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16. Abstract

This research study developed a methodology to perform mandatory dynamometer vehicular emissions tests on real roads, performed on-road emissions tests, and compared the test results to the estimates using the current EPA emissions estimation model.

Currently, mandatory vehicular exhaust emission tests are performed on chassis or engine dynamometers using the Federal Test Procedure (FTP)/Supplemental Federal Test Procedure (SFTP) drive schedules. Based on the developed real-world in-use emissions testing methodology with using a modified test vehicle, authors could follow the FTP/SFTP drive schedules while the vehicle was driven on real roads, and measure emissions during the in-use on-road FTP/SFTP emissions testing. Emissions from the vehicle during the testing were measured, analyzed, and compared to estimated emissions using the current EPA emissions estimation model, MOtor Vehicle Emission Simulator (MOVES). The authors observed discrepancies between the measured data and the MOVES estimates, especially when associated with cold-start emissions. More detailed analysis results, along with the detailed test methodologies, are provided in this report.

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COMPARISONS BETWEEN VEHICULAR EMISSIONS FROM REAL-WORLD IN-USE TESTING AND EPA MOVES ESTIMATION

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DISCLAIMER

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EXECUTIVE SUMMARY

This research study proposed a methodology to perform mandatory dynamometer vehicular emissions tests on real roads. The methodology was applied to actual on-road in-use emissions tests, and the collected test results were analyzed and compared to emission estimates produced with using the current United State Environmental Protection Agency (EPA) emissions estimation model, MOtor Vehicle Emission Simulator (MOVES).

Currently, mandatory vehicular exhaust emission tests are performed on chassis or engine dynamometers following the Federal Test Procedure (FTP)/Supplemental Federal Test Procedure (SFTP) drive schedules by a driver. With a modified test vehicle, which will allow two drivers to maneuver the vehicle simultaneously to follow the drive schedules on actual roads, authors could follow the drive schedules and measure emissions during the in-use on-road FTP/SFTP emissions testing.

During the in-use on-road testing, authors could follow the speed profiles most of time. On average, for about 90% or more of time, speeds of the modified test vehicle were maintained within the EPA tolerance limits of test drive schedules, i.e., FTP schedule, Urban Dynamometer Drive Schedule (UDDS), SFTP (US06 and SC03) schedules, and Highway Fuel Economy Test (HWFET) schedule.

Emissions from the vehicle during the testing were measured using portable emissions measurement systems (PEMS). The measured emission results were analyzed and compared to the estimated emissions using MOVES. The analyzed and compared results are summarized:

- Generally, measured carbon dioxide (CO_2) emissions were similar or slightly higher than the MOVES estimates.
- For other measured pollutants (carbon monoxide [CO], oxides of nitrogen [NOx], hydrocarbon [HC], and particulate matter [PM]), MOVES estimates were mostly higher than the measured with only exception that CO and HC during the US06 SFTP testing, addressing aggressive, high speed and/or high acceleration driving behavior.
- Cold-starts increased emissions of CO, NOx, and HC significantly and CO_2 emissions slightly based on the FTP testing results.
- The operation of A/C increased NOx and HC emissions significantly, CO emissions modestly, and CO_2 emissions slightly while following HWFET schedule.

CHAPTER 1
INTRODUCTION

Federal emission standards for engines and vehicles are established by the US Environmental Protection Agency (EPA). Currently, vehicular exhaust emission tests are performed on chassis or engine dynamometers using drive or duty cycles depending on the types of vehicles. Car and light truck emissions are measured on chassis dynamometers in testing laboratories over the Federal Test Procedure (FTP; or, so-called FTP-75) and additional Supplemental Federal Test Procedures (SFTP), which are designed to address shortcomings with the FTP-75 in the representation of aggressive, high speed driving (US06), and the use of air conditioning (SC03).

In June 2005, EPA announced the final rule on in-use testing program, which ensures that the benefits of more stringent emission standards are realized under real-world driving conditions. Since then, there have been many real-world in-use vehicular emissions studies with both of light-duty and heavy-duty cycles. However, none of studies have been successful to follow the FTP or SFTP. In order to follow the FTP or SFTP, a driver needs to watch prescribed drive cycles on a screen, and to follow the speed profiles very closely. During real-world driving, it is not possible to follow the cycles because a driver cannot steer the vehicle, handle the brake and accelerator at the same time while watching a screen to follow the speed profiles. Therefore, there are no real-world emissions results directly comparable to regulatory dynamometer testing results.

In this study, TTI researchers modified a TTI test vehicle by adding slave acceleration and brake pedals, which allowed two drivers to maneuver the vehicle simultaneously to follow the FTP/SFTP drive cycles while driving on a test track. After the modification, the vehicle was tested while following the drive cycles on a test track. The collected emission data on the test track were analyzed and compared to estimated emissions using MOVES.

In December 2009, EPA released MOtor Vehicle Emission Simulator (MOVES), EPA's state-of-the-art tool for estimating emissions from highway vehicles. The model is currently used for state and local agencies to calculate vehicular emissions for state implementation plan (SIP). Using MOVES along with the driven speed profile information during the actual on-road tests, emissions of the vehicle during the tests were estimated. The estimated emissions were compared to the measured emissions.

This problem statement is translated to a mathematical format using an objective function and a series of constraints. The proposed objective function is composed of combined emission reduction benefits. The framework's structure is made flexible so that it can be applied to a broad range of emission reduction strategies for optimal deployment. The following steps are involved in achieving the goal of this study:

The research project was focused on the following four objectives:

- Modification of a TTI's test vehicle to perform real-world vehicle emissions measurement while following FTP/SFTP drive schedules.
- Development of a methodology for emissions measurement tests.
- MOVES emissions estimation for the drive cycles.
- Analysis and comparison of the measured vehicle emissions data with MOVES emission estimates.

The research objectives were accomplished through the completion of the following work tasks.

Task 1–Literature Review: Current EPA vehicular emissions standards and test procedures and MOVES emission estimation methodology were reviewed. Existing reports and articles pertaining to regulatory dynamometer and in-use real-world vehicular emissions tests and MOVES emission estimation were examined; that is, TTI researchers examined the principle(s) how dynamometer and in-use test data are incorporated in MOVES.

Task 2–Test Methodology and Plan Development: TTI researchers developed a testing methodology for on-road in-use emissions measurement while following FTP/SFTP drive schedules in order to make the measured results comparable to EPA MOVES emission estimation results. Also, a detailed test plan of the testing on a 9-mile circular track at Pecos Research and Testing Center (RTC) in Pecos, TX, was developed.

Task 3–Test Vehicle Modification: A TTI test vehicle (a light-duty gasoline vehicle) was modified for the on-road in-use vehicle emissions testing. Slave acceleration and brake pedals were added in the vehicle to allow the vehicle to follow the drive cycles on the Pecos RTC test track. After the modification, the modified vehicle's drivability on a test track for the emissions testing was examined prior to the actual emissions testing.

Task 4–Emissions Testing: Real-world emissions testing were performed on the Pecos RTC track. Using TTI's portable emissions measurement systems (PEMS), emissions of the vehicle were measured while following the FTP/SFTP drive schedules on the test track. Testing with a drive schedule was repeated at least three times to obtain statistically meaningful data.

Task 5–Emission Result Comparisons and Analysis: The measured emissions data collected from the test track testing were analyzed and reported. Also the emissions data were compared with emissions estimated by MOVES with the tested drive schedules.

The report has been divided into six chapters. Chapter 1 includes an introduction to the research and covers aspects such as project objectives and task, and organization of the report. Chapter 2 provides a literature review on the current EPA emission procedures and MOVES emission estimation. Chapter 3 focuses on test methodology. Chapter 4 provides on-road drive schedule test results. Chapter 5 discusses emission results measured during the on-road tests and compares the measure results to the estimates using MOVES. Chapter 6 contains the concluding remarks.

CHAPTER 2
LITERATURE REVIEW

This chapter provides an overview of the current literature regarding EPA's current mandatory emissions testing and MOVES emissions estimation, focused on light-duty gasoline vehicles (LDGVs).

EMISSIONS TESTING

Currently, regulatory vehicle tests for emissions and fuel economy need to follow EPA and/or California Air Resources Board (CARB) test procedures. In the U.S., emissions standards are managed on a national level by EPA. In California, however, an exception is granted to the state of California. California's exemption was granted in the early years of mobile-source regulation because air pollution was more severe in California than in the rest of the nation, and the state had a long history of establishing its own emissions standards for on-road vehicles and other mobile sources [1].

EPA divides emission standards of on-road (or, highway) vehicles and engines into the following three categories:

- Cars and light trucks.
- Heavy-trucks, buses, engines.
- Motorcycles.

The heavy-duty highway engines and vehicles can be further categorized into compression-ignition engines and buses, and spark-ignition engines. The purpose of this study is for emissions and emission test procedures of cars and light trucks (LDGVs), of which emissions need to be tested on chassis dynamometer as vehicles; for heavy-duty vehicles, instead of the vehicles, their engines are tested on engine dynamometers. Therefore, this chapter focuses on test procedures for LDGVs only.

