	<b>4</b>	<b>11</b>	<b>0</b>	<b>-5</b>	<b>5</b>	<b>43</b>	<b>-15</b>

\* N/A: Not available or applicable due to malfunctioning of the THC emission measurement instrument during either for cold-start or Stabilized condition, or both.

\*\* -: Results are not applicable because the Stabilized data for the comparisons were 0, i.e., denominator = 0.

**Table 24. Comparisons between Emission Rates during the 5-Min. Soak High Tests and for Stabilized Emissions.**

Truck Number	Difference in Emission Rates during the 5-Min. Soak to the Stabilized Emission Rates for Hot Tests (%)					Difference in Emission Rates during the 5-Min. Soak High to the Stabilized Emission Rates for Cold Tests (%)				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
#1	131	109	-27	108	-100	121	132	-10	118	1200
#2	71	70	47	14	82	98	44	62	78	145
#3	46	65	21	56	104	49	44	14	63	269
#4	73	128	-26	163	-**	42	31	9	68	-**
#5	98	16	-35	N/A*	-**	104	-14	46	N/A*	-**
#6	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#7	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#8	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#9	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#10	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#11	51	-6	-8	78	-**	38	-12	-1	69	-**
#12	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#13	56	177	71	126	116	130	38	132	23	277
#14	110	166	-24	137	71	-47	63	-72	564	-44
#15	63	214	-50	158	19	219	-11	334	8	194
<b>Average</b>	<b>78</b>	<b>104</b>	<b>-3</b>	<b>105</b>	<b>49</b>	<b>84</b>	<b>35</b>	<b>57</b>	<b>124</b>	<b>340</b>

\* N/A: Not available or applicable due to malfunctioning of the THC emission measurement instrument during either for cold-start or Stabilized condition, or both.

\*\* -: Results are not applicable because the Stabilized data for the comparisons were 0, i.e., denominator = 0.

\*\*\* No: No high idle results because the corresponding test trucks did not allow high idling.

**Table 25. Comparisons between Emission Rates during the 15-Min. Soak High Tests and for Stabilized Emissions.**

Truck Number	Difference in Emission Rates during the 15-Min. Soak High to the Stabilized Emission Rates for Hot Tests (%)					Difference in Emission Rates during the 15-Min. Soak High to the Stabilized Emission Rates for Cold Tests (%)				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
#1	115	97	-22	99	956	117	122	2	117	1104
#2	74	101	48	34	127	105	60	49	74	-100
#3	46	70	10	55	124	45	48	12	61	363
#4	82	122	-9	152	-**	44	62	-1	74	-**
#5	99	28	-39	N/A*	-**	157	-17	34	N/A*	-**
#6	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#7	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#8	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#9	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#10	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#11	50	2	-9	77	-**	38	-18	-3	61	-**
#12	No***	No***	No***	No***	No***	No***	No***	No***	No***	No***
#13	N/A*	N/A*	N/A*	N/A*	N/A*	28	304	224	127	92
#14	88	120	33	109	15	-47	94	-54	737	-53
#15	64	178	-26	136	34	67	78	62	94	33
<b>Average</b>	<b>77</b>	<b>90</b>	<b>-2</b>	<b>95</b>	<b>251</b>	<b>62</b>	<b>81</b>	<b>36</b>	<b>168</b>	<b>240</b>

\* N/A: Not available or applicable due to malfunctioning of the corresponding emission measurement instrument during either for cold-start or Stabilized condition, or both.

\*\* -: Results are not applicable because the Stabilized data for the comparisons were 0, i.e., denominator = 0.

\*\*\* No: No high idle results because the corresponding test trucks did not allow high idling.

*5-Min. Soak vs. Stabilized Normal Idling*

In general, 5-min. soak emissions were similar to the Stabilized emissions, except for PM emission of hot tests and of THC emission for cold tests. Table 22 shows that:

- Most test results including CO<sub>2</sub>, CO, and NO<sub>x</sub> for both hot and cold tests, and HC for hot tests and PM for cold tests were similar to the Stabilized with high variability, in the range of -78 percent to 123 percent.
- THC emissions for 5-min. soak cold tests were higher than the Stabilized, 53 percent on average, with greater variability, from -77 percent to 318 percent.
- For PM for hot tests, the variability was even greater than that of THC above, ranging from -100 percent (i.e., no emissions detected) to 1514 percent (approximately 15 times higher) while the 5-min. soak emissions were higher (191 percent on average) than the Stabilized idling emissions.

These mixed results along with high variability are also ascribed to the different engine, emission controls, and CAP features.

#### *15-min Soak vs. Stabilized Normal Idling*

As shown in [Table 23](#), 15-min. soak emissions were generally similar to the Stabilized emissions with the exception of PM and cold tests' THC. Comparing to the Stabilized emissions:

- Most test results (CO<sub>2</sub>, CO, and NO<sub>x</sub> for both hot and cold tests, and HC for hot tests) were similar to the Stabilized with still high variability, in the range from -77 percent to 61 percent.
- For HC for cold tests, 15-min. soak emissions were higher than the Stabilized with the variability, from -14 percent to 311 percent.
- For PM for hot tests, the 15-min. soak emissions were slightly higher (12 percent on average) for hot tests and slightly lower (-15 percent on average) for cold tests than the Stabilized with the variability, from -100 percent to 145 percent.

The different engine, emission controls, and CAP features are determined to be the main contributing factors for this trend.

#### *5- and 15-Min. Soak High Idle vs. Stabilized Normal Idle*

Due to the higher engine speed (1100 rpm) compared to the other conditions (600 to 700 rpm), and as expected and shown previously in other studies, emissions from 5- and 15-min. soak high Idle tests were higher than the Stabilized Normal Idle emissions except for the NO<sub>x</sub> emissions for hot tests (see [Table 24](#) and [Table 25](#)) (54). NO<sub>x</sub> emissions for hot tests were on average similar to the Stabilized Normal Idle, i.e., 3 percent less for 5-min. and 2 percent less for 15-min. soak high, respectively. The variability of hot test NO<sub>x</sub> was also less than the other conditions; in the range from -50 percent to 71 percent.

Because engine speeds during the 5- and 15-min. soak high tests were, on average, higher than the Stabilized tests of the corresponding vehicles, those results having lower emissions than the Stabilized (mostly NO<sub>x</sub> emissions along with a few others, especially for cold tests) should be caused by other engine/emissions controls than engine speed increases; for example, EGR manipulation. Further investigations of the causes of the mixed results are beyond the scope of this study.

## PM Emissions Verification

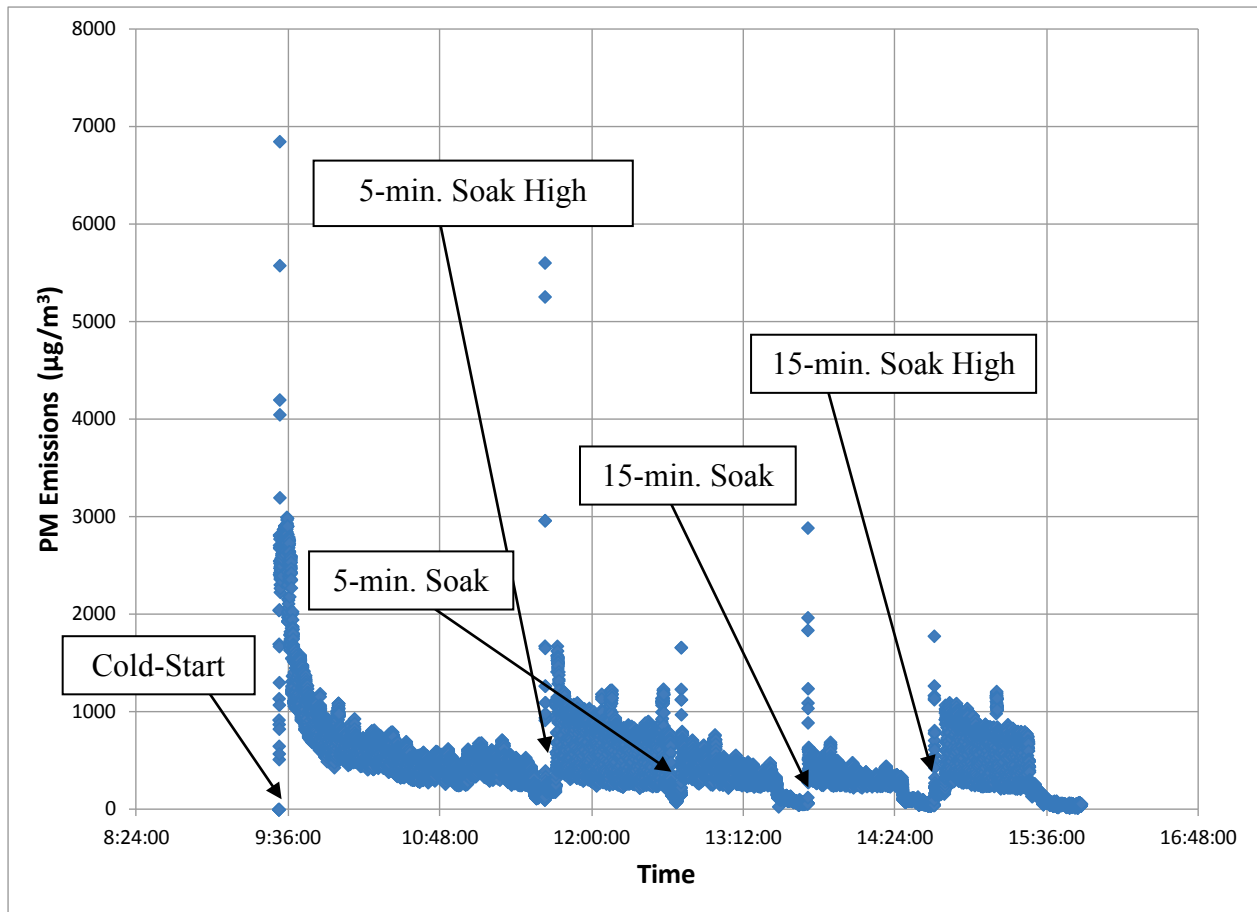
As described in the test equipment section, TTI researchers also used DMM for PM measurements to verify PM filter results. The EPA considers as valid observations only those PM emissions that PM filters<sup>7</sup> have measured. The DMM equipment, on the other hand, provides real time second-by-second data. With monitoring and analyzing these second-by-second DMM results, TTI researchers checked the irregularities in the data to ensure the quality of the PM emission data.

As expected, PM emissions that the DMM had measured showed the similar results measured using PM filters. For example, [Figure 36](#) shows that PM emissions at cold-start were highest at the beginning and decrease gradually; those during the high idling tests (for both 5- and 15-min. soak high) that are similar to each other, were higher than those during the normal idling tests (for both 5- and 15-min. soak), that are similar to each other. These results matched with the PM results measured using PM filters:

- 0.26 g/hr and 0.11 g/hr for cold-start and Stabilized idling.
- 0.22 and 0.24 for 5- and 15-min. soak high.
- 0.11 and 0.09 for 5- and 15-min. soak.

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<sup>7</sup> The weight of trapped PM on a filter collected over a period of time.



**Figure 36. PM Results Measured by the DMM for Truck #3 for Hot Tests.**

An examination of DMM results for Truck #3’s cold test as well as for other trucks (hot and cold conditions) showed similar trends.

### COMPARISON WITH EXISTING DATA

The research team reviewed the HDDV data sources that were identified in Task 1 and performed a comparison with the data collected in this task. Only the data sources with comparable testing conditions were included in this effort. This comparison included idling emissions data from the following studies:

- RMC0-6629 (current study), performed by TTI, 15 vehicles, 2011–2013.
  - Cold test temperature:  $-1.1^{\circ}\text{C}$ .
  - Hot test temperature:  $37.8^{\circ}\text{C}$ .

- New Technology Research and Development Program N-42, performed by TTI, *Development of a NO<sub>x</sub> Verification Protocol and Actual Testing of Onboard Idle Reduction Technologies*, three vehicles, 2012.
  - Cold test temperature: -17.8°C.
  - Hot test temperature: 37.8°C.
- Storey, John et al., *Particulate Matter and Aldehyde Emissions From Idling Heavy-Duty Diesel Trucks*, SAE 2003-01-0289; five vehicles, 2003.
  - Cold test temperature: -18°C.
  - Hot test temperature: 32°C.
- Lim, Han, *Study of Exhaust Emissions from Idling Heavy-Duty Diesel Trucks and Commercially Available Idle-Reducing Devices*, EPA420-R-02-025, nine vehicles, 2002.
  - Cold test temperature: -17.8°C.
  - Hot test temperature: 32.2°C.

Figure 37 and Figure 38 show the NO<sub>x</sub> and PM results of these studies. The results for other pollutants are in Appendix E. The following is a summary of the observations based on these comparisons:

- Idling NO<sub>x</sub> emissions are generally in the same range as the previous studies, i.e., older model years. This indicates that the NO<sub>x</sub> emissions control technologies deployed on the newer model years, such as EGR, do not perform well under idling conditions.
- Idling PM emissions show a dramatic drop for post-2007 diesel trucks indicating the effectiveness of PM control devices in reducing idling PM emissions.
- Idling CO<sub>2</sub> and CO emissions show the same trend as NO<sub>x</sub>, i.e., in the same general range as older vehicles and other studies.
- Idling THC emissions for post-2007 truck show a slight reduction compared to the older trucks. This is potentially a side benefit of PM control technologies on the newer vehicles.



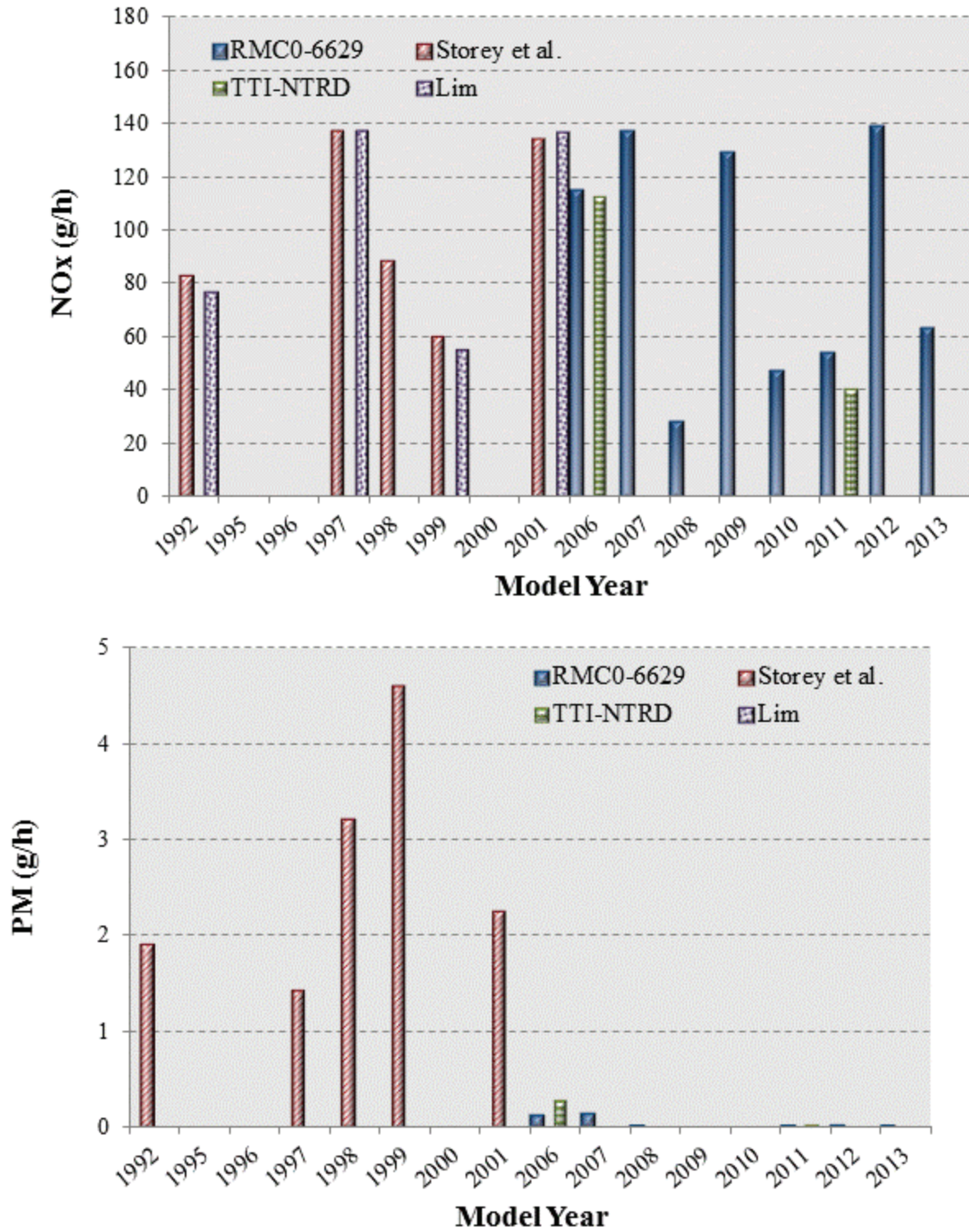
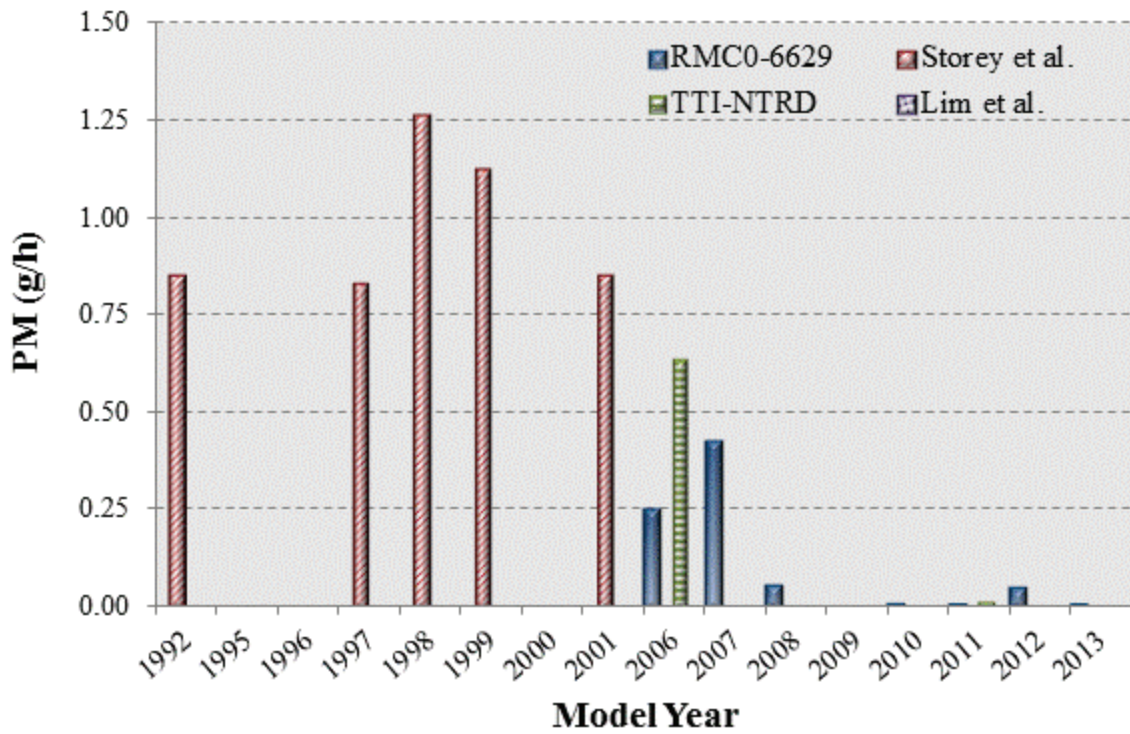
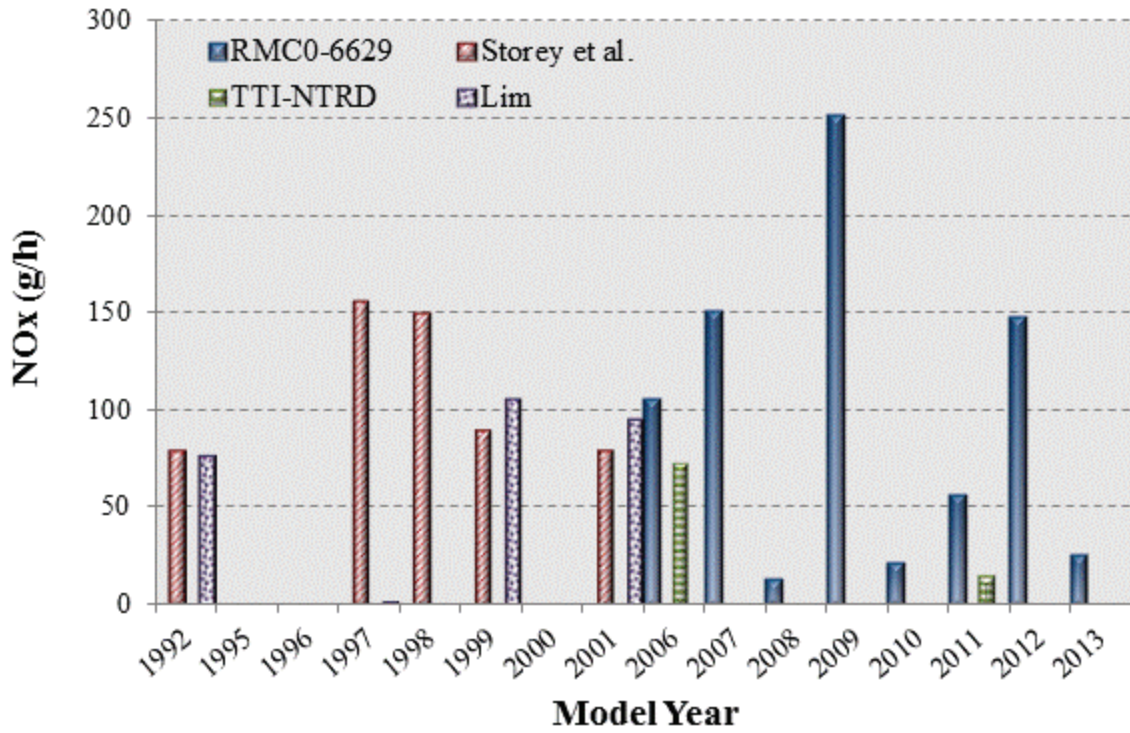


