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Study of the Driving Cycle for Heavy Duty Trucks in Hilly Terrain and Its Effect on Calculated Emissions, and Comparison of Two Mobile Emission Models

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To the Graduate Council:

I am submitting herewith a dissertation written by Jeongran Yun entitled "Study of the Driving Cycle for Heavy Duty Trucks in Hilly Terrain and Its Effect on Calculated Emissions, and Comparison of Two Mobile Emission Models." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Joshua S. Fu, Major Professor

We have read this dissertation and recommend its acceptance:

Wayne T. Davis, Chris D. Cox, Mary C. Holcomb

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(Original signatures are on file with official student records.)

Study of the Driving Cycle for Heavy Duty Trucks in Hilly Terrain and Its Effect on Calculated Emissions, and Comparison of Two Mobile Emission Models

A Dissertation Presented for the Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Jeongran Yun
August 2012

DEDICATION

This dissertation is dedicated to my parents and brothers
for their love and constant moral support throughout the course of my study.

ACKNOWLEDGEMENTS

Many people deserve lots of thanks for helping me complete this research. First, I would like to express my sincere gratitude to my major professor Dr. Joshua S. Fu for his support and guidance throughout the course of my doctoral study. He provided me with an opportunity to work with him and finish my doctoral study successfully. Without him, I would not have finished. Next, I would like to acknowledge each of the committee members Dr. Wayne T. Davis, Dr. Chris D. Cox, and Dr. Marry C. Holcomb. I would like to express my sincere gratitude to Dr. Wayne T. Davis for his critical comments and guidance on my dissertation. He spent his valuable time discussing with me. My sincere thanks goes to Dr. Chris D. Cox for giving me an opportunity to finish my doctoral study and serving on my committee. I would also like to thank Dr. Marry C. Holcomb for her comments and help on my dissertation.

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Finally, I would like to thank all my family members and friends who have encouraged me to finish my study.

ABSTRACT

Vehicle emissions were estimated using MOVES2010a and MOBILE6.2 for a Pittsburgh case study involving a modal shift in freight transportion. MOVES2010a (hereafter referred to as MOVES) is currently the USEPA official mobile source emissions computer model; it replaced the older model, MOBILE6.2. Changing the method of hauling freight from highway to waterway is the transport modal shift. Results from this part of the study showed that emission estimates for all vehicle types using MOVES were higher than emissions estimated using MOBILE6.2/NMIM for CO, NO_X, PM_{10}, $PM_{2.5}$, and VOC, but emissions were lower for CO_2 and NH_3 using MOVES relative to MOBILE6.2. For heavy-heavy duty diesel (HHDD) vehicles, higher emissions were estimated using MOVES for all pollutants except for NH_3 when compared to MOBILE6.2. The largest difference between the two models was seen in PM_{10} and $PM_{2.5.}$

The second part of this dissertation focused on driving cycles for HHDD vehicles in hilly terrain and its effect on emissions. The MOVES model incorporates 12 default driving schedules for HHDD vehicles. Each driving schedule represents different average vehicle speeds, which tend to over generalize the driving patterns for these vehicles in hilly terrain. The characteristics of HHDD vehicle driving cycles were analyzed by using actual GPS speed and terrain data from driving activity that occurred on a section of the Federal Interstate to demonstrate possible drawbacks of default driving schedules in the current version of MOVES. Profiles of speed versus time as well as road grades were constructed to validate this. Emissions were calculated using a MOVES' operating mode approach. Results showed that a wider range of speeds and higher scaled tractive power occurred in the driving cycles constructed from the real activity data in hilly terrain than the MOVES default driving schedules. NO_X, $PM_{2.5}$, and THC emissions and total energy consumption calculated using the synthetic driving cycles of the trucks with grades, associated with the hilly terrain, were 7.6%, 14%, 3%, and 11%, respectively, higher than when using the MOVES default driving schedules at the same average speed (63.9 mph) for 0.3% average road grade. On the other hand, CO emissions were 3.4% lower for the synthetic driving cycles. More analyses associated with the driving cycles were presented in this dissertation, and recommendations were made regarding an improvement of default driving schedules in MOVES as well.