Federal Test Procedures (FTP)

Based on the current Tier 2 EPA emissions standards, car and light truck (i.e., LDGV) emissions should be measured over the FTP-75 test cycle. A vehicle in that category needs to be driven on a chassis dynamometer following the 11.04 mile long test cycle for 1874 seconds for certification testing. The cycle consists of three phases: the first cold start phase (for the first 505 seconds), the second transient phase or so-called cold stabilized phase (for next 864 seconds), and the third hot start phase (for the last 505 seconds) as shown in Figure 1. The first two phases are also collectively called as the urban dynamometer driving schedule (UDDS) that represents urban driving. The third phase is identical to the first phase, but the third phase is followed as the vehicle is warmed-up. Because the first phase was driven in a cold (ambient) temperature before the engine and catalyst to be stabilized, emissions over the first phase are greater than those over the third although the parameters of the both phases are identical.

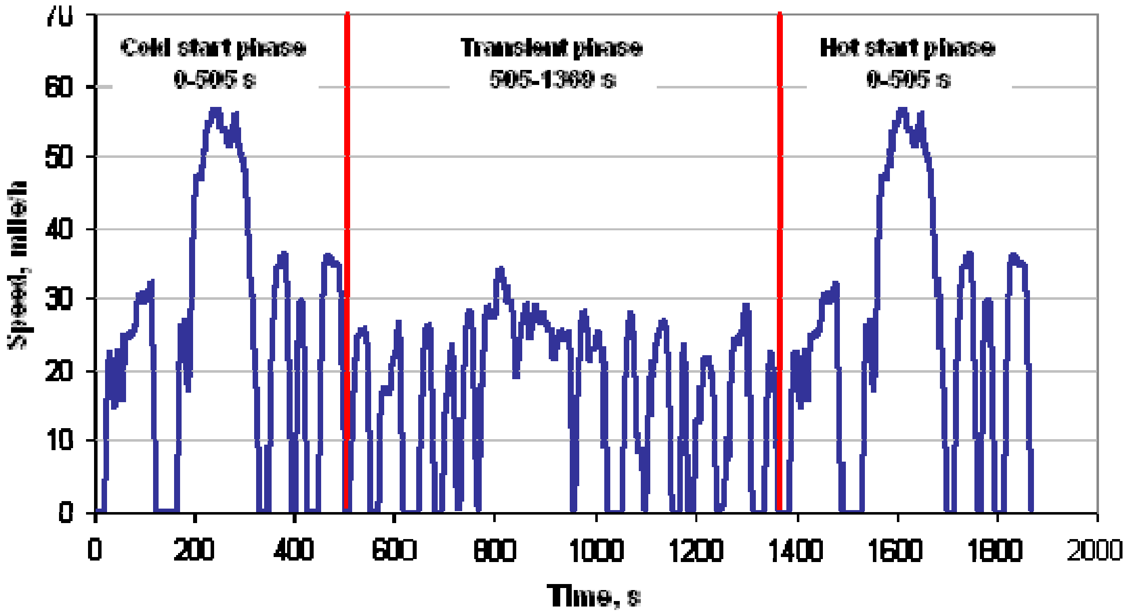

Figure 1. FTP-75 Test Drive Schedule.
(Source: [2])

For emissions calculations, the first cold start phase and the second transient phase are collectively called as cold cycle, and the third cold start phase and the fourth transient phase (identical to the second transient phase) are collectively called as hot cycle. Because the fourth phase is exactly same to the second, the results measured over the second phase are used for emissions of the fourth phase instead of conducting a new test over the fourth phase (for additional 864 seconds). In developing the FTP, this time-saving element was prescribed [3].

The parameters of the UDDS are:

- Length: 7.45 miles.
- Duration: 1369 s.
- Average speed: 19.59 mph (along with a maximum speed of 56.7 mph).

More detailed information of the UDDS as well as FTP can also be found in Code of Federal Regulations (CFR) Title 40 Part 86 (or, so-called 40 CFR 86) [4], Control of Emissions from New and In-Use Highway Vehicles and Engines.

Supplemental Federal Test Procedure (SFTP)

EPA revised the rule containing the preexisting conventional FTP (i.e., FTP-75) by adding the SFTP, so that this new set of requirements (containing both of the FTP and the SFTP) more accurately reflect real road forces during the emissions testing [5]. The final rule [6] on Motor Vehicle Emissions Federal Test Procedure Revisions for LDVs and LDTs was published on October 22, 1996, in the Federal Register. Details of the rule can also be found in 40 CFR 86.

In addition to the FTP-75 test, certification of a vehicle up to 8,500 lb gross vehicle weight rating (GVWR) requires to conduct tests over an SFTP, which were designed to address shortcomings with the preexisting conventional FTP in the representation of aggressive driving behavior, rapid speed fluctuations, driving behavior following startup, and use of air conditioning. The SFTP consists of two test cycles: US06 & SC03.

US06 (SFTP)

The US06 SFTP was developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations with more aggressive acceleration and braking, and driving behavior following startup. A vehicle needs to be driven on a chassis dynamometer following the 8.01 mile long test cycle for 596 seconds for the US06 SFTP certification testing. Basic parameters of the US06 SFTP are:

- Length: 8.01 miles.
- Duration: 596 s.
- Average speed: 48.37 mph (along with a maximum speed of 80.3 mph).

Compared to the UDDS (the basic component of the FTP), described in Federal Test Procedure (SFTP) section, a test vehicle needs to be driven a little bit longer distance (8.01 miles vs. 7.45 miles of UDDS) for much shorter time (596 s vs. 1369 s for UDDS) in the US06 SFTP to simulate aggressive highway driving. The US06 drive schedule is shown in Figure 2.

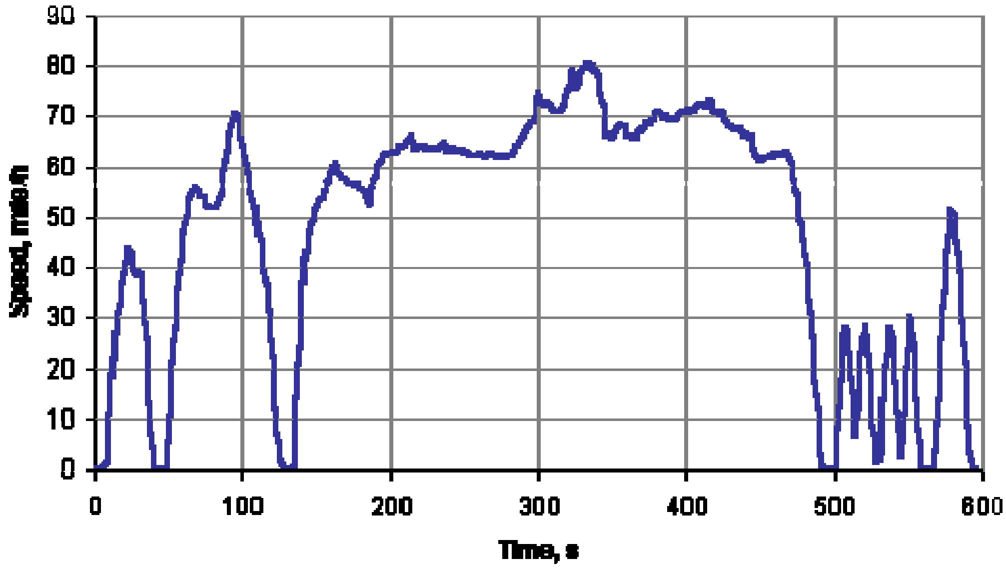

Figure 2. SFTP-US06 Test Drive Schedule.
(Source: [7])

SC03 (SFTP)

Another SFTP, the SC03 SFTP, is designed to represent the engine load and emissions associated with the use of air conditioning units in vehicles under hot outside conditions (95°F and solar load). For the SC03 SFTP testing, a vehicle needs to be driven on a chassis dynamometer following the 3.58 mile long test cycle for 596 seconds. Basic parameters of the SC03 SFTP cycle are:

- Length: 3.58 miles.
- Duration: 596 s.
- Average speed: 21.55 mph (along with a maximum speed of 54.8 mph).

The SC03 drive schedule is shown in Figure 3. More detailed information of the SFTP (both of US06 & SC03) can be found in 40 CFR 86.