Figure 37. Comparison of Idling Emissions Rates with Other Studies–Cold Test.



**Figure 38. Comparison of Idling Emissions Rates with Other Studies–Hot Test.**

## **CHAPTER 7: COMPARE MOVES RESULTS WITH IN-USE RESULTS**

This chapter compares the real-world emissions data with estimated emissions rates from MOVES for different classes of vehicles. Real-world emissions data from a sample of vehicle types were used for this task. These data include the HDDVs emissions data (vehicle type 62) discussed in the previous chapter. Emissions data for passenger cars (vehicle type 21) and passenger trucks (vehicle type 31) were obtained from a previous TTI study (55).

Researchers compared the results of observed in-use emissions and MOVES estimates in two ways:

- Drive cycle (aggregate) for light duty vehicles.
- Operating mode comparison (disaggregate) for HDDVs.

In the aggregate level comparison, the observed driving schedules (second-by-second speed profile) of test vehicles were input to MOVES for the same ambient conditions. The total emissions associated with the period of the drive schedule were estimated by the model. These results were then transformed into average distance-based emission rates (g/mi) for different pollutants. The researchers compared these estimates to the corresponding distance-based emissions obtained from field observations.

The VSP/speed points approach consisted of a more disaggregate level of analysis. In this approach, observed data from a series of operating mode bins were compared to MOVES emissions rates estimates for those bins. The following three operating modes from HDDVs tested in Task 7 were included in this comparison:

- Extended idling under hot conditions.
- Extended idling under cold conditions.
- Cold start under cold conditions.

The MOVES model was used to estimate emissions rates associated with those operating modes for the same ambient conditions. These estimated emissions rates were then compared to average operating mode bins' emissions data from PEMS measurements. [Figure 39](#) graphically shows the comparison methodology for both cases.

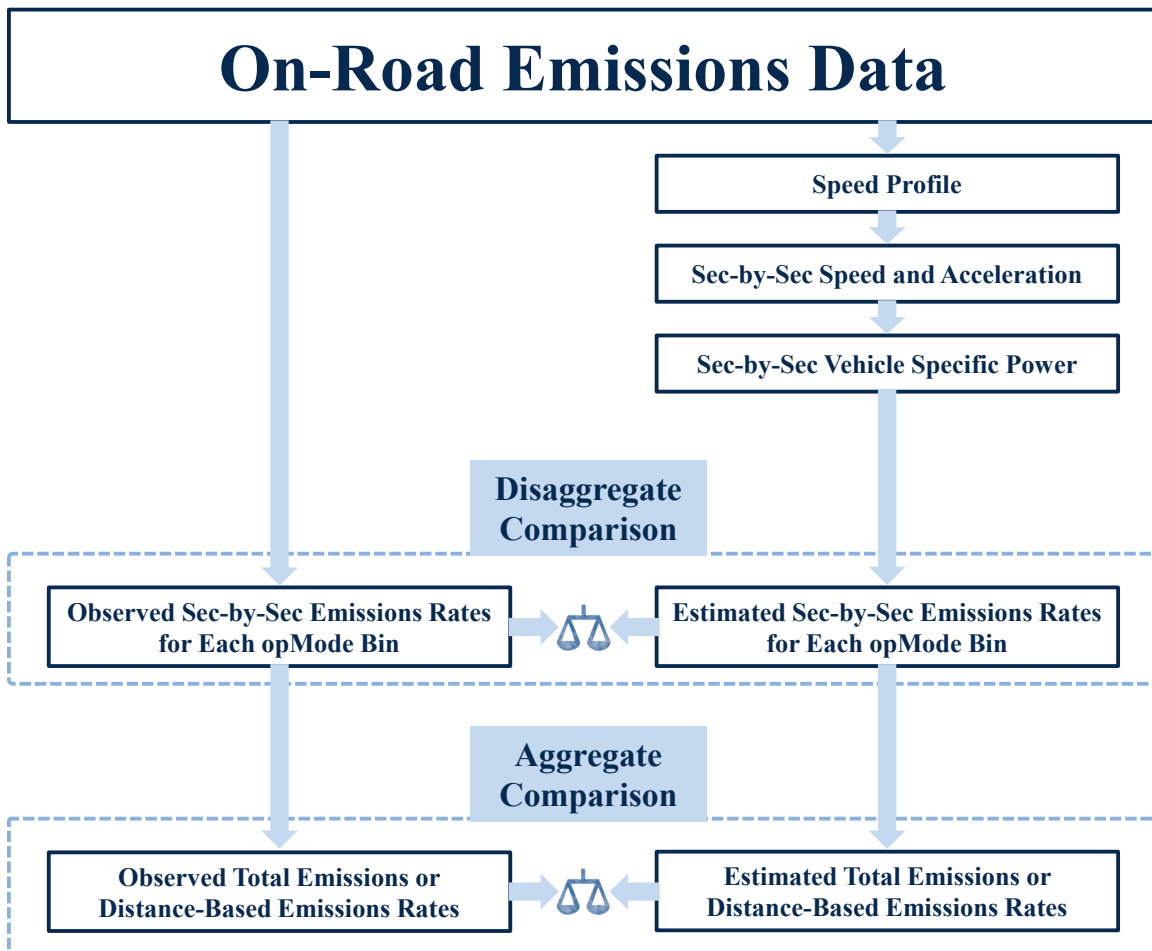


Figure 39. Comparison Methodology.

## OPERATING MODE COMPARISON—HDDV

Table 26 shows the specifications of the vehicles included in this comparison. More details on these vehicles are provided in Chapter 6.

**Table 26. Heavy-Duty Test Vehicle Specifications.**

Vehicle Type	Make	Model	MY	Displacement
62	Freightliner	Colombia	2006	15.2 L
62	International	94001 SBA 6 × 4	2007	15 L
62	International	Prostar	2008	15 L
62	Peterbilt	N/A*	2008	11 L
62	Mack	CHU 613	2009	12.8 L
62	Mack	CHU 613	2010	12.8 L
62	International	Prostar+ 122 6 × 4	2011	12.4 L
62	Navistar	8600 SBA 6 × 4	2011	12.4 L
62	International	ProStar+ 122 6 × 4	2011	12.4 L
62	Mack	CHU 613	2011	12.8 L
62	Mack	CHU 613	2012	12.8 L
62	Volvo	N/A*	2012	12.13
62	Mack	CXU 613	2013	12.8 L
62	Mack	CXU 613	2013	12.8 L
62	Mack	CXU 613	2013	12.8 L

\* N/A—Certain specifications of some vehicles were not available.

The emissions data for these vehicles were discussed in [Chapter 6](#). Since MOVES produces emissions rates for different model years, the observed emission rates were aggregated to model year level to be consistent with MOVES. The data set includes eight sets representing different temperatures, soak times, and idling states. The following three subsets were selected for this comparison effort:

- Extended Idling—Hot Conditions: this set represents idling on a summer day in Houston at a temperature of 100°F and relative humidity of 70 percent.
- Extended Idling—Cold Conditions: this set represents idling on a winter day in north Texas at a temperature of 30°F.
- Cold Start—Cold Conditions: this set represents idling with cold start emissions included at a temperature of 30°F.

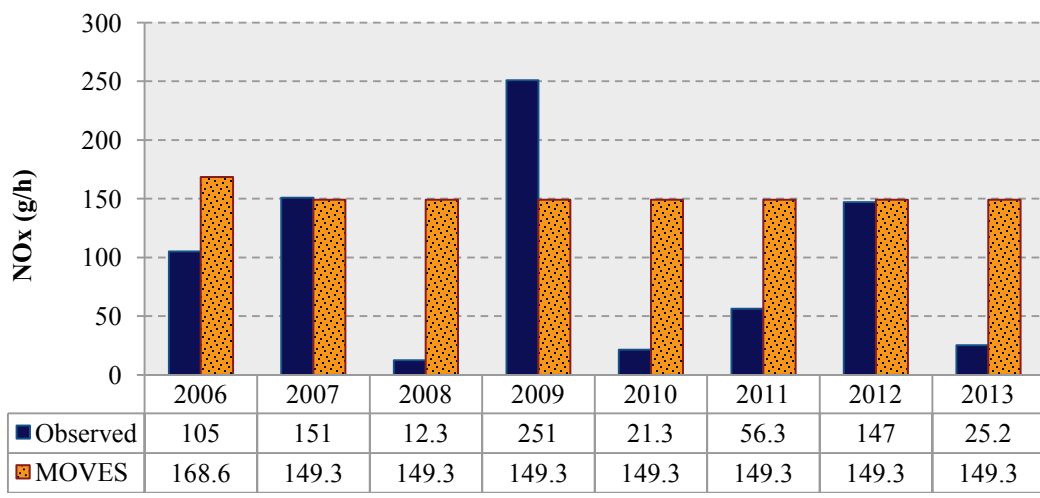
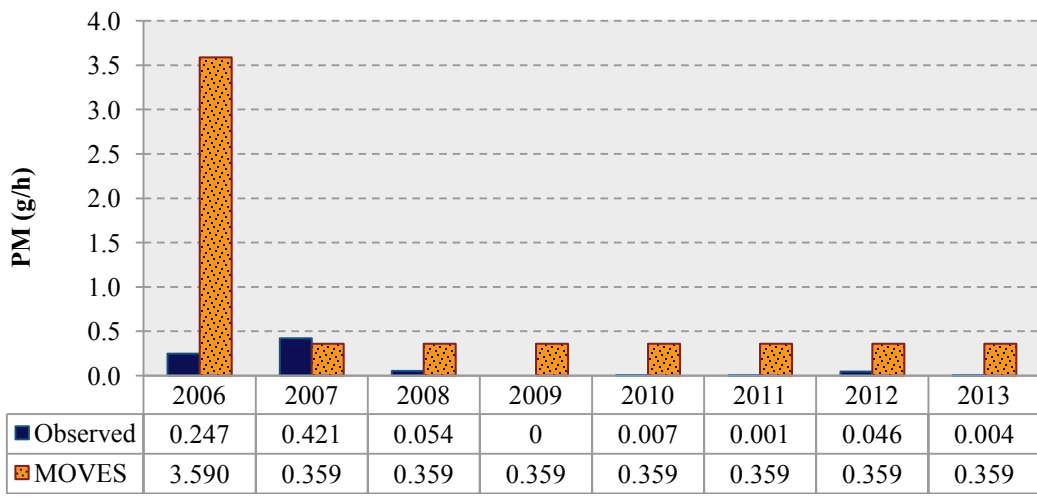
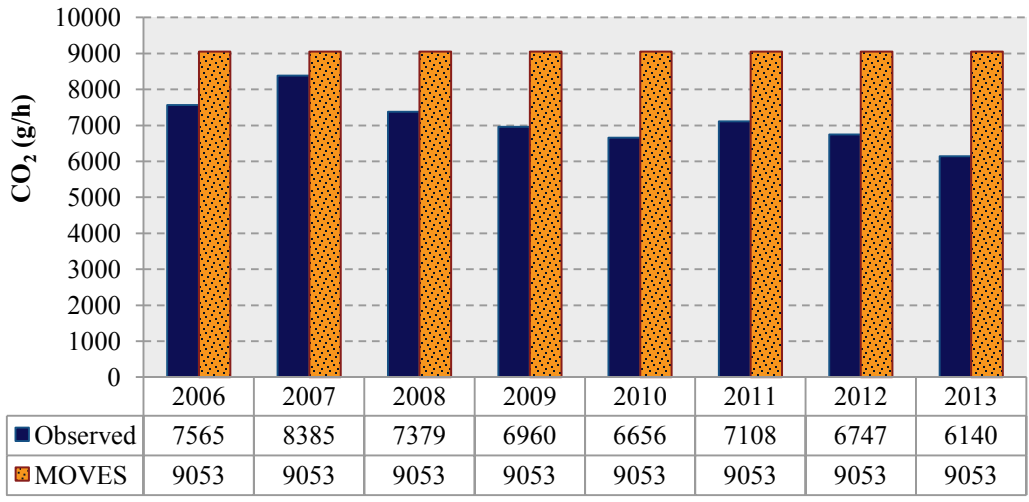
The details of data analysis and results are discussed in [Chapter 6](#). All the observations are converted to grams per hour format to be consistent across the testing conditions.