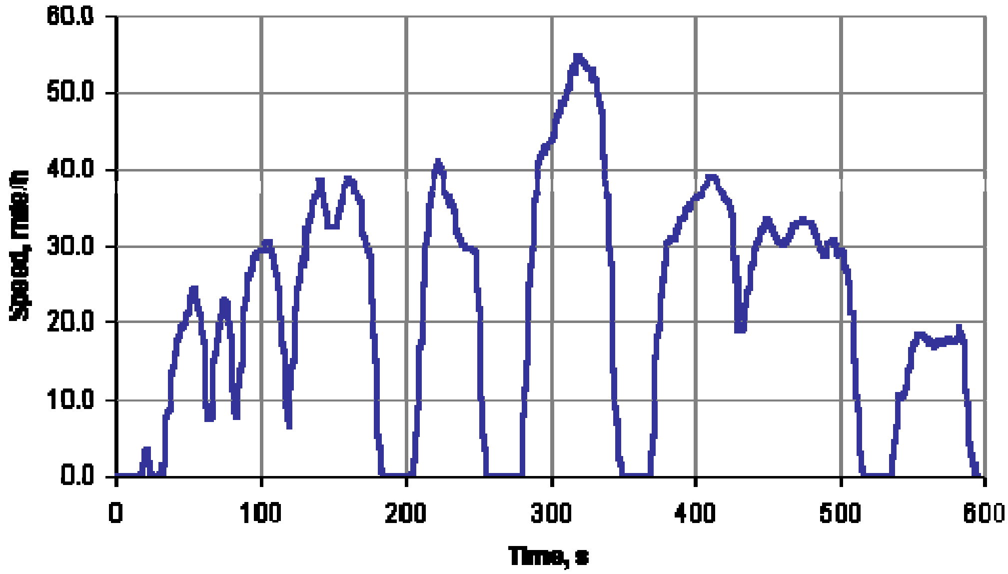

Figure 3. SFTP-SC03 Test Drive Schedule.
(Source: [8])

Highway Fuel Economy Test Procedure (HWFET)

Another drive schedule used for this study was the one from highway fuel economy test procedure (HWFET). Every new car and light truck sold in the U.S. is required to have a fuel economy window sticker label, which contains the city and highway miles per gallon (mpg) estimates that are designed to help consumers compare and shop for vehicles [9]. Similar to emission tests, EPA tests vehicles by running them on chassis dynamometers through a series of driving schedules [10]. For 2007 and earlier MY vehicles, FTP and HWFET were used for fuel economy measurements for city and highway, respectively. Beginning with 2008 models, EPA [11] added two SFTP (US06 and SC03) and the cold FTP (FTP-75 test performed at 20°F [−7°C]) to the former FTP and HWFET to provide drivers with a more accurate estimate of the fuel economy that they are likely to achieve on the road.

The basic parameters for the HWFET drive schedule consisting of relatively smooth driving conditions compared to the FTP/SFTP drive schedule described earlier in this chapter are:

- Length: 10.26 miles.
- Duration: 765 s.
- Average speed: 48.3 mph (along with a maximum speed of 59.9 mph).

The HWFET drive schedule is shown in Figure 4. More detailed information of all the fuel economy test procedures including the HWFET driving schedule can be found in 40 CFR 600 [12].

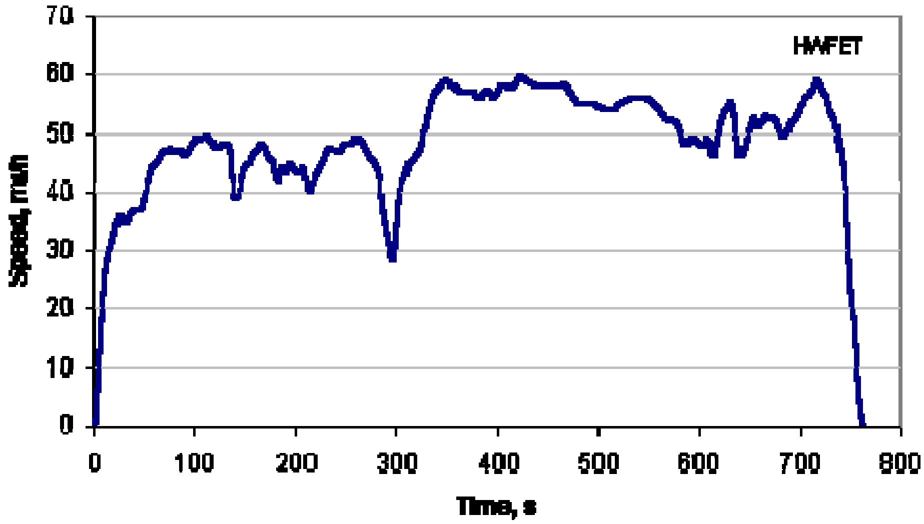

Figure 4. EPA Highway Fuel Economy Test Drive Schedule.
(Source: [13])

EMISSION ESTIMATION MODELS

The Clean Air Act defines the EPA's responsibilities for protecting public health and improving the nation's air quality [14]. The Act enables the EPA to set and enforce clean air standards that contribute to the improvement in human health. It also requires the EPA to develop and regularly update emissions factors and emissions estimation models for all emissions sources in the United States. The EPA has employed several emissions estimation methodologies. This section provides an overview of the current EPA emissions models, MOVES [15].

MOVES (MOtor Vehicle Emission Simulator)

The current EPA's emissions model, MOVES, utilizes 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 previous model, MOBILE6.2 [16]. MOBILE6.2 is an emissions factor model that generates pollutant emissions factors for vehicles classes based on data collected from dynamometer tests of predefined driving schedules, which are coupled with vehicle activity information in the simple form of vehicle miles travelled (VMT) and average speeds. The MOVES flexible database approach enables user to perform estimation at different analysis levels such as at the national, state, and local levels, as necessary. New input options and changes in the way MOVES handles existing information require the users to create local information for an accurate analysis [17].

For MOVES, users can use any drive schedules (or drive cycles in MOBILE models) to perform an accurate analysis. Unlike the aggregate approach used for the MOBILE model (for example, the average speed of an drive schedule), MOVES utilizes a disaggregate measure called Vehicle Specific Power (VSP), which is a combined measure of instantaneous speed, acceleration, road grade, and road load [18]. VSP is calculated on a second-by-second basis for a vehicle operating over these drive schedules based on equation 1.

$$VSP = \frac{A \times u + B \times u^2 + C \times u^3 + M \times u \times a}{M} \tag{1}$$

In equation 1, u is the instantaneous speed of the vehicle, a is the instantaneous acceleration of the vehicle including the impact of the grade ($a = a + sin(atan(G/100)$)); 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, and M is the vehicle's mass). The emissions associated with any given driving pattern are modeled based on distribution of time spent in operation modal bins that are defined based on VSP bins and speeds [17].

Table 1 shows driving activities categorized into 23 different operating mode bins based on vehicle speed and VSPs for running emissions estimations. 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 5 shows this process graphically.

Table 1. Operating Mode Bin Definitions for Running Emissions.

Braking (Bin 0)			
Idle (Bin 1)			
VSP / Instantaneous Speed	**0-25 mph**	**25-50 mph**	**> 50 mph**
< 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

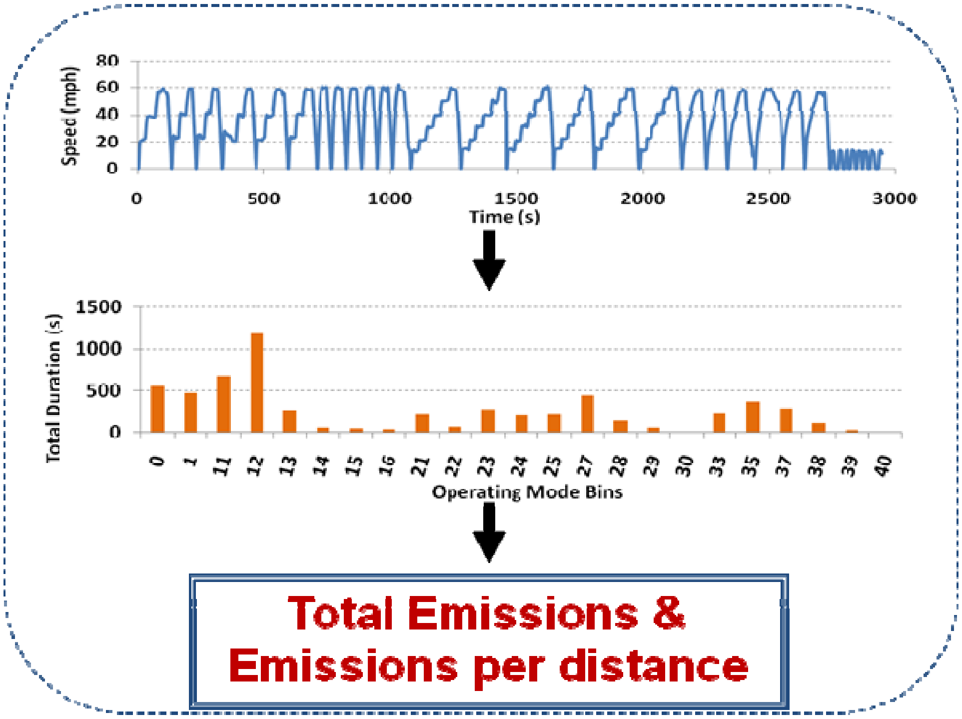

Figure 5. Emissions Estimation Process in MOVES.
(Source: [17])

When a drive schedule tested is provided into MOVES along with other input parameters such as vehicle type (shown in Table 2) and model year, fuel type, and meteorology data, MOVES calculate emission rates for operating mode bins associated with the input parameters and, then, provide an aggregate emission rate (or total emissions) over the test by using the emission rates and operating mode distribution. In MOVES, the emissions emission rates are reported for HC (as total hydrocarbon [THC]), CO, NOx, PM (as $PM_{2.5}$ and PM_{10}), methane (CH_4), nitrous oxide (N_2O), and CO_2 [19]. For fuel type, MOVES currently considers the following fuel types: Gasoline, Diesel Fuel, Compressed Natural Gas (CNG), Liquid Propane Gas (LPG), Ethanol (E85), Methanol (M85), Gaseous Hydrogen, Liquid Hydrogen, and Electricity [19].

Table 2. 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

CHAPTER 3
TEST METHODOLOGY

For the in-use on-road FTP/SFTP/HWFET testing on the Pecos RTC test track, TTI researchers modified a test vehicle and were trained to follow the FTP/SFTP/HWFET drive schedules prior to the actual testing on the track. Then, the actual on-road testing was performed on the 9-mile circular track at Pecos RTC in Pecos, TX. Details of the test preparation and testing methodology are described in this chapter.

TEST VEHICLE AND MODIFICATION

TTI's 1999 Dodge Grand Caravan was used for tests after being modified by addition of slave acceleration and brake pedals in the assistance seat. Figure 6 shows the test vehicle and the slave pedals. Using the slave pedals, the person in the assistant seat can also control the speed of the vehicle; the person in the driver seat can control both of the speed and steering of the vehicle.

Figure 6. Test Vehicle (Left) and Slave Pedals in the Assistant Seat of the Test Vehicle (Right; Closed-up Pictures of the Pedals Are Also Shown in the Bottom Corner at Right).

For MOVES emission estimates, this vehicle (a minivan) is classified as MOVES source type 31 as shown in Table 2.

ON-ROAD FTP/SFTP/HWFET TESTING

For successful FTP or SFTP emissions testing, or HWFET fuel economy testing, speeds of a test vehicle need to be maintained within the tolerance (or, so-called allowable range) of the speeds of the test drive schedule all the time. EPA specifies the allowable range in 40 CFR 1066, Vehicle-Testing Procedures [20]. 40 CFR 1066 specifies that speeds of the test vehicle must be followed the target test drive schedule as closely as possible, and their instantaneous speeds must stay within the tolerances (the allowable ranges shown in Figure 7: that is, the upper limit is 1.0 m/s (2 mph) higher than the highest point on the trace within 1.0 s of the given point in time, and the lower limit is 1.0 m/s (2 mph) lower than the lowest point on the trace within 1.0 s of the given time.

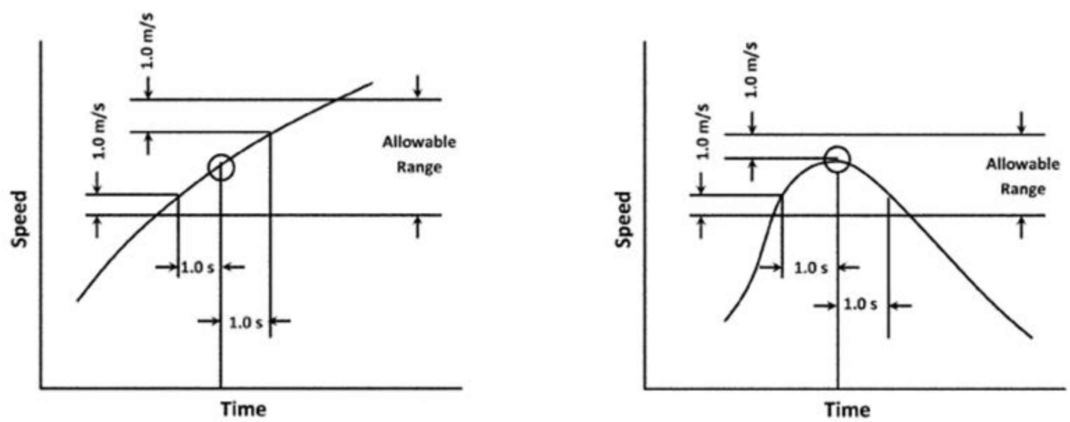

Figure 7. Examples of the Allowable Ranges for Driver's Trace (Left: for portions of the speed curve that speeds are increasing or decreasing throughout the 2-second time interval, Right: for portions of the speed curve that include a maximum or minimum value).
(Source: [20])

In order to follow a drive schedule within the tolerance for testing, a driver needs to watch prescribed drive cycles on a screen, and to follow the speed traces (or profiles) very closely. A trained driver can conduct such precise driving on chassis dynamometer. On actual roads, however, a driver cannot conduct such driving because he also needs to steer the vehicle in addition to drive the vehicle still in such precise ways. Also, even on test tracks, where testing can be conducted without any traffic interferences, it is much difficult for a driver to perform such precise driving due to other conditions such as wind, compared to driving on a chassis dynamometer inside a laboratory, where such condition like wind are not issues. Due to these limitations/difficulties to conduct on-road FTP/SFTP/HWFET testing, the authors believe any studies for such testing have not been performed, with the authors' best knowledge.

With the modified test vehicle that instrumented with the slave pedals, however, such testing can be performed on actual roads; a driver can perform such precise driving using the slave pedals in the assistance seat while another driver in the driver seat steer the wheel. Prior to actual on-road testing, TTI researchers were trained to watch prescribed drive cycles on a screen, and to follow the speed profiles very closely. Figure 8 shows such driving on a computer screen; the driver using the slave pedals tried to follow speed profiles of a prescribed drive schedule (shown as white line on the screen) with watching the actual vehicle speeds (shown as white dot on the screen).

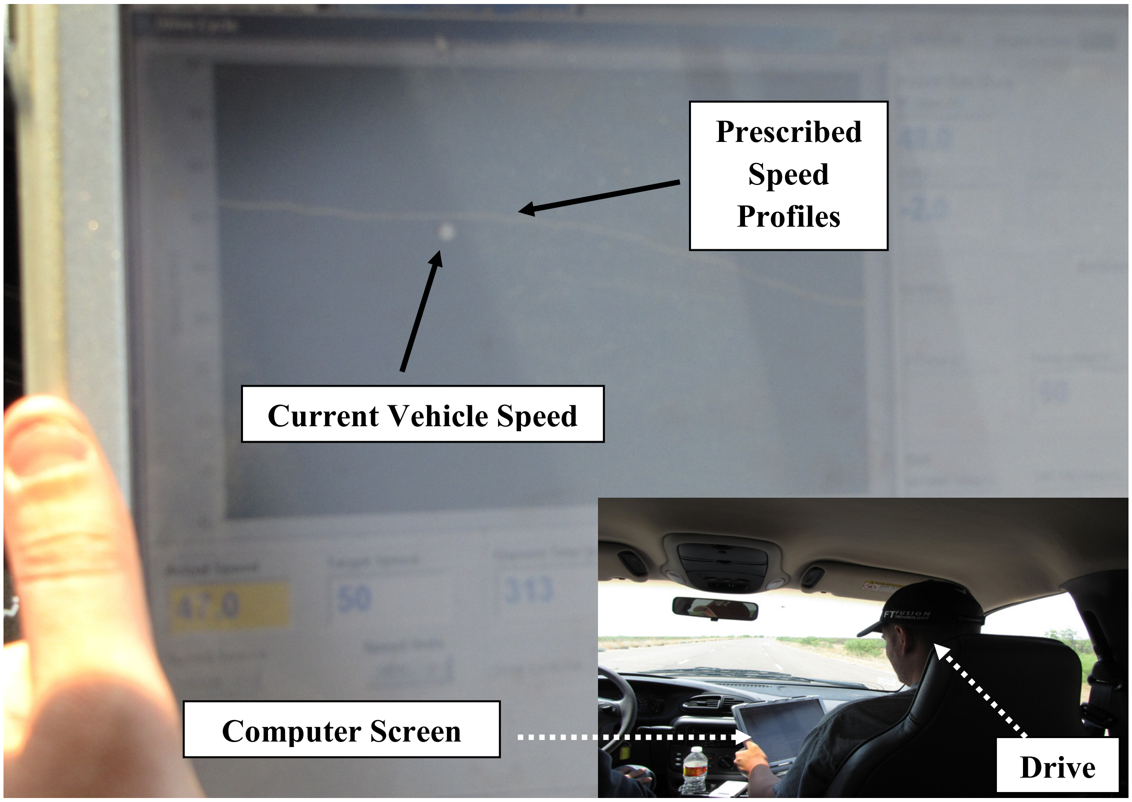

Figure 8. Screenshot while Following Prescribed Speed Profiles for a Testing (the Computer Screen Is Also Shown in the Picture at the Right Bottom Corner along with the Driver to Follow the Speed Profiles Using the Slave Pedals).

Test Track

In order to perform FTP/SFTP/HWFET testing, TTI researchers chose one of largest test tracks in the US, the 9-mile circular track at Pecos RTC. Although TTI has a 3-mile rectangular track in TTI's nearby premise in Texas A&M Riverside Campus, Bryan, TX, TTI researchers recognized that high speed driving with sharp turns could be unavoidable at the rectangular corners and such driving could endanger driving safety. Therefore, authors decided to perform the testing at the Pecos RTC circular track, where such sharp turns would not occur.

The Pecos RTC, located near Pecos, Texas, is a 5,800 acre complex that includes nine different test tracks. The test tracks included a (9-mile circular) high speed test track, a road coarse track, and seven additional tracks for many different purposes. The facility has the capability of testing vehicles, tires, pavements, human factors, intelligent transportation systems, and many other technologies and research areas. For the on-road testing, TTI researchers performed tests on the 9-mile circular track that allows for continuous testing with no stops, unless specified in the test drive schedules, and no sharp turns. Figure 9 shows the 9-mile circular track and other test tracks located inside the circular track.

Figure 9. Pecos RTC Test Tracks (the 9-Mile Circular Test Track and Other Tracks inside the Circular Track).

Emissions Measurement

During the on-road in-use FTP/SFTP/HWFET testing on the Pecos RTC 9-mile circular track with the modified test vehicle, real-time second-by-second emissions from the test vehicle were measured with using PEMS. The PEMS used for this study was SEMTECH-DS and Axion systems. Figure 10 shows PEMS and sampling probes and tubing installed on and in the test vehicle; both PEMS were placed in the test vehicle, which had its back seat removed. Details of PEMS are described in the following sub-sections.