The research team used the input values representing the observations conditions to extract MOVES emission rates for extended idling (operating mode 200) and cold start (operating mode 101). The input variables used in this effort included location, operating mode

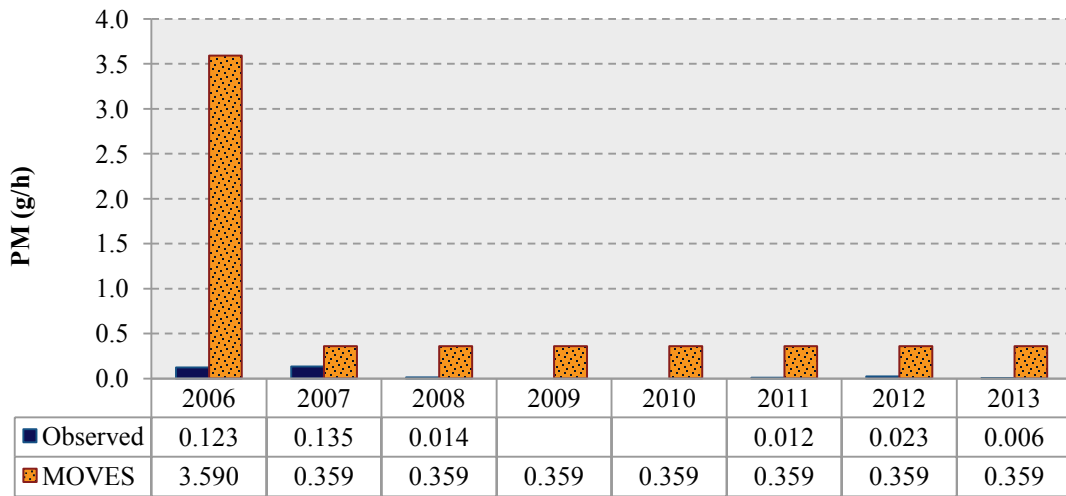
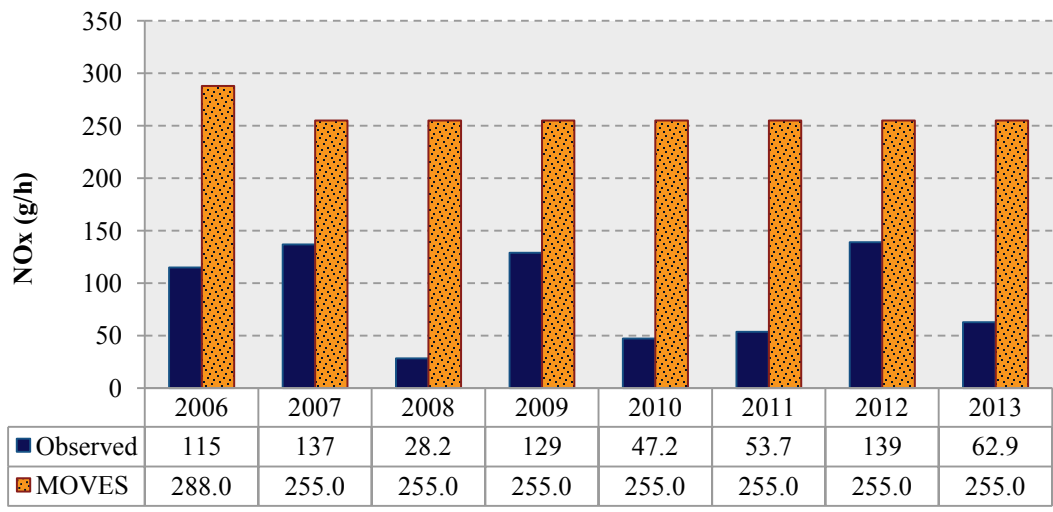
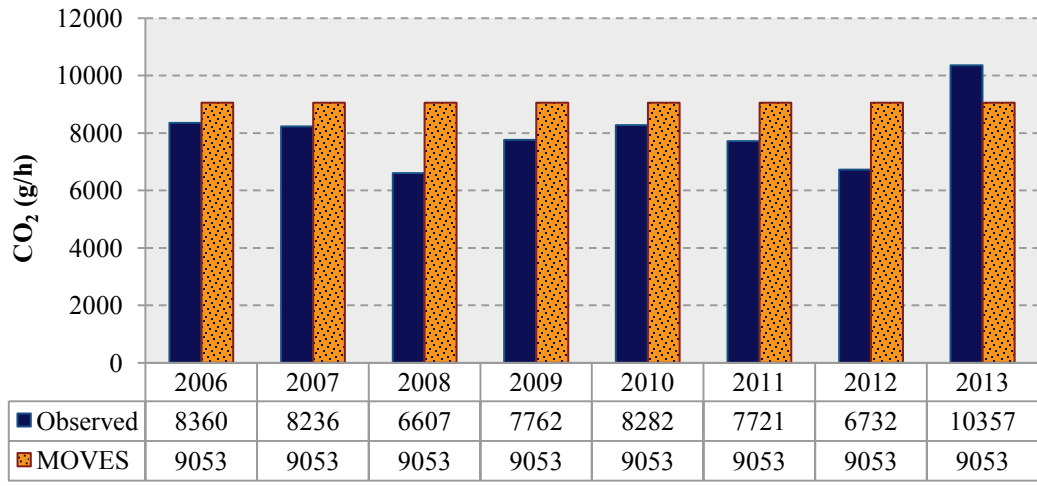
distribution, temperature, and relative humidity. A generic ultra-low-sulfur diesel (ULSD) was assumed for this effort. Since the data collection was performed during 2012 and 2013, the analysis year of 2013 was used to extract emission rates from MOVES.

The results were assembled and grouped based on model years. Researchers developed graphs and data tables to compare these against the observations. [Figure 40](#) through [Figure 42](#) show the results of this comparison for CO<sub>2</sub>, NO<sub>x</sub>, and PM, which are the most important pollutants from a diesel engine. The results for the other pollutants are shown in [Appendix F](#).

The results show that MOVES' estimates for all the scenarios are generally within the range of CO<sub>2</sub>, although consistently higher than the observations. NO<sub>x</sub> and CO estimates from MOVES are generally higher than observations by a factor of 2 or more. The observed PM, THC formaldehyde, and acetaldehyde emissions are consistently lower than MOVES estimates by a large margin. However, both set of results indicate a significant reduction of PM for vehicles newer than 2007, which represents the implantation of the new PM standards for on-road diesel engines.

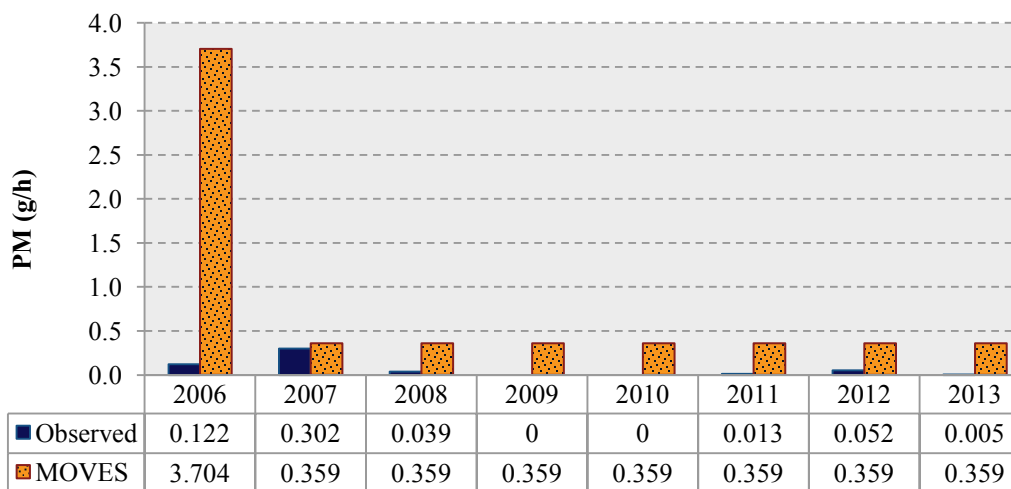
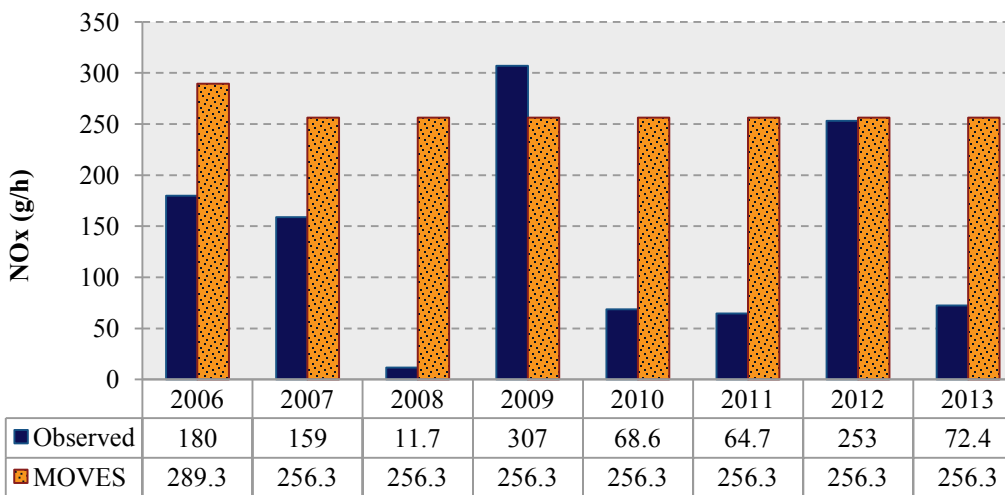
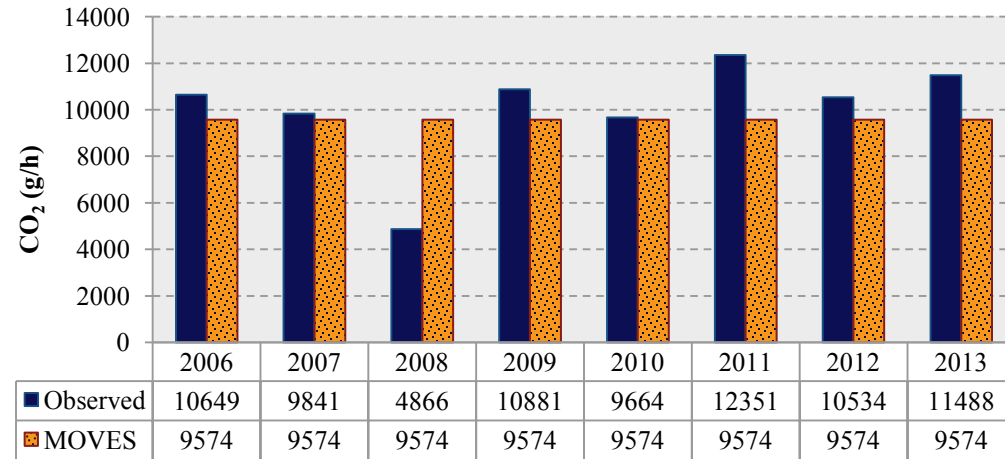


**Figure 40. Extended Idling Emissions Rates from MOVES and Observations: Vehicle Type 62, Hot Testing.**



**Figure 41. Extended Idling Emissions Rates from MOVES and Observations: Vehicle Type 62, Cold Testing.**





**Figure 42. Cold Start Idling Emissions Rates from MOVES and Observations: Vehicle Type 62, Cold Testing.**

## DRIVE CYCLE COMPARISON–LDGV

Table 27 shows the specifications of the two vehicles included in this comparison. These vehicles were recruited and tested in El Paso for a 2009 TTI study (55).

**Table 27. Light-Duty Test Vehicle Specifications.**

<b>Make and Model</b>	<b>Model Year</b>	<b>Engine Size (L)</b>	<b>GVWR (lb)</b>	<b>MOVES Vehicle Type</b>
Nissan Sentra	1996	1.6	3413	Passenger Car–Type 21
Ford F-150	2000	4.2	6000	Passenger Truck–Type 31

The study focused on the El Paso–Ciudad Juárez border area. Five light-duty vehicles representing common makes and models were tested with PEMS units for emissions behavior. PEMS collected second-by-second emissions of nitrogen oxide (NO<sub>x</sub>), hydrocarbons (HC), carbon monoxide (CO), PM, and carbon dioxide (CO<sub>2</sub>). The collected emissions data were analyzed according to the operating modal bin concept implemented in the Environmental Protection Agency’s MOVES model.

The research team developed and implemented a data collection and data analysis methodology based on the EPA’s MOVES model’s analysis framework. The methodology is based on the concept of second-by-second modal emissions rates based on vehicle specific power. Driving patterns were developed to cover a broad range of vehicle operations. Each vehicle tested repeated the same drive cycle for a minimum of five repetitions for each test. Exhaust flow meters were installed on the tailpipes of the vehicles with diluted samples sent to PEMS units located in the back seats or trailer beds of the vehicles. Ambient monitoring was also installed to an outside portion of a vehicle.

Second-by-second emissions data were carefully aligned with the instantaneous speed obtained from the GPS. A linear smoothing was applied to speed and grade data to cancel out noise and fine-scale changes due to GPS accuracy limitations and other factors. For purposes of the current study, three trips were separated from the data set of two of the test vehicles; each trip consisted of multiple runs of different driving conditions such as low and high accelerations, cruising, and creep idling. Table 28 summarizes each vehicle’s trips used in this effort.

The research team used input values representing the testing conditions to extract MOVES emission rates for the selected trips. Input variables used in this effort included:

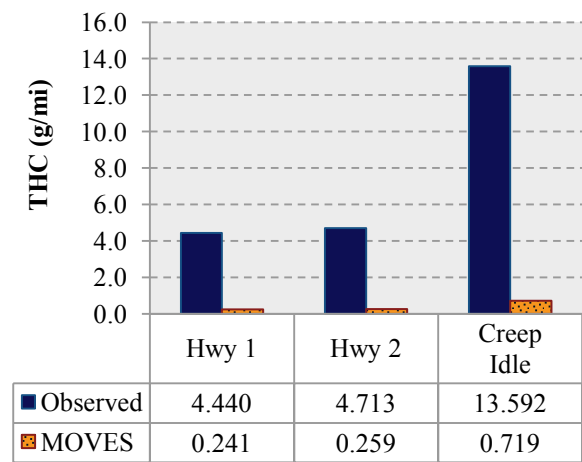
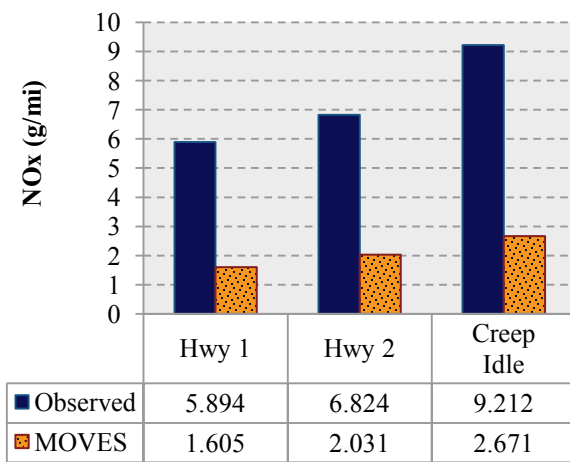
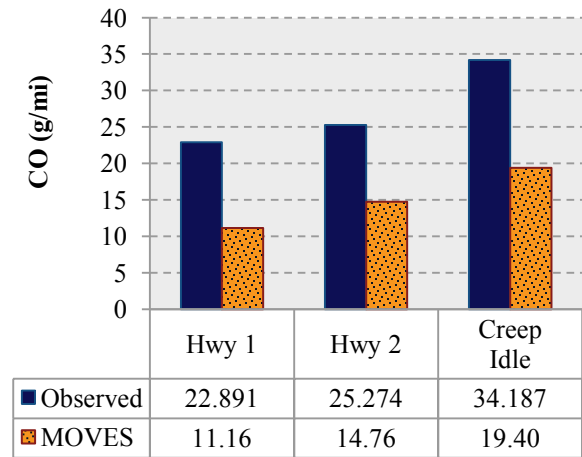
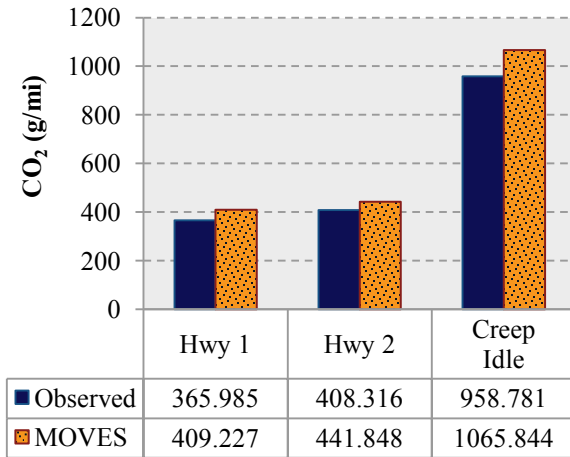
- Location.
- Second-by-second speed profile of the trips.
- Temperature and relative humidity.
- Local fuel.

The researchers used the analysis year of 2009 to extract emission rates from MOVES. The results are assembled and grouped for each vehicle. Graphs and data tables were developed to compare these against the observations.

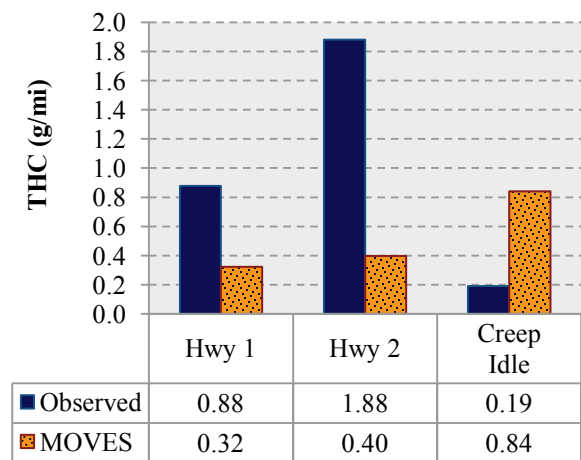
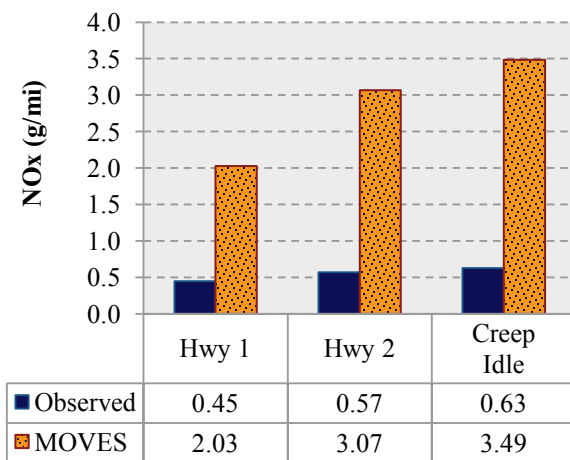
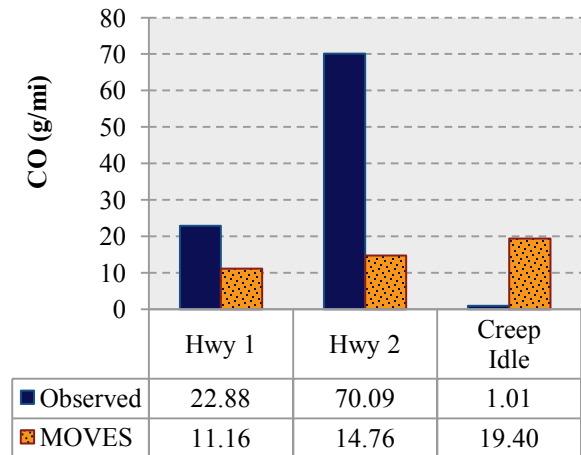
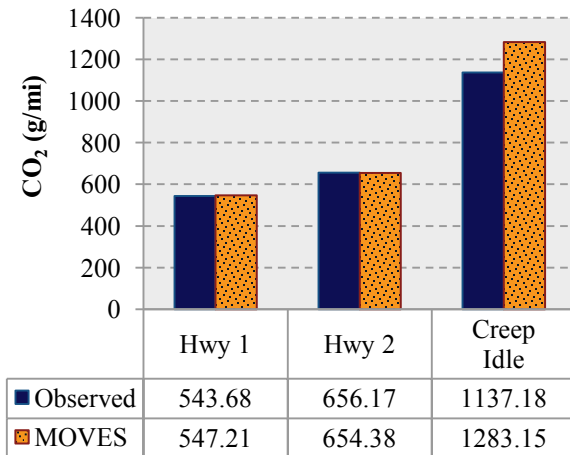
**Table 28. Characteristics of the Trips Used in the Comparison.**

		<b>Length (mi)</b>	<b>Average Speed (mph)</b>	<b>Max Speed (mph)</b>	<b>% Idling</b>
<b>1996 Nissan Sentra</b>	<b>Highway 1</b>	12.7	27.95	60.4	20.2
	<b>Highway 2</b>	13.63	27.81	65.5	25.5
	<b>Creep Idle</b>	1.9	5.64	41.1	33.2
<b>2000 Ford F150</b>	<b>Highway 1</b>	17.52	32.79	65.3	13.9
	<b>Highway 2</b>	9.99	32.95	71.8	22.9
	<b>Creep Idle</b>	2.52	6.28	48.7	39.6

Figure 43 and Figure 44 show that CO<sub>2</sub> results for both vehicles are generally consistent with the observations. The NO<sub>x</sub>, CO, and THC observations for the 1996 Nissan Sentra are all significantly higher than MOVES estimates, usually an indication of the failure of both catalysts of a three-way catalytic converter; oxidation catalyst for THC and CO, and reduction catalyst for NO<sub>x</sub>. The observations for the 2000 Ford F-150 show that the vehicle emitted significantly more THC and CO emissions than what MOVES had estimated for the highway trip. On the other hand, the observations for both pollutants were quite lower than MOVES estimates for the creep idle trip. This is usually an indication of a malfunction of the oxidation catalyst. The NO<sub>x</sub> estimates from MOVES were four to six times higher than the observed values.