Figure 10. Test Vehicle Installed with PEMS (Left: Sampling Probes and Tubing Installed on Test Vehicle and Connected to Vehicle Exhaust, Right: SEMTECH-DS and Axion in Test Vehicle).

In this study, TTI researchers modified a TTI test vehicle by adding slave acceleration and brake pedals, which allowed two drivers to maneuver the vehicle simultaneously while driving on a test track. After the modification, the vehicle was tested while following the drive cycles on a test track. The collected emission data on the test track were analyzed and compared to estimated emissions using MOVES.

SEMTECH-DS

The SEMTECH-DS is a PEMS, which complies with the 40 CFR 1065 emissions testing and is used for the emission measurements during the on-road FTP/SFTP/HWFET testing. The SEMTECH-DS is used in conjunction with the SEMTECH electronic flow meter (EFM), which measures the vehicle exhaust flow rate as well as exhaust temperature. This allows for the calculation of exhaust mass emissions from all measured gasses. The SEMTECH-DS consists of a set of gas analyzers, an engine diagnostic scanner, and a GPS unit. The gas analyzers measure the concentrations of NOx (both nitrogen oxide [NO] and nitrogen dioxide [NO_2]), HC, CO, CO_2, and oxygen (O_2) in the vehicle exhaust. The SEMTECH-DS uses a Garmin International, Inc. GPS receiver to track the route, elevation, and ground speed of the vehicle on a second-by-second bases. The SEMTECH-DS is powered and controlled by software embedded in the system. Using the post-processor application that runs with the SEMTECH-DS, along with the EFM information, the total mass emissions for all measured gasses are calculated. Figure 11 shows the both PEMS used for this study; SEMTECH-DS, described in this sub-section and Axion, describe in the following sub-section.

Figure 11. PEMS (Left: SEMTECH-DS, Right: Axion).

Axion

Another PEMS used to collect PM was the Axion system (Axion) manufactured by Clean Air Technologies International, Inc. The Axion consists of gas analyzers, a PM measurement system, an engine diagnostic scanner, a GPS, and an on-board computer. For this study, only the PM measurement system was used. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The PM concentrations are converted to PM mass emissions using concentration rates measured by the Axion and the exhaust flow rates collected by the SEMTECH EFM. During the testing, most of measured PM concentration was under the detection limits.

Test Protocol

Fuel consumption and emissions testing of the modified test vehicle were conducted on Pecos RTC test track with following FTP/SFTP/HWFET drive schedules for 4 days. The drive schedules followed during the test are summarized in Table 3 along with their characteristics such as duration, distance, and average speed. For each drive schedule, at least 4 tests were conducted in a day or multiple days during the 4 days of test period. The number of tests conducted for each drive schedule is also shown in Table 3. For each day, a FTP test, which required 12 hours of soak time (overnight), was conducted first, and other tests were followed in a random order.

Table 3. Test Drive Schedules and Their Characteristics.

		Duration (s)	Distance (mi)	Average speed (mph)	Number of tests
FTP (3 phases)	Phase 1 (cold start)	505	3.59	25.6	4
	Phase 2 (transient)	864	3.86	16.1	
	Phase 3 (hot start)	505	3.59	25.6	
UDDS		1369	7.45	19.6	9
US06		596	8.01	48.4	8
SC03		596	3.58	21.6	4
HWFET*		765	10.26	48.3	9

* For HWFET, tests were performed with and without operating air conditioning system.

Each test (for a test run with a drive schedule) was conducted by three of TTI researchers. One researcher sat in the driver's seat and controlled the steering of the vehicle, which allowed the second researcher who sat in the assistant seat focused on controlling vehicle speed to follow a test drive schedule by utilizing the slave acceleration and brake pedal. The third researcher sat in a back seat and checked/monitored the test and emission measurements during the test.

The researcher who controlled speeds of the vehicle used a feature of the embedded SEMTECH-DS software, which allows for user to input a prescribed drive schedule, and then to play back the target speed profiles of the drive schedule along with the current speed of the test vehicle in real time. Using this feature that displayed both of the current vehicle speed and the prescribed speed profiles of a test drive cycle on a laptop computer screen as shown in Figure 8, the researcher controlled the slave pedals to follow the prescribed target speed profiles during the each test.

During each test, gaseous and PM emissions were measured using two PEMS that were installed on the test vehicle. The PEMS were warmed-up and calibrated prior to the testing. Pictures taken during the testing are shown in Figure 12. The measured emission results along with driving characteristics were analyzed to address the followings:

- Drivability of test drive schedule on actual roads (discussed in chapter 4).
- Comparison with respect to estimated emissions using MOVES (discussed in chapter 5).

- Cold-start effect on emissions (discussed in chapter 5).
- Air conditioning (A/C) operation effects on emissions (discussed in chapter 5).

Figure 12. Pictures of a Test Vehicle during the In-Use Real World Testing.

CHAPTER 4
ON-ROAD FTP/SFTP/HWFET DRIVING CHARACTERISTICS

For each drive schedule testing, at least four tests (i.e., test runs) were conducted to follow the drive schedule within the acceptable tolerance set on EPA's 40 CFR 86 & 1066 and also described in chapter 2. In this chapter, the ability to follow speed profiles of the test drive schedules (FTP/SFTP/HWFET schedules) on actual roads within the tolerance is reported and discussed.

Figure 13 show speed profiles of US06 SFTP drive schedule (blue line), speed tolerance (red lines; one showing higher speed tolerance limit and the other for lower), and speed profiles driven on actual roads (at the Pecos RTC track) during the tests (green circles). For the US06 testing, a total of eight test runs were conducted to follow the US06 drive schedule. As shown in Figure 13, TTI researchers could follow the speed profiles fairly closely within the tolerance while the prescribed speeds did not change rapidly; for example, from about 200 to about 450 seconds of the test period when the prescribed were within a 20 mph range (between about 60 and 80 mph). However, when the prescribed speeds changed rapidly with stop-and-go situations (that is, after 500 second during the test in Figure 13), TTI researchers were unsuccessful to follow the speed profiles, which is shown as lots of scattered speeds (green circles) above and below the tolerance as shown in Figure 13.

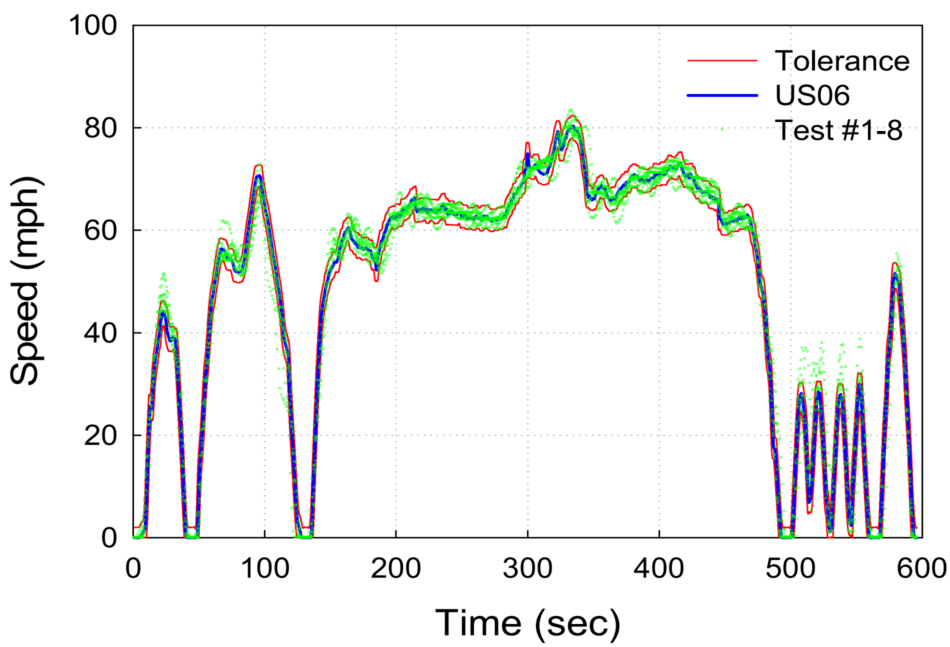

Figure 13. Speed Profiles for US06 (SFTP) Tests.

When all of actual driven speed profiles during the US06 test runs are averaged, the average speeds were within the tolerance limits for 90% of the test duration, that is, the average speeds were within the tolerance for 535 seconds during the entire test time of 596 seconds. For tests of other drive schedules but HWFET one, similar results were observed. For FTP, UDDS, and SC03 drive schedules, 1650 out of 1874 seconds, 1198 out of 1369 seconds, and 537 out of 596 seconds of average speeds were within their tolerance limits, respectively. In other words, frequencies of speeds within the tolerance limits for FTP, UDDS, and SC03 were 88%, 88%, and 90%, respectively. These frequencies as well as those for US06 and HWFET are listed in Table 4 along with their numbers of test runs.

Table 4. Test Driving Characteristics as Following the Prescribed Test Drive Schedules.

Drive schedule	Number of test runs	Frequency within the acceptable tolerance based on average speed profiles
FTP (3-phase)	4	88%
UDDS	9	88%
US06	8	90%
SC03	4	90%
HWFET	9	97%

For HWFET schedule, the observed frequency was 97% as shown in Table 4, which was higher than those for other schedules. During the 765 seconds of test duration, the average speeds were within the tolerance limits for most of time 745; that is, only 20 seconds out of 765 second, the average speeds were beyond the limits. This better performance (the best among all test schedules) was ascribed that the speed profiles of the HWFET schedule varied less compared to those of other schedules and did not have any stop-and-go situations as their prescribed speed profiles are shown in **Error! Reference source not found.** and Figure 4 (for HWFET schedule) as well as Figure 1, Figure 2, and Figure 3 (for other drive schedules). **Error! Reference source not found.** shows the HWFET drive schedule (blue line), speed tolerance (red lines; one higher and the other lower speed tolerance limits), and speed profiles driven during the tests (green circles).

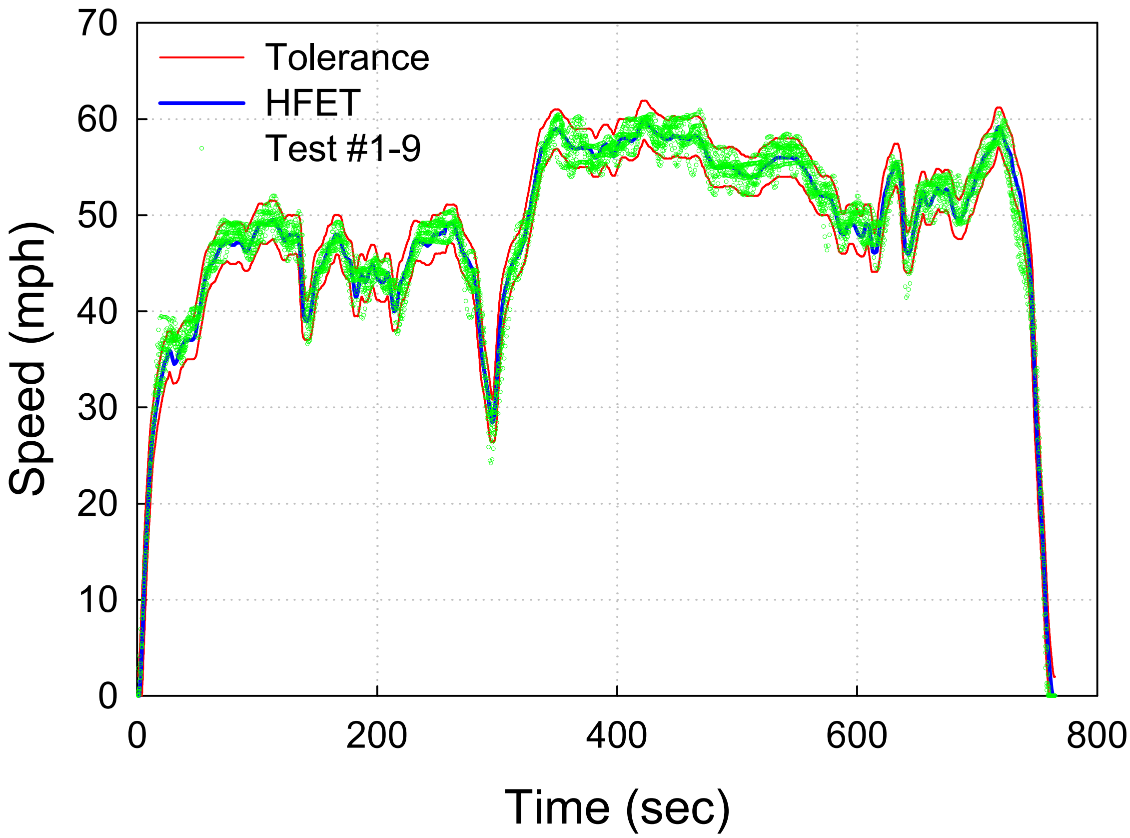

Figure 14. Speed Profiles for HWFET Tests.

Although TTI researchers could not follow the prescribed drive schedule on actual roads all the time as shown in Table 4 and Figure 13 and Figure 14, TTI researchers were quite successful to follow the schedule within the tolerance limits and showed the possibility to follow a drive schedule for all the time based on the test results; as for example of the HWFET testing that the average speed profiles for the HWFET testing were off from the tolerance limits only for 20 seconds out of 765 seconds. TTI researchers believed that more training would make it to possible to follow a drive schedule within its tolerance limits for all the time. When a test vehicle is equipped with mechanical devices such as actuators along with precise electric and/or electronic real-time vehicle speed feedback control, TTI researchers believe that, for any drive schedules that can be driven on chassis dynamometers within their tolerance limits, the test vehicle can be driven on roads for the drive schedules within the tolerance limits in similar degrees of precisions. Then, in-use emissions testing with such vehicle on actual roads can be performed relatively easily and cost-effectively compared to the current mandate chassis dynamometer emissions testing in laboratories.

CHAPTER 5
ON-ROAD IN-USE EMISSIONS TESTING RESULTS

For FTP/SFTP/HWFET testing, emissions of the modified test vehicle were measured using PEMS. The measured emissions results were also compared with MOVE estimates. In this chapter, the measured and compared emissions results are reported and discussed. In addition, cold-start and A/C operation effects on measured emissions were also discussed.

MEASURED EMISSIONS RESULTS

For each test, second-by-second gaseous and PM emissions measurement data along with driving characteristic data (such as vehicle speeds and vehicle miles driven [VMT]) were collected during the test. The collected emission data were aggregated for the entire test and then divided by the total VMT during the test to provide emission rates of the test as g/mi. For each drive schedule testing, as shown in Table 4, at least four different tests were conducted. For each testing, emission rates of the test runs were averaged and shown in **Error! Not a valid bookmark self-reference.**.

Table 5. Measured Average Emission Rates.

	Average Emission Rate (g/mi)				
	CO_2	CO	NOx	THC	PM
FTP (3-phase)	626	2.88	0.69	0.35	0.001
UDDS	615	1.17	0.42	0.11	UD*
US06	572	42.95	0.62	0.53	UD*
SC03	701	2.28	0.59	0.07	UD*
HWFET	385	0.75	0.20	0.03	UD*

* UD: under the detection limit

For PM, the measured emission values for all of drive schedule testing except FTP were under the detection limits. For the FTP testing, at the beginning of the cold-start phase (phase 1), small amounts of PM emissions were measured, and the corresponding average PM emission rate (0.001 g/mi) is reported in Table 5.

For gaseous emissions, the average emission rates of all measured pollutants (CO, NOx, and THC as well as CO_2) for HWFET testing were least compared to those for all other testing, as shown in Table 5. For CO, the measured average emission rate for the aggressive US06 testing were the greatest, 42.95 g/mi, which was more than one order of magnitude higher than those from other testing (2.88, 1.17, 2.28, and 0.75 g/mi for FTP, UDDS, SC03, and HWFET testing, respectively). For THC, the measure emission rate for US06 testing (0.53 g/mi) was also higher than those of other testing; 0.35 g/mi, the second highest for FTP, followed by 0.11, 0.07, and 0.03 g/mi for UDDS, SC03, and HWFET testing, respectively. For NOx, the average emission rate of FTP testing (0.69 g/mi) was slightly higher than those of US06 and SC03 (0.62 and 0.59 g/mi, respectively), somewhat higher than that of UDDS (0.42 g/mi), and more than three times higher than that of HWFET (0.20 g/mi) as shown in Table 5. For CO_2, the average emission rate of SC03 testing was the highest (701 g/mi) followed by those of FTP, UDDS, US06, and HWFET (626, 615, 572, and 385, respectively).

Authors believe that those different measured emission rates for different testing and pollutants, described above in this sub-section, were due to different characteristics of test driving schedules (such as cold-start for FTP, frequent stop-and-go situations for FTP and UDDS, aggressive driving (high speed driving and acceleration) for US06, A/C operations for SC03, and relatively smooth driving and acceleration with no stop-and-go situations for HWFET drive schedule) for the test vehicle. More detailed analyses including detailed analysis of instantaneous vehicle responses (including catalyst emission controls) with respect to each driving characteristic component such as vehicle speed and acceleration would explain the measured difference and their causes, but such analyses are beyond the scope of this study due to limited time and resources.

EMISSIONS COMPARISON BETWEEN THE MEASURED AND MOVES ESTIMATES

In order to examine if the current EPA emission model, MOVES, realistically represents measured in-use on-road emissions of the test vehicles, MOVES emission rates were calculated based on the driven speed profiles, and the calculated emission rates were compared with the measured ones. As described in chapter 2, vehicular emission rates are estimated using MOVES once speed profiles of the vehicle and other parameters such as vehicle type are provide into MOVES.

After completing in-use on-road testing, TTI researchers prepared all necessary input parameters for MOVES emission estimation such as driven speed profiles and vehicle type (31), and other test specific parameters such as fuel type, temperature and humidity (based on the test locations and test dates). Using MOVES2010a, the latest MOVES version at time of the emission estimation, TTI researchers obtained emissions estimates for each test based on the prepared driven speed profile and other parameters for the test. For each testing, the estimated MOVES emissions of test runs for the testing were averaged. The average emission estimates are shown in Table 6.

Table 6. MOVES Emission Estimate Averages.