**Figure 43. Running Emission Rates from MOVES and Observations:  
1996 Nissan Sentra Vehicle Type 21, Cold Testing.**



**Figure 44. Running Emission Rates from MOVES and Observations:  
2000 Ford F-150 Type 31.**



## **CHAPTER 8: INTEGRATION OF RESULTS INTO MOVES**

This chapter investigates the issues relevant to incorporating the results of this study into MOVES-based emissions analysis for different purposes. The focus is on local drive schedules and cold start and idling emissions of HDDVs. The chapter covers both technical (methodology) and tactical (legitimacy, acceptability, and formal approval) aspects of such integration.

It is the responsibility of the users to obtain and input local data into MOVES for an accurate analysis. Although EPA has provided guidance on this process for the majority of the factors; currently there are no clear guidelines on how to collect, develop, and integrate drive schedules and local emissions test data into an emissions analysis. The issues surrounding such integration of local data can be divided into two broad categories:

- Technical: concerning the technical methodologies of incorporating local drive schedules and emissions data into a MOVES-based analysis (e.g., how to include new drive schedules and emissions rates).
- Tactical: concerning the relevant formal and legal processes to ensure that the resulting emissions estimates are legitimate and acceptable for formal analysis purposes such as SIP and conformity analyses.

This chapter covers both aspects by presenting a thorough review and examination of the model's technical documentation and policy-related guidelines as well as information obtained through the research team's professional contacts with relevant EPA staff.

### **DRIVE SCHEDULES AND TARGET OPERATING MODE DISTRIBUTIONS**

The primary role of MOVES, and the application of primary interest to TxDOT, is to support conformity demonstration. Therefore, it is important to identify the suitable procedures of officially incorporating the findings of this study into the conformity analysis.

Transportation conformity is a Clean Air Act requirement that ensures that federally supported highway and transit projects are consistent with state air quality implementation plans. Conformity helps protect public health through early consideration of the air quality impacts of transportation decisions in places where air quality does not currently meet federal standards or has not met them in the past.

Many actions can trigger the need for a conformity determination, such as project changes in the MPO Transportation Improvement Program, the MPO Metropolitan Transportation Plan, the Statewide Transportation Improvement Program, the National Ambient Air Quality Standard for various pollutants, and similar items. Title 40 CFR Part 93 describes transportation conformity requirements and the conditions under which a Metropolitan Planning Organization must have a conformity determination completed. Part 51.390 of Title 40 CFR requires the Texas Commission on Environmental Quality to publish procedures for interagency consultation. Those procedures are published in TAC Title 30 Rule 114.260. Title 40 CFR 93.105 also provides guidance for the consultation process.

The term Consultative Partners is used during the transportation conformity process to refer to representatives of EPA Region VI, FHWA/Federal Transit Authority, TCEQ, and TxDOT. Note that this is only a portion of the agencies listed in TAC Title 30, Part 1, 114.260(d)(1)(A). A major portion of the Transportation Conformity is the Interagency Consultation process. In general, this process is an ongoing, almost daily, process. The consultative partners must agree on specific actions or decisions.

The research team consulted the EPA staff with regard to the tactical requirements for implementation of the local drive schedules in an official capacity, most importantly the transportation conformity determination. They found that the EPA currently does not have a routine approach for reviewing and accepting local drive schedules in conformity determination analysis. The EPA staff advised working through the consultative partners to get approval for such drive schedules. The regional EPA representative will consult appropriate EPA staff on technical review of the local drive schedules.

The researchers also investigated the technical steps required for implementing the developed local drive schedule in a regional analysis. The following summarize the possible approaches.

### **Modifying MOVES' Default Database**

Currently there is no formal guidance from EPA on replacements for drive schedules in the MOVES model's default database. In an FHWA-sponsored study, ERG in consultation with EPA staff developed an approach to achieve this task (56). The main advantage of this approach is that the user can use both Inventory and Rates calculation modes. However, the alteration of



the MOVES database in this way will affect all future modeling runs. The following is a summary of their approach.

Drive schedules information in the MOVES default database are stored in three data tables: *driveschedule*, *drivescheduleassoc*, and *driveschedulesecond*. Since these tables are interconnected, it is necessary to completely replace the existing drive schedules for a specific vehicle. This is done by removing selected drive schedules from the default database, and importing the new drive schedule data using completely new *drivescheduleIDs*.

After populating updated tables containing new local drive schedules, it is necessary to then replace each of the existing MOVES default drive schedule tables and perform additional modeling. MySQL Administrator program, which is typically included in a normal MOVES installation, can be used to make a SQL backup of the three default tables for drive schedule information. This will ensure that there is a backup of the affected tables and the user is able to easily switch back to the default MOVES drive cycles for future modeling. Note that alteration of drive schedule tables in this way will affect all future modeling runs and therefore it is crucial to back up the default drive schedules so these can be easily restored. ERG developed a series of SQL scripts for loading the updated drive cycle tables and making a backup of data tables.

### **Extracting Emission Rates from Project Level Analysis**

Alternatively, users can choose to extract emission rates using the project-level analysis in emission rates mode. The main advantage of this approach is that the user does not have to alter the MOVES' default database and it is easy to implement; specifically for users who already have a rate-based post processing process in place.

Under the project-level analysis, users need to prepare and load different data tables including vehicle activity information. There are two options for loading vehicle activity data into MOVES:

- Drive schedules for second-by-second speed profiles.
- Operating mode (opMode) distribution.

Two sets of results were developed in this study:

- A target set, which is the opMode distribution of all the observations for a specific average speed.
- A cycle set, which is the second-by-second representative speed profiles for a specific speed.

The research team recommends using the target set whenever possible because it is based on all the available data.

To extract the emission rates in the project-level analysis mode, users should assign each drive schedule or opMode distribution to a single link. Assigning opMode distributions to links is done in *OpMode Distribution* table and requires time fraction values of each operating mode bin for each pollutant process.

The research team prepared the developed drive schedules and target opMode distributions in an Excel database format. To facilitate the implementation of the results, Visual Basic scripts are used to generate the required data tables for the project level inputs inside the excel database.

## **COLD START AND IDLING EMISSIONS DATA**

Currently there is no formal guidance from EPA on replacement for emissions rates in the MOVES model's default database. The research team consulted the EPA staff on the implementation of the collected extended idling and cold start emission rates. The EPA staff advised working through the consultative partners to submit the collected data to the agency. The regional EPA representative will submit the emissions data to appropriate EPA staff for technical review and considerations for inclusion in future versions of the MOVES model. Users can also use the collected emission rates in an off-model analysis. Similar to any off-model analysis, consultative partners need to review and approve the findings and calculations.

## **CHAPTER 9: CONCLUSIONS**

This project developed Texas-specific drive schedules to be used with the MOVES model, characterized the idling and cold start emissions of heavy-duty vehicles, and compared their emissions with MOVES' rates. The project is divided into two phases that were executed in parallel.

- Phase 1 dealt with the data collection and development of local drive cycles for different regions of Texas.
- Phase 2 addressed the cold start and idling emissions of HDDVs.

Following a literature review and state of practice assessment, the research team developed a data collection protocol for each of the phases of the study.

In Phase 1 of the project, developing the drive schedule, the research team recruited a total of 83 light-duty, 50 medium-duty, and 112 heavy duty vehicles, with the medium- and heavy-duty vehicles recruited from private and public fleets, for GPS data collection. A 30-vehicle-day data collection for medium-duty vehicles, and 650 miles of data for electric vehicles supplemented this initial collection. These vehicles were recruited from five major urban areas of Texas: Austin, Dallas–Fort Worth, El Paso, Houston, and San Antonio. Engine data for two vehicles were collected for verification and quality control. A total of 15 heavy-duty vehicles have been recruited and tested for the emissions testing phase of the project (Phase 2). These vehicles were obtained through daily or weekly lease from truck leasing companies.

The main GPS data collection effort consisted of recruiting individual and fleet vehicles to record their normal activity during an extended period of time. After assembling a pool of potential candidates, the participants each reviewed and signed a consent form, then provided information about the vehicle make, model, year, fuel type, number of cylinders, and engine size. Three GPS data loggers were installed on each vehicle; this helped ensure accuracy in case that one unit malfunctioned or provided erroneous data. Typically, the devices were set in the driver-side storage compartment to ensure that the vibration detector started recording whenever the vehicle door was opened, which was usually at the beginning of a trip. Participants returned the data loggers after approximately two weeks when the power supply for the unit was expected to be completely drained.

The data obtained from the GPS units were processed and analyzed following a 4-step process. The process starts with a series of quality control checks on the raw data, followed by merging data from the three units into one data set. A second round of quality control checks was performed on this consolidated data set. Micro-trips were extracted from this data set using a set of criteria specifically developed for this purpose. These micro-trips were grouped according to their average speed. For each average speed group, an ideal solution (i.e., the target operating mode distribution) and a cycle solution (i.e., a drive schedule representing the ideal opMode distribution in the form of a drive cycle) were developed.

The major findings of the drive schedule data collection and development are:

- The use of three GPS units proved to be effective in ensuring the highest quality of data and minimizing the data losses.
- Using a motion-activated GPS system made the relatively prolonged data collection possible. Because the GPS units were battery-powered, no connections to the vehicle were necessary, which made installation a quick and easy process for the participants.
- Accurate logging of data collection activities is a crucial part in ensuring the quality of data in a large-scale data collection. The research team maintained a detailed log of activities throughout the study. All data collection and processing activities used this log table to assign appropriate data labels.
- The research team considers the ideal solution for an average speed bin to be the operating mode distribution based on all the micro-trips of that bin. While these operating mode distributions cannot be internally implemented in the current version of MOVES, emission rates for these can be calculated using the project-level option in the model. These emission rates can then be used in a post-processing manner for inventory calculations.
- A representative drive schedule was developed for each average speed bin. The research team forged a modified methodology based on what was used to develop default drive schedules for MOVES. Instead of using speed and acceleration, this modified methodology uses the operating mode bin distribution as the target parameter for developing the drive schedules.

- The research team performed a simplistic comparison of emission rates obtained from the developed opMode distributions and drive schedules with those from MOVES default drive schedules. The results show that the largest differences between the MOVES defaults rates and those based on this study's results are for low and high speeds, i.e., speeds lower than 10 mph and higher than 40 mph.

To provide TxDOT with an understanding of the characteristics and impacts of idling emissions, TTI researchers performed idling emissions testing using 15 recent model year HDDVs (from MY 2006 to MY 2013). These trucks were tested in TTI's EERF under controlled test conditions. PM filters and MSAT cartridge samples and continuous mass monitoring were taken in addition to PEMS emission measurements. The following lists the different test conditions (hot at 100°F with 70 percent relative humidity and cold at 30°F), different soak time, and engine speeds used in this study:

- Cold-start–normal idle after over 12 hours of soak time.
- 5-min. soak–normal idle after 5-min. soak time.
- 15-min. soak–normal idle after 15-min. soak time.
- 5-min. soak high–high idle (with engine speed of the range of 1000–1100 RPM) after 5-min. soak time.
- 15-min. soak high–high idle after 15-min. soak time.
- Stabilized–normal idle with no soak time (i.e., continuous idle).

The following is a summary of the task findings:

- TTI researchers performed statistical analyses (t-test) to determine if there are any statistical idling emission difference between the HDDVs meeting the most recent emissions standards (2010 standard for NO<sub>x</sub> and 2007 standard for PM) and all of other HDDVs complying with previous standards. The t-test results showed that, at the 95 percent confidence level, no statistically significant differences were observed for both NO<sub>x</sub> and PM for any test conditions for any soak time and engine speeds.
- With comparisons to the Stabilized emissions, TTI researchers observed the following trends:
  - Cold-start emissions were higher than or similar to the Stabilized emissions, except those of HCHO for hot tests and of CO for cold tests.

- 5-min. soak emissions were similar to the Stabilized emissions, except those of PM for hot tests and of HC.
- 15-min. soak emissions were similar to the Stabilized emissions, except those of PM for hot tests and of HC and PM for cold tests.
- 5-min. and 15-min. soak high emissions were higher than the Stabilized emissions for all but that of NO<sub>x</sub>, which were similar to the Stabilized for hot tests.
- Different trucks with different engine and emissions control strategies, such as Cold Ambient Protection, showed differing emissions characteristics. Additional studies collecting more information, such as temperature at emissions control devices and CAP parameters, would explain the different emissions characteristics. Cold-start emissions are usually higher than restart emissions for intervening soak times of up to 59 minutes.
- One finding of the study is that trucks with California ARB clean idling stickers<sup>8</sup> do not always meet the 30 g/h NO<sub>x</sub> emissions threshold during the idling under real-world conditions. Among 15 trucks tested, nine trucks were CA clean idle certified:
  - Four out of nine trucks produced more than 30g/h of NO<sub>x</sub> emissions (up to 78.5 g/h) during the (Stabilized) hot tests.
  - Five out of nine trucks produced up to 106.2 g/h during the (Stabilized) cold tests.
  - Three trucks produced NO<sub>x</sub> emissions of over 30 g/h for both hot and cold tests.
- The research team believes that the difference was due to varying test conditions and methodologies between the certification testing (i.e., engine dynamometer testing at room temperature) and the testing of this study (truck testing with different test conditions and different loads).
- A comparison was made between the data of this study and other studies with similar testing conditions within an environmental chamber. Only PM idling emissions show a significant decrease for the newer model years, i.e., post-2007 trucks. Other pollutants' emissions were generally in the same range as the other studies and older model years; indicating that the emissions control technologies currently used to reduce NO<sub>x</sub> from diesel trucks are not as effective in idling conditions.

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<sup>8</sup> Idling NO<sub>x</sub> emissions from these vehicles are certified to be equal or less than 30 g/h.

The research team also compared the emission rates from the MOVES model and a sample of real-world observations. The comparison included an operating mode bin approach (disaggregate) and a drive cycle-based approach (aggregate). The real-world observations used in this effort included a subset of the heavy-duty diesel idling and cold-start emissions data collected in Task 7 and data collected from a couple of light-duty gasoline vehicles in a previous TTI study. To extract the comparable emissions rates from MOVES, the research team used input values that were representative of the testing conditions for each set of data. The following are the findings of this exercise:

- MOVES CO<sub>2</sub> results were generally consistent with observations for both comparison approaches. The results for other pollutant showed a great variability. The greatest discrepancies belonged to the PM, THC formaldehyde, and acetaldehyde emissions for HDDVs, which were consistently lower than MOVES estimates by a large margin.
- Some of the discrepancies for LDGVs are potentially the result of the failure of one or both catalysts of the vehicles' catalytic converter.

The research team investigated the tactical and technical aspect of implementing the developed drive schedules and emission rated into a MOVES-based analysis. The investigation included a review of MOVES technical documentation and other relevant documents, and consulting with the EPA staff. The findings of this task are:

- The EPA currently does not have a routine approach for reviewing and accepting local drive schedules into MOVES-based regional analyses. The EPA staff advised working through the consultative partners to get approval for local drive schedules.
- Similarly, the EPA staff recommended working with the consultative partners for using extended idling and cold-start emission rates in an off-model analysis as well as submitting the data for inclusion in the future releases of the MOVES model.
- To implement local drive schedules into a MOVES-based analysis, users can either replace MOVES' default drive schedules or use project-level analysis mode to extract emission rates.

The results from this project provide TxDOT, TCEQ, and metropolitan planning agencies of Texas with local vehicle activity profiles, i.e., opMode distributions and drive schedules. These vehicle activity profiles are developed based on locally collected GPS data and thus represent the average driving behavior for their region. The main purpose for their development is to use these with the EPA MOVES model for regional-level air quality analyses such as conformity analysis. This study also provided idling and cold start emissions rates for HDDVs under conditions representing Texas' summer and winter. These rates can be used for off-model analyses and future updates of MOVES.

The following are the research team's recommendations for future investigation regarding local vehicle activity profiles and emissions rates:

- The vehicle activity profiles of this study cover the general vehicle activity types: highway and non-highway driving. There is the potential to use the GPS data collected in this study to develop vehicle activity profiles for specific activities such as ramps and near intersections driving.
- The GPS data can also be used for project-level analyses such as PM and CO hot spot analyses, specifically for projects involving intersections.
- The use of idling and cold start emission rates based on Texas-specific conditions rather than rates based on extrapolations would provide more accurate estimates for emission rates from a local perspective.



## APPENDIX A: PARTICIPANT INFORMATION

### CONSENT FORM

#### **Introduction**

The purpose of this form is to provide you information that may affect your decision as to whether or not to participate in this research study. If you decide to participate in this study, this form will also be used to record your consent.