	MOVES Emission Estimates (g/mi)				
	CO_2	CO	NOx	THC	PM
FTP (3-phase)	542	9.91	1.74	0.49	0.005
UDDS	562	10.87	1.91	0.51	0.003
US06	544	16.25	2.82	0.50	0.036
SC03	557	12.52	2.21	0.51	0.019
HWFET	408	8.18	1.67	0.31	0.003

Similar to the measured emission results, describe in the previous Measured Emissions Results section, the estimated emission rates for HWFET were the least, and the CO emission rate for US06 was the highest. However, some other MOVES estimated results are different from the measured, such that the estimated CO emission rate for US06 were, at most, only about twice higher others, and the estimated CO_2 emission rates for SC03 were similar to others (for FTP, UDDS, and US06). The reasons for the differences can be mainly ascribed to the emission factors embedded in MOVES for its emission rate estimates. The emission factors are based on the emission data that EPA collected from different vehicles, so that the emission estimates based on the emission factors do not necessarily represent measured emissions of a vehicle, although some estimate results can be similar to the measured; for example, the estimated CO_2 emissions for HWFET (385 g/mi in Table 5) was similar to the measured one (408 g/mi in Table 6).

More detailed analyses of emission factors of MOVES operation mode bins and measured instantaneous emission results at corresponding driving characteristics (as VSP) for test drive schedules could provide explanations of the differences and reasons for the differences, but such analyses are beyond the scope of this study. TTI researchers, however, examined the differences between MOVES estimates and the in-use on-road emissions results of the test vehicles, which is within the scope of this study.

The average MOVES estimates for each FTP, SFTP, or HWFET testing were compared with the corresponding measured average emission rates (shown in Table 5) and the comparison results are shown in Table 7 as differences in percentage (that is, [MOVES estimates - measured emission rates] / measured emission rates × 100%). For CO_2, as shown in Table 7, the MOVES estimates were similar to the measured for UDDS, US06, and HWFET testing; the differences between MOVES estimates and the measured were less than ±10%, −8%, −4%, and 6% for UDDS, US06, and HWFET, respectively. That is, in general, MOVES estimates were similar to the measured for UDDS, US06, and HWFET testing. For FTP and SC03, the MOVES CO_2 estimates were slightly lower than the measured; MOVES underestimated CO_2 emissions by 13% for FTP testing and by 21% for SC03, as shown in Table 7.

Table 7. Comparisons of Measured Emission Rates to MOVES Emission Rate Estimates.

	Percentage Difference				
	CO_2	CO	NOx	THC	PM
FTP (3-phase)	-13%	244%	153%	38%	329%
UDDS	-8%	833%	357%	376%	N/A*
US06	-4%	-62%	353%	-5%	N/A*
SC03	-21%	450%	278%	619%	N/A*
HWFET	6%	999%	738%	930%	N/A*

* N/A: not applicable (because that the measured PM emission rates were under the detection limits).

For FTP, authors believe that the difference was caused by the effect of cold-start of the first phase, which was not accounted for MOVES. For FTP testing, the first (cold-start) phase, described in chapter 2, increases emissions; by about 6% based on the test results in the following Cold-Start Effects subsection. However, the cold-start effect was not incorporated in the MOVES estimates. If the effect had been incorporated, the difference would have shown about 6% less, that is, −7% instead of −13%. Details for the cold-start effects for CO_2 and other pollutants are discussed in the following subsection.

For SC03, authors believe that the difference was caused by the effect of A/C operations. Following the SC03 SFTP testing procedures, A/C was on operations during the testing. For MOVES estimates, however, the A/C effects could not be incorporated into the emission estimation. Instead, MOVES utilizes its internal algorithm to incorporate A/C operation regarding test conditions (ambient temperature) and VSP. In order to incorporate 100% of A/C operation into the MOVES emission estimations, the following steps need to be conducted:

- Emission rates for each operation mode bin for each driven speed profiles are disaggregated.
- The A/C effects on the emission rates are decoupled using A/C correction factors with respect to ambient temperature conditions for corresponding operation mode bins.
- Using the A/C correction factors, emission rates need to be recalculated for 100% A/C operation.
- The recalculated emission rates for each operation mode bin for each temperature condition for each driven speed profiles are aggregate for the testing.

Due to limited time and resources, it was beyond the scope of this study to conduct such additional calculation processes. Through the on-road in-use testing, however, A/C operation effects were examined using measured emissions as mentioned in Test Protocol section. The examined A/C operation effects are discussed later in A/C Effects subsection in this chapter.

For other pollutants (CO, NOx, THC, and PM), MOVES overestimated emission rates of all pollutants for all testing but CO and THC emission rates for US06 testing, as shown in Table 7. For US06 testing, MOVES underestimate CO and THC by 62% and 5%, respectively. In other words, when MOVES estimated CO and THC emission rates are used for emission inventory reports for the test vehicle with the speed profiles driven for the US06 SFTP testing instead of actual measured emission rates, the reported emissions are lower than actually measure values.

For all other testing (for FTP, UDDS, SC03, and HWFET drive schedules), however, MOVES overestimated CO, NOx, and THC emissions from by 38% (THC for FTP) up to by about 10 times (999%; CO for HWFET) as shown in Table 7. For even the aggressive US06 testing MOVES overestimated NOx emissions by 357%. For PM, only one valid comparison for FTP testing was made, and the comparison showed in Table 7 that MOVE overestimate the PM emission for FTP testing by more than three times (329%); for all other testing, no valid PM comparisons could be made because measured PM values for all other testing were under detection limits. When MOVES estimated emission rates are used for emission inventory reports for the test vehicle for the pollutants along with speed profiles of the corresponding testing, the reported emissions are much greater than actually measured ones.

Based on the comparison results of the test vehicle described above, for most pollutants most testing of the mandatory FTP/SFTP/HWFET drive schedules, MOVES overestimated emissions by up to about 10 times. In other words, when the actual in-use on-road emissions that were measured while following such drive schedules are used for emission inventory reports for the vehicle instead of MOVES estimates of the vehicle along with the drive schedules, the reported emissions would be greatly reduced for most pollutants. Through the comparison results based on a pilot testing with a test vehicle, authors addressed that MOVES estimates of a vehicle would not necessarily represent real-world emissions of the vehicle depending on characteristics of drive schedules.

COLD-START EFFECTS

Using FTP and UDDS testing results, cold-start effects were examined. As described in chapter 2, the first two phases of FTP testing (i.e., phase 1 and phase 2) are exactly same with UDDS testing except for the status of a test vehicle if it is warmed up or not. For the FTP (phase 1 and 2) testing, which is called as UDDS (cold) testing in this subsection, TTI researchers started testing with the test vehicle that had been soaked (or exposed to ambient air without turning on the vehicle) overnight soaking; that is, the test vehicle and its emission control devices were cooled down when the testing started. However, for the UDDS testing, which is called as UDDS (hot) testing in this subsection, the testing conducted with the vehicle and the emission control devices that were already warmed up.

The measured CO_2 and CO emissions results during the UDDS (cold) and (hot) testing are shown in Figure 15. CO emission results, which were affected greatly by the warm-up status of emission control devices of the vehicle, were higher at the beginning for UDDS (cold) as shown as filled red circles connected with a black solid line in Figure 15 than those for UDDS (hot) as shown as unfilled red circle with a black dotted line. Then, CO emissions for both UDDS (cold) and (hot) became similar to each other as time passed while following the UDDS speed profile (shown as a blue solid line in Figure 15), that is, as the vehicle and its emission control devices warmed up. (Figure 15 shows that both emission results overlap as driving time increases.)

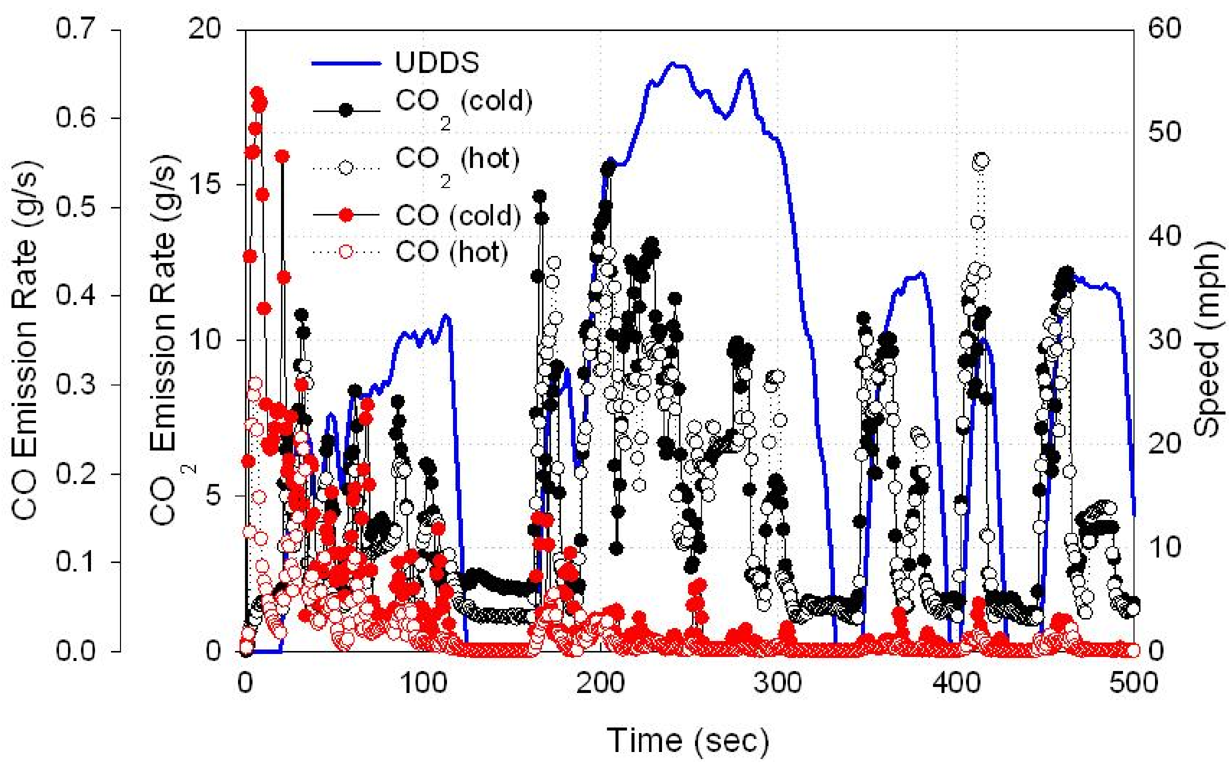

Figure 15. CO_2 and CO Emissions Results for UDDS (Cold) and (Hot) Testing.

For CO_2 emissions, which were not affected by the warm-up status of emission control devices, CO_2 emissions for both UDDS (cold) and (hot) were similar to each other from the beginning, as shown as the overlaps of the CO_2 emission results in Figure 15. Including CO and CO_2, the measured emission rates for the UDDS (cold) and (hot) testing are shown in Table 8 and compared. The compared results (as percentage difference, that is, [measured emission rates for UDDS (cold) - measured emission rates for UDDS (hot)] / measured emission rates for UDDS (hot) × 100%) are also shown in Table 8.

Table 8. Emission Rate and Comparison Results for Cold-Start Effects.

	Average Emission Rate (g/mi)				
	CO_2	CO	NOx	THC	PM
UDDS (cold)	652	3.46	0.79	0.48	0.001
UDDS (hot)	615	1.17	0.42	0.11	UD*
	Percentage Difference				
	6%	196%	88%	337%	N/A**

* UD: under the detection limit

** N/A: not applicable (because that the measured PM emission rates were under the detection limits).

For PM, measured PM concentrations during the UDDS (hot) testing were under the detection limits, so that valid PM emissions could not be reported; as shown as UD, under the detection limit, in Table 8. Therefore, no comparisons between PM emission rates for UDDS (cold) and (hot) are applicable, even though valid PM emission rate, measured for UDDS (cold), was reported in Table 8.

As shown in Table 8, CO_2 emission rates for both of UDDS (cold) and (hot) were similar to each other, only 6% increase, because CO_2 emission is not greatly affected by the warm-up status of the vehicle/emission control devices, as discussed earlier in this subsection. However, emissions other pollutants (CO, NOx, and THC), which are greatly affected by the warm-up status, their emission rates increased greatly from 88% to 337%. Based on the testing with the vehicle, the emissions of the vehicle increased 196%, 88%, and 337% for CO, NOx, and THC, respectively.

A/C Effects (for HWFET schedule)

TTI researchers also examined A/C operation effects on emissions of the test vehicle. In order to examine the A/C effects, TTI researchers followed the HWFET drive schedule with and without turning the A/C system on the vehicle. The measured emission rates of the HWFET testing with A/C system on are shown in Table 9, as HWFET (A/C) testing. Also, the measured emission rates of the HWFET testing with A/C system off are shown shown in Table 9, as HWFET (No A/C) testing. The measured emissions rates were compared and, also, shown in Table 9 as percentage difference, that is, [measured emission rates for HWFET (A/C) - measured emission rates for HWFET (No A/C)] / measured emission rates for HWFET (No A/C) × 100%).

Table 9. Emission Rate and Comparison Results for A/C Effects.

	Average Emission Rate (g/mi)				
	CO_2	CO	NOx	THC	PM
HWFET (A/C)	457	1.15	0.47	0.10	UD*
HWFET (No A/C)	385	0.75	0.20	0.03	UD*
	Percentage Difference				
	19%	53%	135%	233%	N/A**

* UD: under the detection limit

** N/A: not applicable (because that the measured PM emission rates were under the detection limits).

For PM, measured PM concentrations during both testing were under the detection limits, and no PM comparisons were applicable. As shown in Table 9, CO_2 emission rate for HWFET (A/C) were 19% higher than that for HWFET (No A/C). Emissions rates of other pollutants (CO, NOx, and THC) for HWFET (A/C) were increased by 53%, 135%, and 233%, respectively, compared to those for HWFET (No AC), which are greatly affected by the warm-up status, their emission rates increased greatly from 88% to 337%. Based on the testing with the vehicle, the emissions of the vehicle increased 196%, 88%, and 337% for CO, NOx, and THC, respectively. Based on the test results, TTI researchers found that operations of the A/C system while following HWFET drive schedule increased CO, NOx, and THC emissions more than 50%, and CO_2 emissions by about 20%.

CHAPTER 6
CONCLUSIONS

The goal of this study was to develop a methodology to perform mandatory dynamometer vehicular emissions tests on real roads, to conduct in-use real-world emissions tests using PEMS, to analyze the test results, and to compare the test results to the estimates using the current EPA emissions estimation model, MOVES. In addition, TTI researchers studied effects of cold start and A/C operation on emissions. Accomplishments through and findings of this study are summarized below:

- TTI researchers developed a methodology that enables FTP/SFTP emissions testing to be conducted on real roads, instead of current mandatory testing on chassis dynamometers; researchers also modified a test vehicle with adding slave acceleration and brake pedals in the assistant seat for the on-road testing. The methodology is to follow FTP. For SFTP, or any other prescribed drive schedules (such as HWFET) on actual roads by maneuvering the modified vehicles by two people, one focuses to follow the prescribed drive schedules by using the slave pedal, and the other controls the steering wheel on actual roads while the vehicle is driven.

- With using the modified vehicle, TTI researchers conducted pilot emissions testing with following FTP, SFTP, and HWFET drive schedules on Pecos RTC 9-mile circular track based on the developed methodology. During the in-use on-road testing, TTI researchers could follow the speed profiles of the drive schedules most of time (on average, for about 90% or more of time) within the EPA allowable tolerance limits of speed traces, which indicates possibility of replacing and/or supplementing the current relatively expensive dynamometer testing with relatively easy and convenient in-use on-road PEMS testing, especially with test vehicles equipped with better speed control devices and/or by professional drivers.

- During the pilot testing using PEMS, TTI researchers measured emissions of the test vehicle while following FTP (3-phase), UDDS, US06, SC03, and HWFET drive schedules on roads. For PM, the measured emission values for all of drive schedule testing except FTP were under the detection limits. The average emission rates of all measured gaseous pollutants (CO, NOx, and THC as well as CO_2) for HWFET testing were least compared to those for all other testing. For the US06 testing, the CO and THC emission rates were significantly higher than those of other testing. For NOx, the average emission rates of FTP, US06, and SC03 were similar while that of UDDS testing was somewhat lower than those, and that of HWFET was only about one third of those. For CO_2, the average emission rate of SC03 testing was the highest followed by those of FTP, UDDS, US06, and HWFET (626, 615, 572, and 385, respectively). Authors believe that those different measured emission rates for different testing and pollutants were due to different characteristics of test driving schedules, such as cold-start for FTP, frequent stop-and-go situations for FTP and UDDS, aggressive driving (high speed driving and acceleration) for US06, A/C operations for SC03, and for the test vehicle. Additional instantaneous emission analyses (including catalyst emission controls) with respect to each driving characteristics would explain the measured difference and their causes.

- The measured emission results were compared to MOVES estimates obtained with using the driven speed profiles and other parameters such as ambient conditions and fuel type for the vehicle type (31) and model year (1999). In general, MOVES CO_2 estimates were similar to the measured for UDDS, US06, and HWFET testing. For FTP and SC03, the MOVES CO_2 estimates were slightly lower than the measured. For other pollutants (CO, NOx, THC, and PM), MOVES overestimated these emission rates greatly from by 38% (THC for FTP) up to by about 10 times (999%; CO for HWFET) except for CO and THC for US06 Testing. For US06 testing, MOVES underestimate CO and THC by 62% and 5%, respectively. More detailed analyses of VSP based emission factors of MOVES could provide explanations of the differences and reasons for the differences, but such analyses are beyond the scope of this study.

- Using UDDS testing (called as UDDS [hot] testing) and the first two phases of FTP testing, which are exactly same with UDDS testing except that the testing were conducted with the test vehicle that had soaked overnight and also called as UDDS (hot) testing in this report, cold-start effects were examined. CO_2 emission rates for both of UDDS (cold) and (hot) were similar to each other, only 6% increase for UDDS (cold) testing, but emissions of other gaseous pollutants (CO, NOx, and THC) were increased greatly during the UDDS (cold) testing compared to those for the UDDS (hot) testing; from 88% to 337%. For PM, because the measured PM concentrations during the UDDS (hot) testing were under the detection limits, no comparisons could be made.

- With and without operating the A/C system while following HWFET drive schedule, A/C operation effects were also examined. With operations of the A/C system, emissions of the test vehicle increased by 19% for CO_2 and by 53%, 135%, and 233% for CO, NOx, and THC, respectively. For PM, again no PM comparisons were measured because PM concentrations during both testing were under the detection limits.

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