You have been asked to participate in a research project studying travel behaviors in your region and how emissions predicted from this behavior compare to actual emissions measured in a region. The purpose of this study is to gather the necessary real-world speed data for various vehicle types to run the modeling software. You were selected to be a possible participant because you responded to a posted recruitment notice. This study is being sponsored/funded by the Texas Department of Transportation (TxDOT).

#### **What will I be asked to do?**

If you agree to participate in this study, you will be asked to carry a set of GPS units in your vehicle for seven to thirty (7 to 30) days to identify the type of roads you travel on, collecting speed and location data while you travel as you normally would during that time.

#### **What are the risks involved in this study?**

The risks associated with this study are that researchers will be able to determine the destinations of your daily travel activity during data collection. Other risks associated in this study are minimal, and are not greater than risks ordinarily encountered in daily life.

#### **What are the possible benefits of this study?**

You will receive no direct benefit from participating in this study; however, your participation will provide TxDOT the data needed to assess the accuracy of air quality predictions provided by the Environmental Protection Agency's MOVES emissions model.

#### **Do I have to participate?**

No. Your participation is voluntary. You may decide not to participate or to withdraw at any time without your current or future relations with the Texas Transportation Institute, The Texas A&M University System, or the Texas Department of Transportation being affected.

#### **Will I be compensated?**

The following groups are not eligible for compensation:

- Employees and their family members of the research organization: Texas Transportation Institute (TTI); and
- Employees and their family members of beneficiary agencies including TxDOT, TCEQ, NCTCOG, ACOG, City of Houston, City of Austin, HGAC.

Eligible participants will receive seventy five dollars (\$75) in cash for participating in the study. Disbursement will occur when you return the GPS unit to the researchers and after researchers validate the data at the end of the study period. In the event of data failure or errors, you might be asked to continue your participation for another round of data collection with another set of data loggers.

**Who will know about my participation in this research study?**

This study is confidential, and all location data gathered will be stored as encrypted data files. Data files will be labeled in such a way that individual file names cannot be linked back to specific participants. The records of this study will be kept private. No identifiers linking you to this study will be included in any sort of report that might be published. Research records will be stored securely and only the research team will have access to the records.

**Whom do I contact with questions about the research?**

If you have questions regarding this study, you may contact Mohamadreza Farzaneh, 512-467-0946, mfarzaneh@tamu.edu.

**Whom do I contact about my rights as a research participant?**

This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979)458-4067 or [irb@tamu.edu](mailto:irb@tamu.edu).

**Signature**

Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

**Signature of Participant:** \_\_\_\_\_ **Date:** \_\_\_\_\_

**Printed Name:** \_\_\_\_\_

**Signature of Person Obtaining Consent:** \_\_\_\_\_ **Date:** \_\_\_\_\_

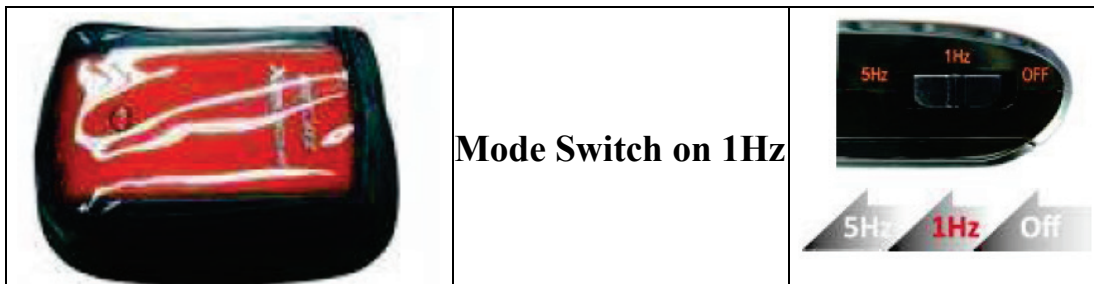
**Printed Name:** \_\_\_\_\_

## INSTALLATION INSTRUCTIONS FOR GPS UNITS

- 1) You must have received three GPS units that are tied together. If you have not received three (3) units, immediately contact TTI researchers at (512) 467-0946 or mfarzaneh@tamu.edu.



- 2) Turn on the GPS units by pushing the mode switch located on the side of the unit to the right. Put the mode switch on **1Hz** (middle position). The 5Hz option (leftmost position) is blocked on all units.



- 3) Confirm that ***ALL*** the units are functioning – both a blue symbol and an orange symbol should light up. The orange symbol will blink when receiving information from the GPS satellite system. The units will beep when they first acquire GPS location data from the system.

- 4) Place the active GPS unit in the driver-side door storage compartment of your vehicle, taking care to place it in such a way that it will not become buried under other items in the compartment.



If your vehicle does not have a door storage compartment, place the units in the glove box or a secure place inside the cabin of the vehicle. The units should be placed in a way that does not pose any danger to the driver; e.g., block the driver's view, etc.

- 5) Leave units in the "ON – 1Hz" position and in the secure location until the end of the research experiment period.
- 6) Upon completion of the research experiment, remove the GPS units from your vehicle, turn off the unit, and return the unit to the researcher in the pre-addressed box that was provided with the unit.

**Return Address:**

Texas Transportation Institute  
Center for Air Quality Studies  
1106 Clayton Lane, Suite 300E  
Austin, TX 78723  
(512) 467-0946

## **APPENDIX B: SAMPLE LETTER TO FLEET MANAGERS**

Dear [Name of Contact]:

The Texas Transportation Institute (TTI), a State-based research institution affiliated with the Texas A&M University System, is currently working with the Texas Department of Transportation to conduct air quality research using vehicle speed and acceleration profiles.

TTI is currently asking businesses for permission to place GPS data loggers in their vehicle fleets for a period of two weeks to collect second-by-second speed data. We specifically need vehicles that have daily travel in the Dallas/Fort Worth, Houston, San Antonio, Austin, and El Paso regions. The devices are self-powered, small, easily securable, and do not require any interaction from the driver or any connection to the vehicle. We are looking to do a minimum of [X] vehicles per fleet, with a potential to do more if you grant us permission. Placement inside each vehicle should take less than a minute. All that we need is a staff representative to let us onto your lot before and after the two-week period to position and remove the devices. Location data is confidential and will not be used to identify, in detail, where the drivers have been. We can give you the raw data for free at your request.

It would be great if you would help us with our research. Feel free to contact me if you have any questions or if you would like to volunteer.

Thanks,

[TTI Researcher in Charge of Recruiting Vehicles]



## APPENDIX C: DATA PROCESSING PROCEDURES

**Table C.1. Procedures Used in Quality Control of GPS Data.**

- 
1. Create a NEW\_SPEED variable that:
    - a. Checks each record to see if the SPEED variable is less than 0.2. If SPEED is less than 0.2, then record a value of 0.0 for the NEW\_SPEED variable in the same record.
    - b. Convert SPEED from a base unit of kilometers per hour (kph) to miles per hour (mph).

**In summary:**

IF(SPEED < 0.02, NEW\_SPEED = 0, NEW\_SPEED = SPEED \* 0.621371192)

---

2. Create a TIME\_CHECK variable that:
  - a. Indicates whether the difference in LOCAL\_TIME between consecutive records in a dataset is one second. YES = one second difference. NO = greater than a one second difference.
  - b. Note: The process will truncate the first second (or record) of any trip because there is either no speed (at the beginning of the dataset) or the beginning of a new series of movements from the vehicle.

**In summary:**

LOCAL\_TIME\_α = Value of LOCAL\_TIME for preceding record, listed directly before

LOCAL\_TIME\_β = Value of LOCAL\_TIME for current record

IF(LOCAL\_TIME\_β – LOCAL\_TIME\_α > 1 second, TIME\_CHECK = “NO”, TIME\_CHECK = “YES”)

---

3. Create an ACCEL\_CHECK variable:
  - c. Similar to the process with TIME\_CHECK, but checking different variables using a different threshold.
  - d. NEW\_SPEED from the preceding record will be checked.
  - e. The threshold is the absolute value of 15 mph/sec.

**In summary:**

NEW\_SPEED\_α = Value of NEW\_SPEED from preceding record

NEW\_SPEED\_β = Value of NEW\_SPEED from current record

IF(ABS(NEW\_SPEED\_α – NEW\_SPEED\_β) > 14, ACCEL\_CHECK = “NO”, ACCEL\_CHECK = “YES”)

---

4. Create a HEAD\_CHECK variable:
  - f. Similar to TIME\_CHECK and ACCEL\_CHECK.
  - g. HEADING will be checked from the preceding record.
  - h. The threshold is 30 degrees.

**In summary:**

HEADING\_α = Value of HEADING from preceding record

HEADING\_β = Value of HEADING from current record

IF(ABS(HEADING\_α – HEADING\_β) > 30, HEAD\_CHECK = “NO”, HEAD\_CHECK = “YES”)

---

**Table C.2. Procedures Used in Merging Data from 3 GPS Units.**

- 
1. Create a series of CHECK\_SPEED variables in the new merged spreadsheet.
    - a. Compare the differences with NEW\_SPEED for every record with the same LOCAL\_TIME and LOCAL\_DATE across all the three spreadsheets within the same Excel file.
    - b. Make a series of IF statements to test the validity of each of the three data loggers.
    - c. A resulting value of 1 indicates the NEW\_SPEED value to be true, 0 is false.

**In summary:**

Create CHECK\_SPEED\_A; CHECK\_SPEED\_B; and CHECK\_SPEED\_C

NEW\_SPEED\_A = NEW\_SPEED from Data Logger A

NEW\_SPEED\_B = NEW\_SPEED from Data Logger B

NEW\_SPEED\_C = NEW\_SPEED from Data Logger C

CHECK\_SPEED\_A = IF(ABS(NEW\_SPEED\_A – NEW\_SPEED\_B) > 2 AND ABS(NEW\_SPEED\_A – NEW\_SPEED\_C) > 2, CHECK\_SPEED\_A = 0, CHECK\_SPEED\_A = 1)

CHECK\_SPEED\_B = IF(ABS(NEW\_SPEED\_B – NEW\_SPEED\_C) > 2 AND ABS(NEW\_SPEED\_B – NEW\_SPEED\_A) > 2, CHECK\_SPEED\_B = 0, CHECK\_SPEED\_B = 1)

CHECK\_SPEED\_C = IF(ABS(NEW\_SPEED\_C – NEW\_SPEED\_A) > 2 AND ABS(NEW\_SPEED\_C – NEW\_SPEED\_B) > 2, CHECK\_SPEED\_C = 0, CHECK\_SPEED\_C = 1)

---

2. Create a SUM\_CHECK\_SPEED variable.
  - a. This variable will be used in a later step to assess every record by LOCAL\_DATE and LOCAL\_TIME against a pre-established threshold.
  - b. Sum the CHECK\_SPEED\_A; CHECK\_SPEED\_B; and CHECK\_SPEED\_C variables.

**In summary:**

SUM\_CHECK\_SPEED = SUM(CHECK\_SPEED\_A; CHECK\_SPEED\_B; CHECK\_SPEED\_C)

---

3. Create a MOD\_AVG\_SPEED variable.
  - a. This variable will average the speeds that are deemed to be valid for every record with the same LOCAL\_DATE and LOCAL\_TIME within a single Excel file.
  - b. The threshold will be set as SUM\_CHECK\_SPEED = 2; or a date and time with at least two recorded speeds that are valid.

**In summary:**

MOD\_AVG\_SPEED = X

if SUM\_CHECK\_SPEED = 3

then X = AVG(CHECK\_SPEED\_A; CHECK\_SPEED\_B; CHECK\_SPEED\_C)

else

if SUM\_CHECK\_SPEED = 2 & CHECK\_SPEED\_A = 1 & CHECK\_SPEED\_B = 1

then X = AVG(CHECK\_SPEED\_A; CHECK\_SPEED\_B)

else

if SUM\_CHECK\_SPEED = 2 & CHECK\_SPEED\_B = 1 & CHECK\_SPEED\_C = 1

then X = AVG(CHECK\_SPEED\_B; CHECK\_SPEED\_C)

else

if SUM\_CHECK\_SPEED = 2 & CHECK\_SPEED\_A = 1 & CHECK\_SPEED\_C = 1

then X = AVG(CHECK\_SPEED\_A; CHECK\_SPEED\_C)

else X = "NO"

---



- 
4. Create a new spreadsheet that averages key variables from the three separate datasets. One record will be shown, as averaged, for every date and time of observation.
    - a. Do not include records with the same date and time if they meet the following conditions:
      - i. TIME\_CHECK = NO
      - ii. ACCEL\_CHECK = NO
      - iii. HEAD\_CHECK = NO
      - iv. MOD\_AVG\_SPEED = NO
    - b. The following variables should be seen in the merged dataset:
      - i. UNIT\_NO
      - ii. LOC\_INSTALL
      - iii. VEH\_CODE
      - iv. LOCAL\_DATE
      - v. LOCAL\_TIME
      - vi. LONGITUDE
      - vii. LATITUDE
      - viii. MOD\_AVG\_SPEED
-

**Table C.3. Procedures Used in Quality Control of Merged Data.**

- 
1. Create a TIME\_CHECK\_2 variable in the new dataset that will check the consecutiveness of recorded times with the averaged dataset.
    - a. Similar to the previous TIME\_CHECK variable.
    - b. If the difference in LOCAL\_TIME from the preceding record is one, then TIME\_CHECK\_2 = "YES", if not then TIME\_CHECK\_2 = "NO".

**In summary:**

LOCAL\_TIME\_α = Value of LOCAL\_TIME for preceding record, listed directly before  
 LOCAL\_TIME\_β = Value of LOCAL\_TIME for current record

IF(LOCAL\_TIME\_β – LOCAL\_TIME\_α > 1 second, TIME\_CHECK\_2 = "NO",  
 TIME\_CHECK\_2 = "YES")

---

2. Create an ACCEL\_CHECK\_2 variable in the new dataset that will check the validity of speed between continuous records in the averaged dataset.
  - a. Similar to the previous ACCEL\_CHECK variable.
  - b. If the difference in MOD\_AVG\_SPEED from the preceding record is less than the absolute value of 15, then ACCEL\_CHECK\_2 = "YES", else ACCEL\_CHECK\_2 = "NO".

**In summary:**

MOD\_AVG\_SPEED\_α = Value of MOD\_AVG\_SPEED from preceding record  
 MOD\_AVG\_SPEED\_β = Value of MOD\_AVG\_SPEED from current record

IF(ABS(MOD\_AVG\_SPEED\_α – MOD\_AVG\_SPEED\_β) > 15, ACCEL\_CHECK\_2  
 = "NO", ACCEL\_CHECK\_2 = "YES")

---

3. Create another new dataset that accounts for this iteration of quality control measures.
    - a. Do not include records if they meet the following conditions:
      - i. TIME\_CHECK\_2 = NO
      - ii. ACCEL\_CHECK\_2 = NO
    - b. The following variables should be seen in the new dataset:
      - i. UNIT\_NO
      - ii. LOC\_INSTALL
      - iii. VEH\_CODE
      - iv. LOCAL\_DATE
      - v. LOCAL\_TIME
      - vi. LONGITUDE
      - vii. LATITUDE
      - viii. MOD\_AVG\_SPEED
-

**Table C.4. Procedures Used to Determine Location, Area Type, and Road Type.**

- 
1. Create a ROAD\_TYPE variable that identifies whether the nearest road is either a highway or non-highway type of facility.
    - a. Batch process all of the x and x coordinates, preform a near function to find the nearest line (highway or road) for each point (recorded observation). Record the ROAD\_TYPE for every point.
    - b. For Highway Travel: ROAD\_TYPE = HIGHWAY.
    - c. For Non-Highway Travel: ROAD\_TYPE = NON\_HIGHWAY.

---

  2. Create a LOC\_TYPE to identify the location of each valid second of observation.
    - a. Create polygons within ArcGIS to identify the five metro areas (AUS, DFW, SAN, HOU, and ELP) as defined by counties in the formal MPO definition.
      - i. Urban areas within the MPO counties will be given a special polygon and noted as URBAN\_MPO.
      - ii. All the space outside the urban area, but within the counties of the MPO, will be defined as RURAL\_MPO.
      - iii. Anything outside the counties of the MPO will be defined as OUTSIDE and will not be primarily used in the study.
    - b. Batch process a point-to-polygon feature within ArcGIS that will identify where each point fits within the three values. Fill LOC\_TYPE with either URBAN\_MPO, RURAL\_MPO, or OUTSIDE.

---

  3. Create a LOC\_METRO to define the location of observations based on the five major metro areas in Texas.
    - a. Use the shapefile of polygons that are bounded by the formal MPO definition for AUS, DFW, ELP, HOU, and SAN.
    - b. Batch process a point-to-polygon function to return the LOC\_METRO value for points that fall within a designated polygon.
    - c. All other points that are located outside of the polygon will have LOC\_METRO = OUTSIDE.
-

**Table C.5. Procedures Used to Extract Micro-Trips.**

- 
1. Create a TRIP\_INDEX variable.
    - a. Starting at the beginning of each dataset, number the records that fall consecutive to each other in time. For example, records that are continuous as labeled under TRIP\_INDEX with LOCAL\_TIME values of 8:31:34 to 8:45:23 (with no gaps) will have the same value for TRIP\_INDEX = 3. Whereas, the next series of records starting at 9:11:07 will have TRIP\_INDEX = 4.
- 
2. Create a VALID\_TRIP variable.
    - a. Count the number of identical TRIP\_INDEX values.
    - b. If the count for any unique TRIP\_INDEX value is less than 150, assign a value of “NO” to the VALID\_TRIP variable, else assign a VALID\_TRIP = “YES” for any count greater than 150.
- 
3. Create a new dataset that does not include trips that are too short for analysis.
    - a. Do not include records if they meet the following conditions:
      - i. VALID\_TRIP = NO
    - b. The following variables should be seen in the new spreadsheet:
      - i. UNIT\_NO
      - ii. LOC\_INSTALL
      - iii. VEH\_CODE
      - iv. LOCAL\_DATE
      - v. LOCAL\_TIME
      - vi. LONGITUDE
      - vii. LATITUDE
      - viii. MOD\_AVG\_SPEED
      - ix. ROAD\_TYPE
      - x. LOC\_TYPE
      - xi. LOC\_METRO
      - xii. TRIP\_INDEX
- 
4. Create and add a TRIP\_ID variable to the dataset that concatenates key variables together in a string of characters.
    - a. The variables included in the concatenation are:
      - i. LOC\_METRO
      - ii. VEH\_CODE
      - iii. ROAD\_TYPE
      - iv. TRIP\_INDEX
    - b. An example of TRIP\_ID: AUS\_HD\_HIGHWAY\_341.
-

## APPENDIX D: SUMMARY OF THE DEVELOPED SOLUTIONS

**Table D.1. Developed Drive Schedules for Heavy-Duty Vehicles–Austin Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Austin	Urban	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0272	0.2943
			10	✓	✓	0.0303	0.0706
			15	✓	✓	0.0320	0.1219
			20	✓	✓	0.0250	0.1405
			25	✓	✓	0.0179	0.0684
			30	✓	✓	0.0302	0.0894
			40	✓	✓	0.0482	0.2544
			50	✓	✓	0.0451	0.2363
			60	✓	✓	0.0350	0.8108
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0492	0.0719
			20	✓	✓	0.0437	0.2557
			30	✓	✓	0.0356	0.1376
			40	✓	✓	0.0255	0.2328
			50	✓	✓	0.0278	0.2128
			60	✓	✓	0.0142	0.7966
70	✓	✓	0.0223	0.4214			

**Table D.2. Developed Drive Schedules for Heavy-Duty Vehicles–Dallas Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Dallas	Urban	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0239	0.2042
			10	✓	✓	0.0582	0.1180
			15	✓	✓	0.0312	0.2163
			20	✓	✓	0.0292	0.1865
			25	✓	✓	0.0320	0.0910
			30	✓	✓	0.0334	0.1015
			40	✓	✓	0.0485	0.2346
			50	✓	✓	0.0488	0.2297
			60	✓	✓	0.0392	0.6960
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0512	0.1668
			20	✓	✓	0.0487	0.2541
			30	✓	✓	0.0448	0.1153
			40	✓	✓	0.0396	0.2217
			50	✓	✓	0.0229	0.1669
			60	✓	✓	0.0144	0.6429
70	✓	✓	0.0191	0.3582			

**Table D.3. Developed Drive Schedules for Heavy-Duty Vehicles–El Paso Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
El Paso	Urban	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0213	0.2070
			10	✓	✓	0.0352	0.0706
			15	✓	✓	0.0232	0.1457
			20	✓	✓	0.0305	0.1793
			25	✓	✓	0.0179	0.0801
			30	✓	✓	0.0508	0.1232
			40	✓	✓	0.0532	0.2639
			50	✓	✓	0.0297	0.2295
			60	✓	✓	0.0537	0.6813
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0457	0.1025
			20	✓	✓	0.0510	0.2046
			30	✓	✓	0.0466	0.1113
			40	✓	✓	0.0329	0.2467
			50	✓	✓	0.0401	0.2008
			60	✓	✓	0.0198	0.6446
70	✓	✓	0.0156	0.2991			

**Table D.4. Developed Drive Schedules for Heavy-Duty Vehicles–Houston Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Houston	Urban	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0072	0.2906
			10	✓	✓	0.0286	0.0645
			15	✓	✓	0.0407	0.1518
			20	✓	✓	0.0283	0.1663
			25	✓	✓	0.0288	0.0768
			30	✓	✓	0.0335	0.1025
			40	✓	✓	0.374	0.3048
			50	✓	✓	0.0560	0.2873
			60	✓	✓	0.0259	0.8509
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0630	0.0738
			20	✓	✓	0.0550	0.1821
			30	✓	✓	0.0533	0.1179
			40	✓	✓	0.0444	0.2060
			50	✓	✓	0.0214	0.2143
			60	✓	✓	0.0108	0.7665
70	✓	✓	0.0119	0.5463			



**Table D.5. Developed Drive Schedules for Heavy-Duty Vehicles–San Antonio Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
San Antonio	Urban	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0197	0.3174
			10	✓	✓	0.0320	0.0688
			15	✓	✓	0.0211	0.1636
			20	✓	✓	0.0193	0.1895
			25	✓	✓	0.0337	0.0974
			30	✓	✓	0.0260	0.0873
			40	✓	✓	0.0336	0.2590
			50	✓	✓	0.0470	0.2770
			60	✓	✓	0.0284	0.8643
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0477	0.1281
			20	✓	✓	0.0560	0.1836
			30	✓	✓	0.0547	0.1361
			40	✓	✓	0.0382	0.2350
			50	✓	✓	0.0323	0.2288
			60	✓	✓	0.0101	0.8219
			70	✓	✓	0.0262	0.6112

**Table D.6. Developed Drive Schedules for Heavy-Duty Vehicles–Rural.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Texas Statewide	Rural	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0303	0.2555
			10	✓	✓	0.0433	0.0917
			15	✓	✓	0.0489	0.1838
			20	✓	✓	0.0454	0.1805
			25	✓	✓	0.0452	0.0809
			30	✓	✓	0.0384	0.0898
			40	✓	✓	0.0177	0.2760
			50	✓	✓	0.0308	0.2375
		60	✓	✓	0.0191	0.7712	
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0293	0.2201
			20	✓	✓	0.0624	0.2149
			30	✓	✓	0.0447	0.1219
			40	✓	✓	0.0578	0.2211
			50	✓	✓	0.0245	0.2034
60	✓		✓	0.0119	0.7257		
70	✓	✓	0.0193	0.3266			

**Table D.7. Developed Drive Schedules for Medium-Duty Vehicles-Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Texas Statewide	Urban	Arterial/Local/Non-Highway	0	✓	✓	0.0106	0.2173
			5	✓	✓	0.0078	0.0574
			10	✓	✓	0.0222	0.1030
			15	✓	✓	0.0299	0.1276
			20	✓	✓	0.0437	0.0714
			25	✓	✓	0.0234	0.0745
			30	✓	✓	0.0522	0.1687
			40	✓	✓	0.0590	0.3401
			50	✓	✓	0.0450	0.2903
		60	✓	✓	0.0547	0.2182	
		Freeway/Highway	0	✓	✓	0.0471	0.0773
			10	✓	✓	0.0350	0.2552
			20	✓	✓	0.0499	0.2049
			30	✓	✓	0.0461	0.1991
			40	✓	✓	0.0583	0.2889
			50	✓	✓	0.0252	0.2419
60	✓		✓	0.0214	0.0285		
70	✓	✓	0.0318	0.0893			

**Table D.8. Developed Drive Schedules for Medium-Duty Vehicles-Rural.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Texas Statewide	Rural	Arterial/Local/Non-Highway	0	✓	✓	0.0316	0.2445
			5	✓	✓	0.0373	0.0485
			10	✓	✓	0.0443	0.1588
			15	✓	✓	0.0566	0.2483
			20	✓	✓	0.0487	0.1021
			25	✓	✓	0.0515	0.0966
			30	✓	✓	0.0552	0.0900
			40	✓	✓	0.0565	0.3111
			50	✓	✓	0.0585	0.3821
		60	✓	✓	0.0393	0.2200	
		Freeway/Highway	0	✓	✓	0.1015	0.2823
			10	✓	✓	0.0620	0.1666
			20	✓	✓	0.0448	0.1740
			30	✓	✓	0.0275	0.2648
			40	✓	✓	0.0193	0.3229
			50	✓	✓	0.0406	0.2422
60	✓		✓	0.0215	0.0444		
70	✓	✓	0.0050	0.1312			

**Table D.9. Developed Drive Schedules for Light-Duty Vehicles–Rural.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Texas Statewide	Rural	Arterial/Local/Non-Highway	0	✓	✓	0.0120	0.1170
			5	✓	✓	0.0230	0.1720
			10	✓	✓	0.0415	0.3910
			15	✓	✓	0.0398	0.1976
			20	✓	✓	0.0388	0.1445
			25	✓	✓	0.0358	0.1227
			30	✓	✓	0.0354	0.0544
			40	✓	✓	0.0382	0.1802
			50	✓	✓	0.0311	0.1081
		60	✓	✓	0.0243	0.0623	
		Freeway/Highway	0	✓	✓	0.0410	0.1450
			10	✓	✓	0.0500	0.2664
			20	✓	✓	0.0461	0.1182
			30	✓	✓	0.0600	0.1763
			40	✓	✓	0.0431	0.2833
			50	✓	✓	0.0333	0.1935
60	✓		✓	0.0202	0.1181		
70	✓	✓	0.0117	0.1846			

**Table D.10. Developed Drive Schedules for Light-Duty Vehicles–Austin Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Austin	Urban	Arterial/Local/Non-Highway	0	N/A	N/A	N/A	N/A
			5	✓	✓	0.0230	0.0920
			10	✓	✓	0.0381	0.2449
			15	✓	✓	0.0382	0.1052
			20	✓	✓	0.0171	0.2091
			25	✓	✓	0.0451	0.1032
			30	✓	✓	0.0321	0.0664
			40	✓	✓	0.0511	0.2000
			50	✓	✓	0.0312	0.0841
			60	✓	✓	0.0391	0.0583
		Freeway/Highway	0	N/A	N/A	N/A	N/A
			10	✓	✓	0.0401	0.2712
			20	✓	✓	0.0331	0.1402
			30	✓	✓	0.0441	0.0703
			40	✓	✓	0.0462	0.1663
			50	✓	✓	0.0272	0.0813
			60	✓	✓	0.0192	0.0893
70	✓	✓	0.0251	0.1081			

**Table D.11. Developed Drive Schedules for Light-Duty Vehicles–Dallas Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Dallas	Urban	Arterial/Local/Non-Highway	0	✓	✓	0.0490	0.0612
			5	✓	✓	0.0487	0.1452
			10	✓	✓	0.0249	0.2431
			15	✓	✓	0.0297	0.1147
			20	✓	✓	0.0274	0.2139
			25	✓	✓	0.0380	0.0972
			30	✓	✓	0.0312	0.0650
			40	✓	✓	0.0376	0.2513
			50	✓	N/A	N/A	0.1858
		60	✓	N/A	N/A	0.1516	
		Freeway/Highway	0	✓	N/A	N/A	0.1986
			10	✓	✓	0.0741	0.2181
			20	✓	✓	0.0371	0.1812
			30	✓	✓	0.0390	0.0633
			40	✓	✓	0.0570	0.2055
			50	✓	✓	0.0365	0.1274
			60	✓	✓	0.0201	0.0981
70	✓		✓	0.0176	0.0396		

**Table D.12. Developed Drive Schedules for Light-Duty Vehicles–El Paso Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
El Paso	Urban	Arterial/Local/Non-Highway	0	✓	✓	0.0171	0.0442
			5	✓	✓	0.0230	0.1760
			10	✓	✓	0.0292	0.2612
			15	✓	✓	0.0241	0.0811
			20	✓	✓	0.0282	0.2142
			25	✓	✓	0.0301	0.0751
			30	✓	✓	0.0192	0.0592
			40	✓	✓	0.0322	0.2271
			50	✓	N/A	N/A	0.0760
			60	✓	N/A	N/A	0.1452
		Freeway/Highway	0	✓	✓	0.0410	0.0410
			10	✓	✓	0.0400	0.3681
			20	✓	✓	0.0442	0.1320
			30	✓	✓	0.0412	0.0662
			40	✓	✓	0.0312	0.1523
			50	✓	✓	0.0281	0.1043
			60	✓	✓	0.0210	0.1361
			70	✓	✓	0.0140	0.0544



**Table D.13. Developed Drive Schedules for Light-Duty Vehicles–Houston Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
Houston	Urban	Arterial/Local/Non-Highway	0	✓	✓	0.0336	0.1634
			5	✓	✓	0.0517	0.1883
			10	✓	✓	0.0459	0.2735
			15	✓	✓	0.0380	0.0880
			20	✓	✓	0.0398	0.2180
			25	✓	✓	0.0413	0.0990
			30	✓	✓	0.0420	0.0676
			40	✓	✓	0.0604	0.2237
			50	✓	✓	0.0537	0.1448
			60	✓	✓	0.0000	0.1391
		Freeway/Highway	0	✓	✓	0.0343	0.1696
			10	✓	✓	0.0585	0.3583
			20	✓	✓	0.0546	0.1458
			30	✓	✓	0.0425	0.1291
			40	✓	✓	0.0358	0.2711
			50	✓	✓	0.0270	0.1822
60	✓	✓	0.0379	0.1822			
70	✓	✓	0.0177	0.1637			

**Table D.14. Developed Drive Schedules for Light-Duty Vehicles–San Antonio Urban.**

<i>Area</i>	<i>Area Types</i>	<i>Road Types</i>	<i>Average Speed Bin (mph)</i>	<i>Target</i>	<i>Cycle</i>	<i>T-C</i>	<i>T-M</i>
San Antonio	Urban	Arterial/Local/Non-Highway	0	✓	✓	0.0420	0.0750
			5	✓	✓	0.0233	0.1522
			10	✓	✓	0.0533	0.2921
			15	✓	✓	0.0421	0.0782
			20	✓	✓	0.0352	0.2174
			25	✓	✓	0.0401	0.1103
			30	✓	✓	0.0342	0.0672
			40	✓	✓	0.0492	0.2061
			50	✓	✓	0.0730	0.0840
			60	✓	✓	0.0000	0.1863
		Freeway/Highway	0	✓	✓	0.0492	0.0831
			10	✓	✓	0.0282	0.5023
			20	✓	✓	0.0262	0.1234
			30	✓	✓	0.0452	0.1503
			40	✓	✓	0.0560	0.2524
			50	✓	✓	0.0411	0.1777
			60	✓	✓	0.0292	0.1001
70	✓	✓	0.0200	0.1744			

## APPENDIX E: AVERAGE EMISSIONS RATES BY MODEL YEAR

**Table E.1. Stabilized MY Idling Emissions Results.**

MY	Average Idling Emissions Rates (g/h or µg/h <sup>†</sup> )													
	Hot Test							Cold Test						
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO
2006	7565	52.1	105	13.9	0.247	100	82.7	8360	51.8	115	10.5	0.123	0.54	0.18
2007	8385	31.7	151	13.0	0.421	0.59	0.21	8236	47.2	137	8.57	0.135	282	305
2008	7379	48.9	12.3	9.79	0.054	217	197	6607	39.7	28.2	6.19	0.014	0.23	11.6
2009	6960	57.6	251	N/A*	0.000	8.5	46.1	7762	155	129	N/A*	0.000	327	44.8
2010	6656	35.0	21.3	N/A*	0.007	18.7	0.23	8282	56.5	47.2	2.02	0.000	0	0
2011	7108	23.5	56.3	5.36	0.001	20.4	77.1	7721	25.6	53.7	3.42	0.012	36.9	57.0
2012	6747	54.1	147	10.2	0.046	185	130	6732	80.9	139	9.98	0.023	74.1	285
2013	6140	36.6	25.2	1.83	0.004	-**	-**	10357	41.4	62.9	1.11	0.006	-**	-**

<sup>†</sup> Emission rates for HCHO and CH<sub>3</sub>CHO are shown as µg/h while all other pollutants are shown as g/h.

\* N/A: Not available due to malfunctioning of the HC measurement instrument.

\*\* Data are not available yet, but will be available on the final report.

**Table E.2. Cold-Start MY Idling Emissions Results.**

MY	Average Idling Emissions Rates (g/h or µg/h <sup>†</sup> )													
	Hot Test							Cold Test						
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	HCHO	CH <sub>3</sub> CHO
2006	8701	52.6	122	10.9	0.265	53.4	76.9	10649	71.1	180	13.4	0.122	153	128
2007	10685	38.0	153	12.7	1.301	0.29	0.14	9841	37.2	159	12.2	0.302	0.11	0.04
2008	8935	86.8	17.0	16.9	0.132	8.9	31.7	4866	18.8	11.7	3.84	0.039	0.85	0.66
2009	9307	49.0	351	N/A*	0.024	0.47	0.01	10881	60.2	307	N/A*	0.000	177	244
2010	8579	16.8	29.4	N/A*	0.000	33.6	74.7	9664	40.9	68.6	N/A*	0.000	39.4	140
2011	9338	26.8	74.5	5.04	0.018	40.8	77.0	12351	17.8	64.7	2.24	0.013	30.4	48.7
2012	8517	49.5	214	11.5	0.138	175	84.8	10534	46.9	253	8.41	0.052	24.5	152
2013	8559	21.6	36.4	1.46	0.060	-**	-**	11488	38.0	72.4	1.47	0.005	-**	-**

<sup>†</sup> Emission rates for HCHO and CH<sub>3</sub>CHO are shown as µg/h while all other pollutants are shown as g/h.

\* N/A: Not available due to malfunctioning of the HC measurement instrument.

\*\* Data are not available yet, but will be available on the final report.

**Table E.3. 5-Min. Soak MY Idling Emissions Results.**

MY	Average Idling Emissions Rates for 5-min Soak Tests (g/h)									
	Hot Test					Cold Test				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
2006	7435	56.3	104	16.6	0.255	8382	52.3	121	10.0	0.138
2007	8758	34.5	152	8.9	0.310	9618	43.0	145	9.10	N/A*
2008	7332	45.9	12.2	8.78	0.057	6606	31.7	27.7	5.37	0.031
2009	7341	57.6	240	N/A*	0.000	8471	184	103	N/A*	0.000
2010	6614	34.8	18.8	N/A*	0.105	18429	45.8	62.9	8.46	0.000
2011	6879	21.1	55.6	6.01	0.003	7828	25.1	60.0	4.97	0.016
2012	6697	50.4	149	11.0	0.059	6396	79.5	126	12.2	0.008
2013	6358	35.7	20.8	1.76	0.005	6233	29.5	34.2	0.93	0.006

\* N/A: Not available due to malfunctioning of the corresponding measurement instrument.

**Table E.4. 15-Min. Soak MY Idling Emissions Results.**

MY	Average Idling Emissions Rate for 15-min Soak Tests (g/h)									
	Hot Test					Cold Test				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
2006	7347	52.9	97.5	16.4	0.273	8314	50.8	119	9.59	0.106
2007	8411	31.2	152	13.9	0.634	9410	40.4	147	10.2	N/A*
2008	7411	47.5	12.8	9.01	0.043	6550	34.8	26.8	5.87	0.031
2009	7214	60.0	245	N/A*	0.000	8876	163	142	N/A*	0.000
2010	6620	36.0	18.9	N/A*	0.000	9946	41.2	48.1	2.06	0.000
2011	6919	21.9	56.2	5.84	0.000	7994	28.1	65.2	5.49	0.004
2012	6695	51.1	149	9.89	0.052	6972	72.2	149	11.6	0.026
2013	6437	38.7	21.0	1.89	0.004	6568	33.6	36.2	1.42	0.005

\* N/A: Not available due to malfunctioning of the corresponding measurement instrument.

**Table E.5. 5-Min. Soak High MY Idling Emissions Results.**

MY	Average Idling Emissions Rates for 5-min Soak High Tests (g/h)									
	Hot Test					Cold Test				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
2006	17455	109	76.8	28.9	-*	18483	120	104	22.8	1.602
2007	14323	53.8	221	14.8	0.767	16269	67.8	222	15.2	0.330
2008	11558	102	13.6	22.5	0.110	9672	54.3	31.6	10.3	0.053
2009	13777	66.9	163	N/A*	0.000	15865	134	189	N/A*	0.000
2010	-**	-**	-**	-**	-**	-**	-**	-**	-**	-**
2011	-**	-**	-**	-**	-**	-**	-**	-**	-**	-**
2012	9237	70.0	182	18.0	0.000	10638	111	187	16.9	0.000
2013	10626	103	23.2	4.39	0.005	15607	51.9	89.9	1.94	0.019

\* N/A: Not available due to malfunctioning of the corresponding measurement instrument.

\*\* -: No tests were performed because the corresponding test trucks did not allow high idling.

**Table E.6. 15-Min. Soak High MY Idling Emissions Results.**

MY	Average Idling Emissions Rates for 15-min Soak High Tests (g/h)									
	Hot Test					Cold Test				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
2006	16234	103	82.2	27.7	2.604	18125	115	118	22.7	1.484
2007	14603	63.8	223	17.4	0.954	16900	75.6	203	14.9	N/A*
2008	11798	101	13.0	21.8	0.120	9578	61.9	30.1	10.4	0.066
2009	13857	73.8	154	N/A*	0.000	19935	129	174	N/A*	0.049
2010	-**	-**	-**	-**	-**	-**	-**	-**	-**	-**
2011	-**	-**	-**	-**	-**	-**	-**	-**	-**	-**
2012	9163	76.3	182	18.0	0.000	10638	104	183	16.1	0.000
2013	10317	105	30.6	4.54	0.007	9791	95.6	92.2	3.06	0.009

\* N/A: Not available due to malfunctioning of the corresponding measurement instrument.

\*\* -: No tests were performed because the corresponding test trucks did not allow high idling.



## APPENDIX F: COMPARISON WITH OTHER STUDIES

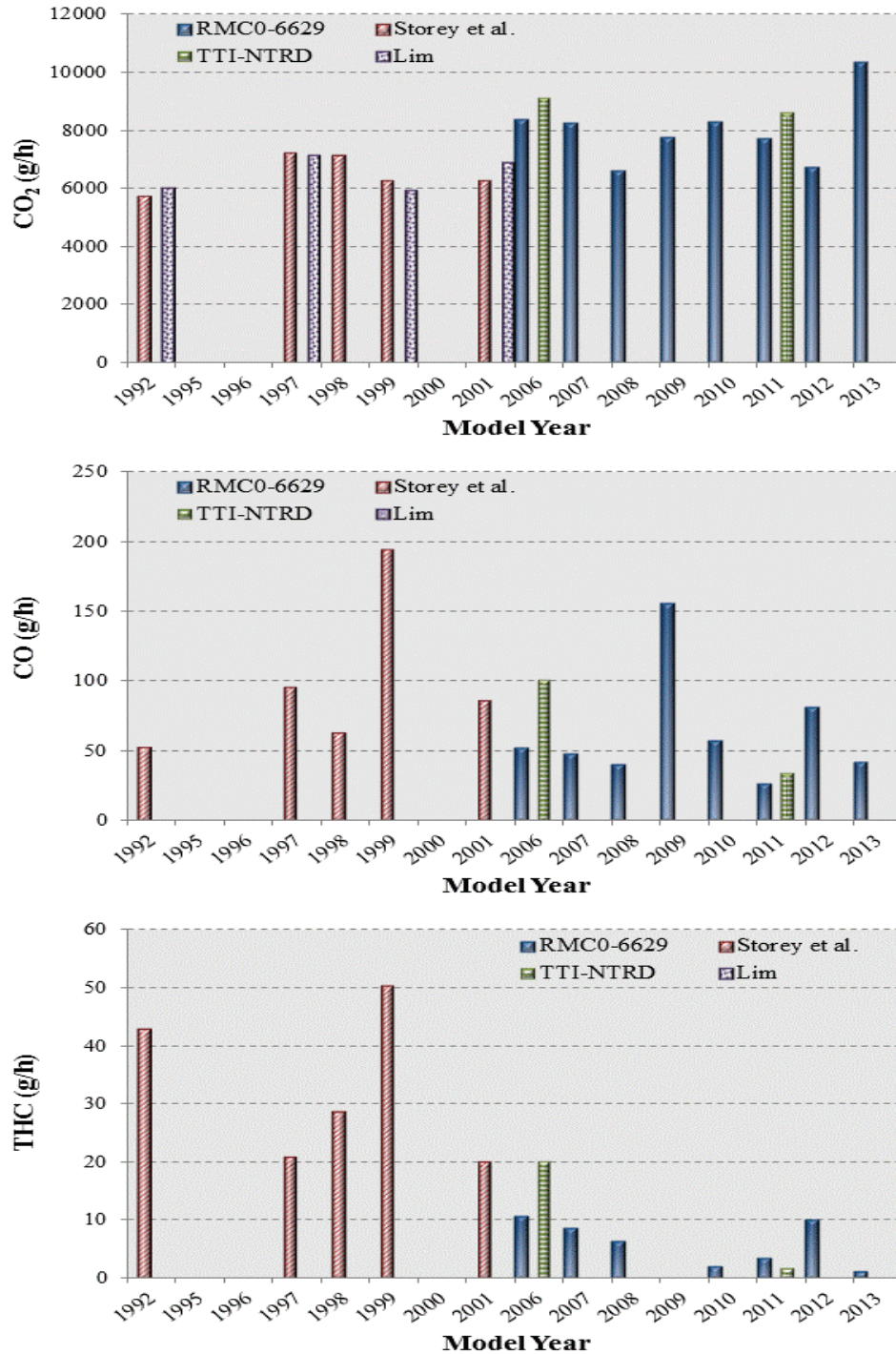


Figure F.1. Comparison of Idling Emissions Rates with Other Studies–Cold Test.

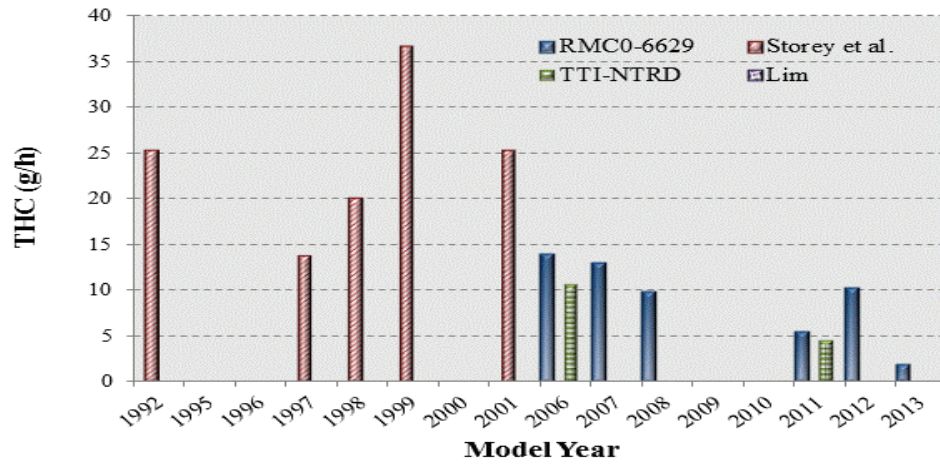
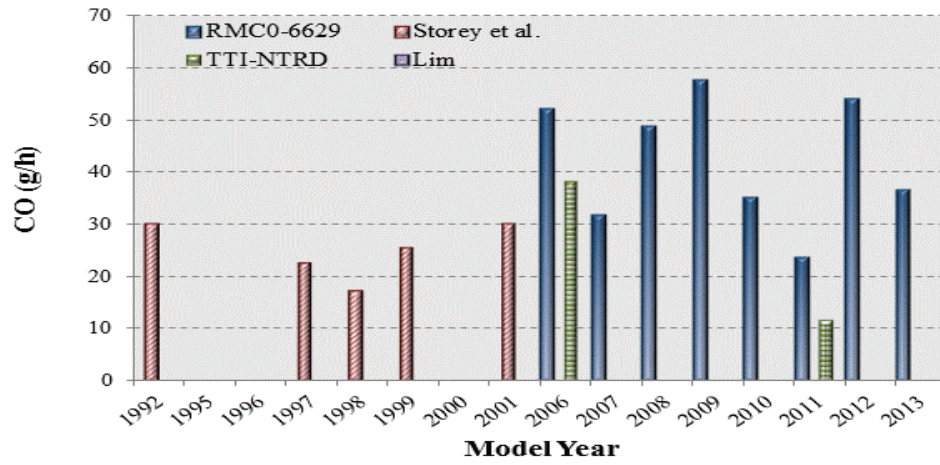
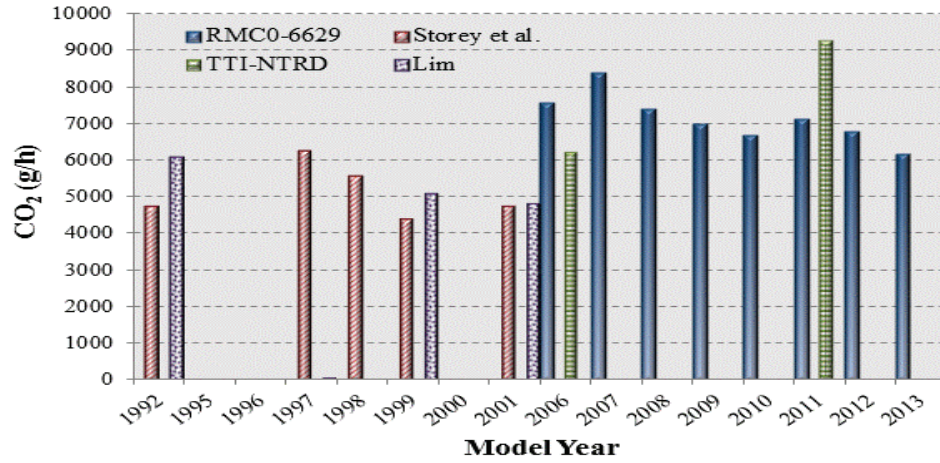
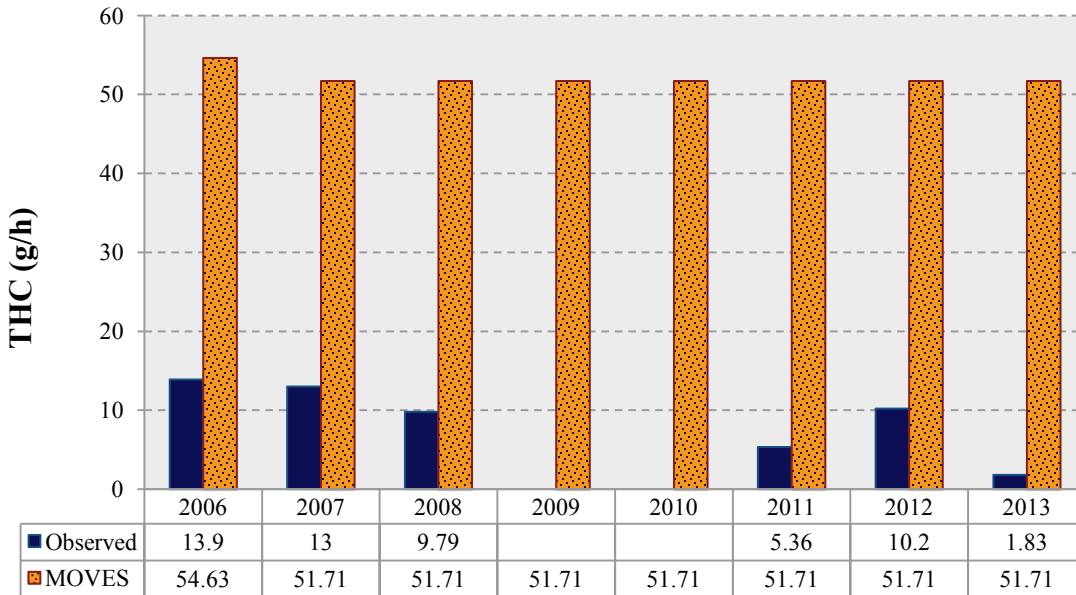
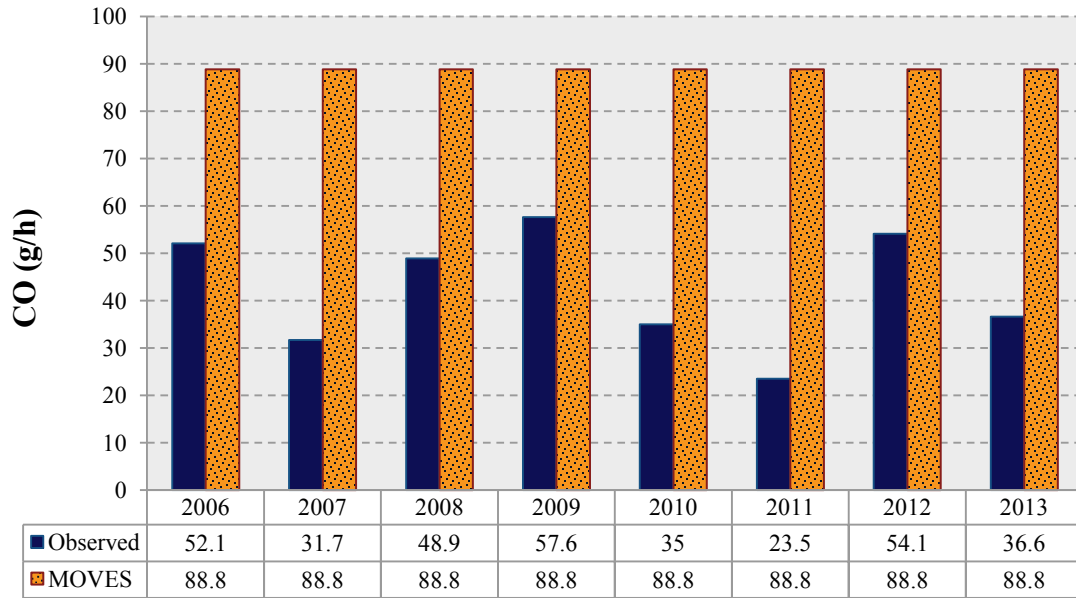


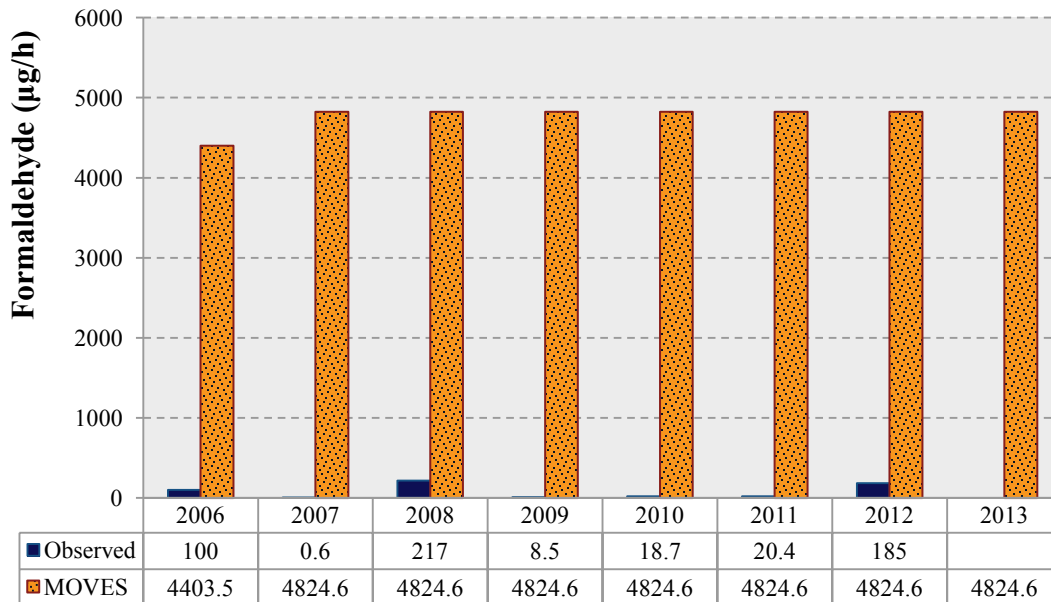
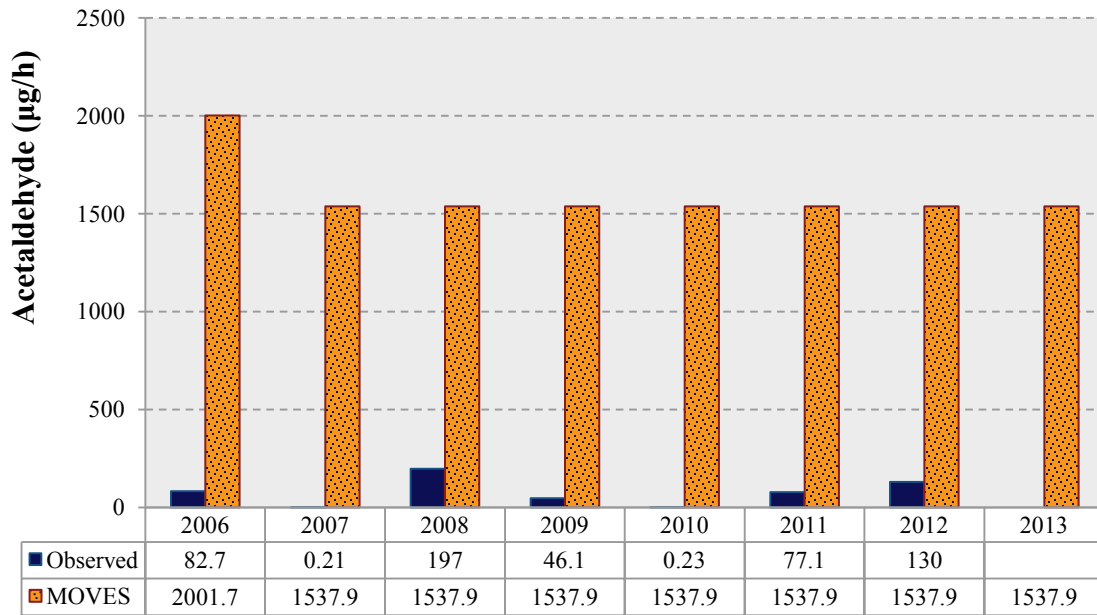
Figure F.2. Comparison of Idling Emissions Rates with Other Studies—Hot Test.



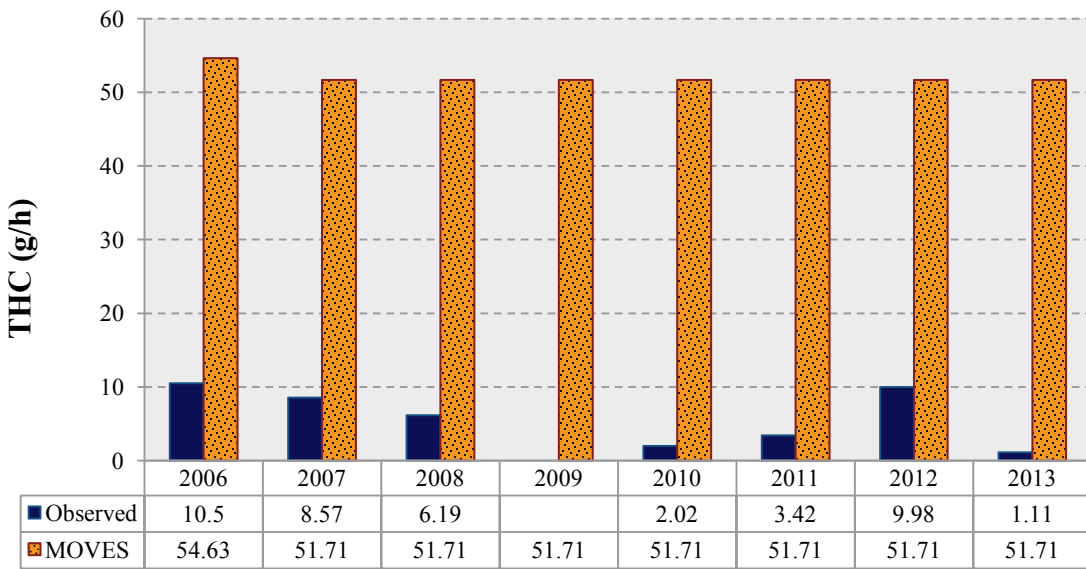
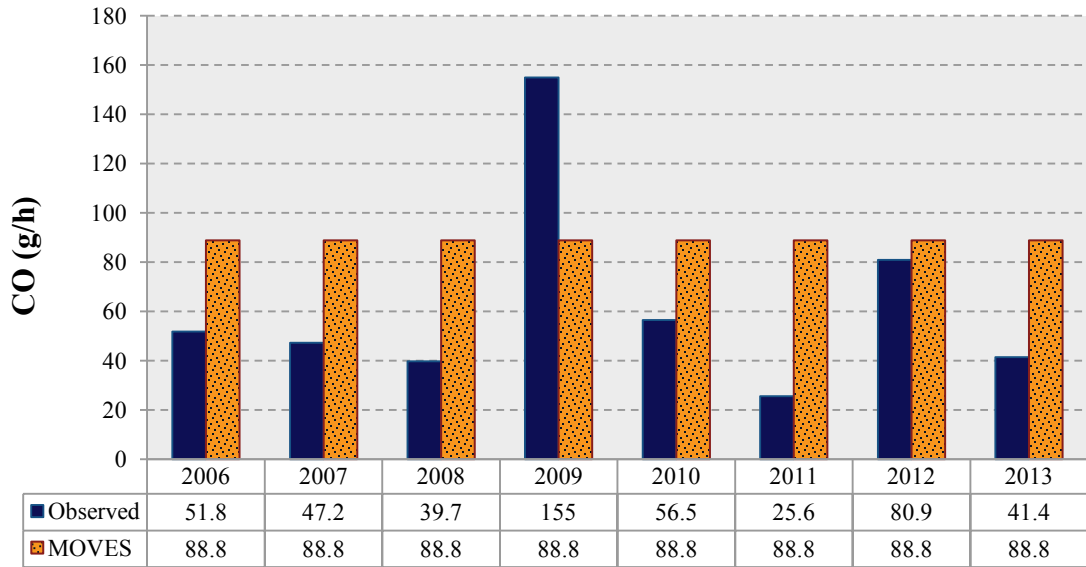
## APPENDIX G: HDDV COMPARISON RESULTS



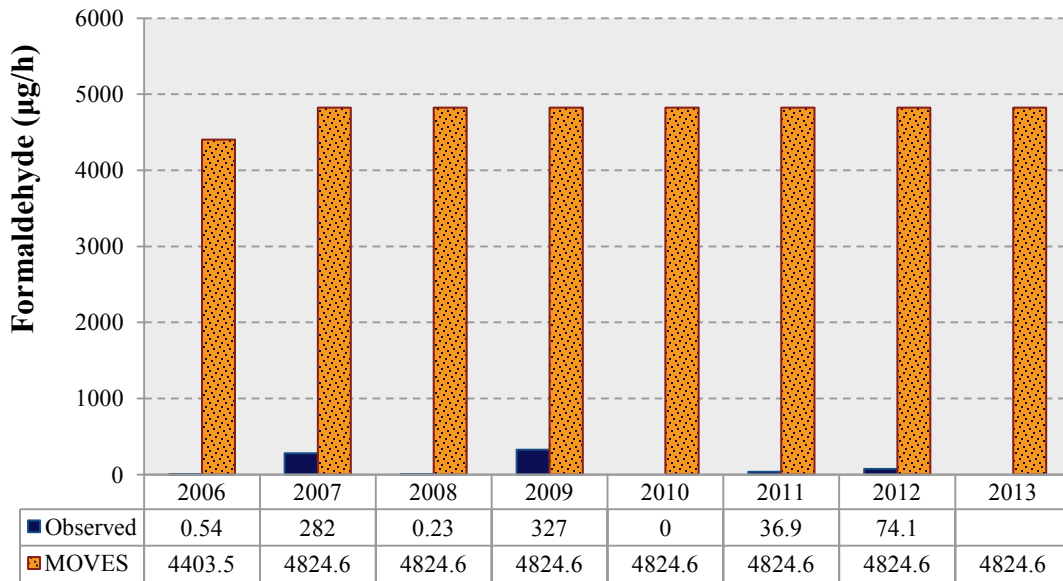
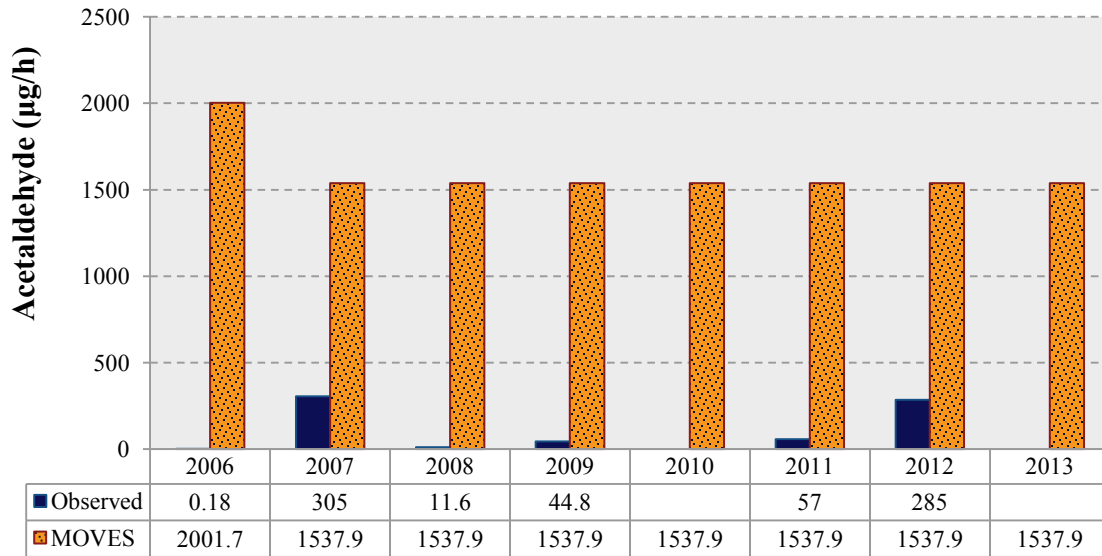
**Figure G.1. Extended Idling Emissions Rates: Vehicle Type 62, Hot Testing.**



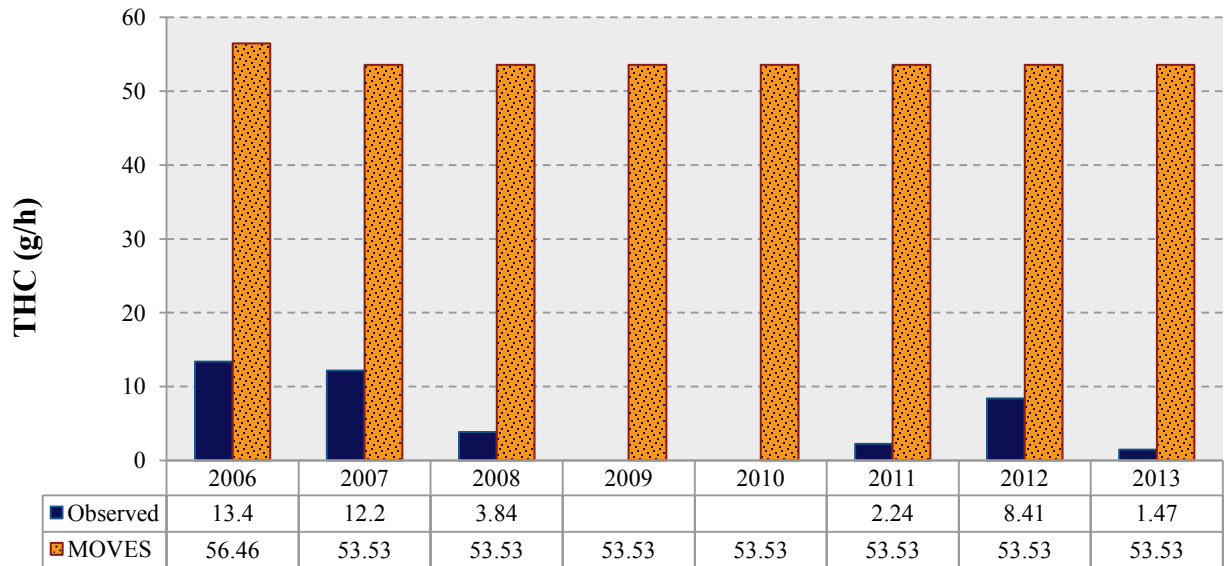
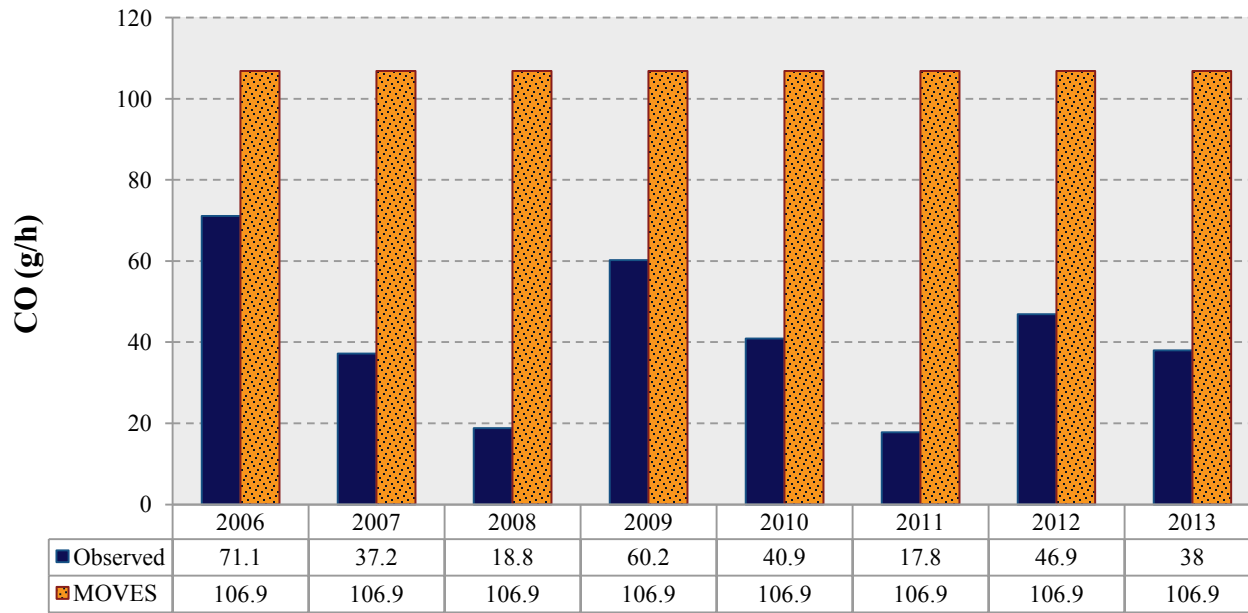
**Figure G.1. Extended Idling Emissions Rates: Vehicle Type 62, Hot Testing (Continued).**



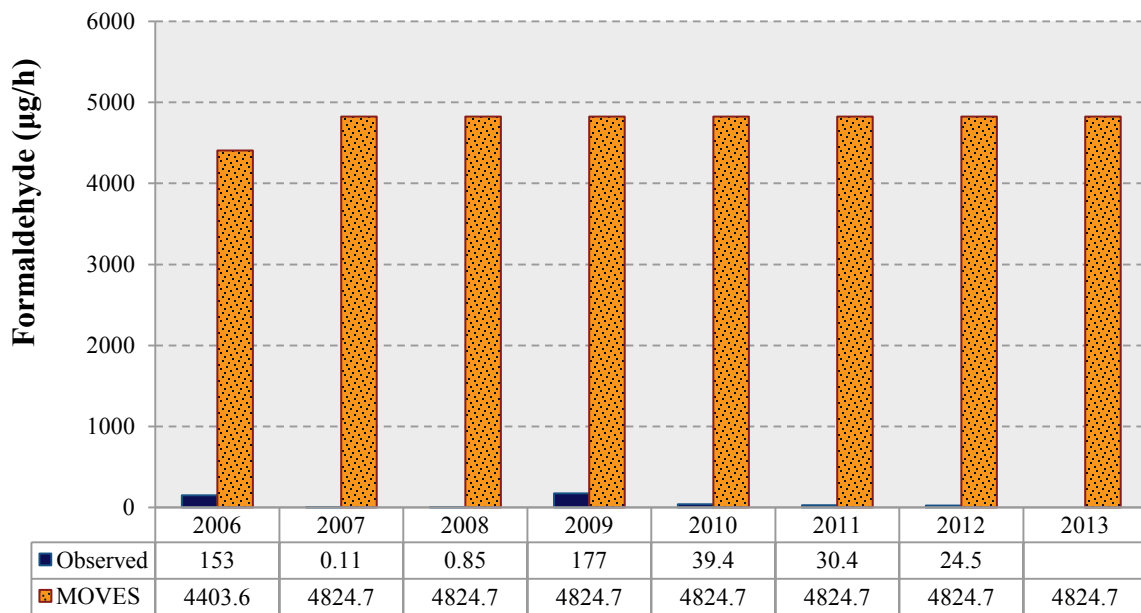
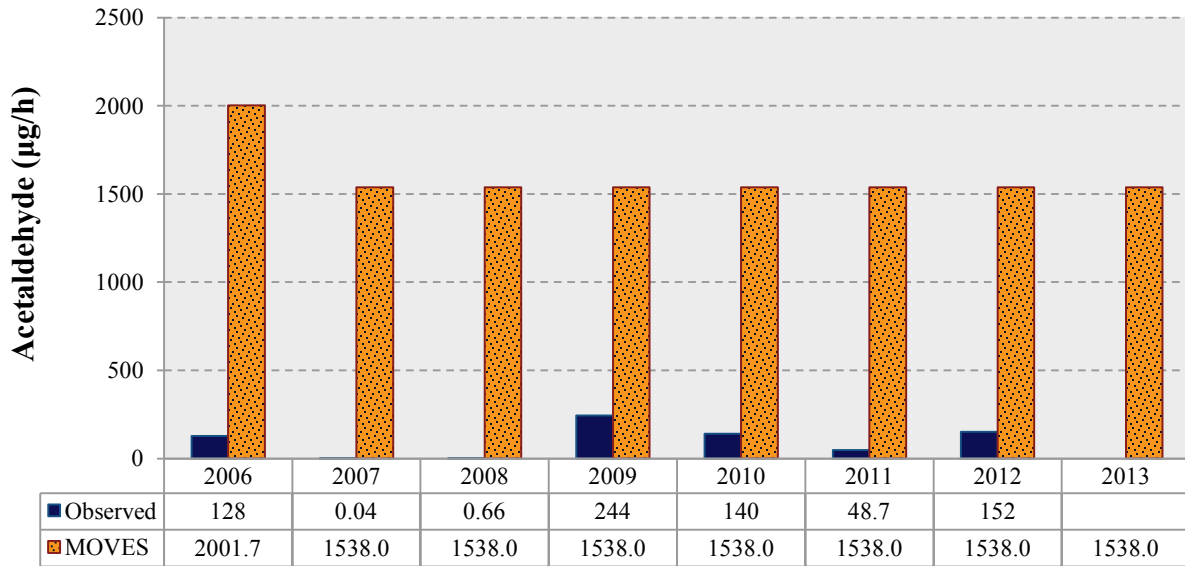
**Figure G.2. Extended Idling Emissions Rates: Vehicle Type 62, Cold Testing.**



**Figure G.2. Extended Idling Emissions Rates: Vehicle Type 62, Cold Testing (Continued).**



**Figure G.3. Cold Start Emissions Rates: Vehicle Type 62, Cold Testing.**



**Figure G.3. Cold Start Emissions Rates: Vehicle Type 62, Cold Testing (Continued).**

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