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LIST OF ABBREVIATIONS

2BHDDV	Class 2B Heavy-Duty Diesel Vehicles (8,501 through 10,000 lbs GVWR)
AASHTO	American Association of State Highway and Transportation Officials
ARB	Air Resources Board
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTR	Center for Transportation Research
EC	Elemental Carbon
EDM	Emsworth, Dashields, and Montgomery
EMFAC	California's EMission FACtor model
EPA	Environmental Protectioin Agency
FHWA	Federal Highway Administrations
GIS	Geographic Information System
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HDD	Heavy Duty Diesel
HDDV	Heavy Duty Diesel Vehicle
HDDV6	Class 6 Heavy-Duty Diesel Vehicle
HDDV7	Class 7 Heavy-Duty Diesel Vehicle
HDDV8A	Class 8A Heavy Duty Diesel Vehicles
HDDV8A	Class 8A Heavy Duty Diesel Vehicles
HDDV8B	Class 8B Heavy-Duty Diesel Vehicles
HDDV8B	Class 8B Heavy-Duty Diesel Vehicles
HHD	Heavy Heavy Duty
HHDDT	heavy heavy-duty diesel truck
HHDDV	Heavy Heavy-Duty Diesel Vehicles
HHDDV	Heavy Heavy-Duty Diesel Vehicles (33,001+ lbs GVWR)
HHDV	Heavy Heavy Duty Vehicle
HPMS	Highway Performance Monitoring System
Hz	Hertz

kJ	Kilojoule
kW	Kilowatt
LDGV	Light Heavy-Duty Diesel Vehicles
LHDDV	Light Heavy-Duty Diesel Vehicles
MHDDV	Medium Heavy-Duty Diesel Vehicles
MOBILE6.2	Mobile Source Emission Factor Model version 6.2
MOVES	Motor Vehicle Emission Simulator model
MOVES2010a	Motor Vehicle Emission Simulator model version 2010a
NAAQS	National Ambient Air Quality Standards
NCD	National County Database
NEI	National Emission Inventory
NH_3	Ammonia
NMIM	National Mobile Inventory Model
NONROAD	Nonroad Model
NOx	Nitrogen Oxides
OC	Organic Carbon
O-D	Origin-Destination
PM_{10}	Particles with a diameter of 10 micrometers or less
$PM_{2.5}$	Particles with a diameter of 2.5 micrometers or less
ppm	Parts per million
RVP	Redi Vapor Pressure
SCF	Speed Correction Factor
SIP	State Implementation Plan
Stdev	Standard Deviation
STP	Scaled Tractive Power
THC	Total Hydrocarbons
UDDS	Urban Dynamometer Driving Schedule
USEPA	United States Environmental Protection Agency
UT	University of Tennessee
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds

VSP	Vehicle Specific Power

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) recently approved the Motor Vehicle Emission Simulator (MOVES) model for official use in air quality State Implementation Plans (SIPs), transportation conformity analyses, and quantitative carbon monoxide (CO), particulate matter of size less than 2.5 micrometers in diameter ($PM_{2.5}$), and particulate matter of size less than 10 micrometers in diameter (PM_{10}) hot-spot analyses outside California.[1, 2] The latest version of the MOVES model is MOVES2010a (released in August 2010 with a minor update to its predecessor, MOVES2010).[3] MOVES2010a (MOVES) was developed from a large amount of in-use vehicle data, reflecting significant updates from MOBILE6.2. The MOVES model incorporates chassis driving cycles over a wide range of operating conditions to reflect various driving patterns, and the model simulates emissions based on second-by-second emission data. Second-by-second emission data from various sources were compiled and classified by fuel type, engine technology, model-year, engine displacement and vehicle weight of each source (or vehicle) type.[4]

MOVES adopted the operating mode concept, which is defined by vehicle specific power (VSP) and speed, to model emissions. Several factors influence emissions from heavy-duty diesel (HDD) vehicles. The factors include vehicle class, weight, age, speed, acceleration, driving cycle, fuel type, engine exhaust after-treatment, and road terrain.[5, 6] Previous studies showed that vehicle speed, driving cycle, and operating mode had a big impact on emissions. Shah et al. (2004) found that the mode of vehicle operation using a speed trace that applied the California Air Resources Board (ARB) heavy heavy-duty diesel truck (HHDDT) cycle had a strong effect on particulate matter (PM), elemental carbon and organic carbon emission rates.[7] Several studies measured emission factors of HDD vehicles while driven and examined the effects of various driving cycles on emissions. Shah et al. (2006) tested 11 HDD vehicles (model years 1996-2000) using the ARB four-mode driving schedule and urban dynamometer driving schedule (UDDS) and showed emission rates were highly dependent on vehicle operating mode.[8]

They found that NO_X emission rates in units of grams per mile for HDD vehicles, which were operated at low speeds in their simulated congested traffic study, were three times higher than while cruising at freeway speeds.

MOVES contains 12 default driving schedules for HHD vehicles, covering two roadway types: non-freeways and freeways. Driving schedules on the non-freeway roads with lower average speeds involve frequent stop-and-go traffic, which indicates city driving. Driving schedules for highway with higher average speeds do not involve idling mode, which is zero speed. The default driving schedules are limited to model various driving patterns for different terrain characteristics. Even though the model was developed based on a large amount of data, the model does not cover all circumstances or situations of vehicle operation activities. One of the concerns is to identify HHD truck driving data collection needs such as speeds on local roads or driving cycles in hilly terrain.

Several driving cycle schedules have been developed and used in the California's EMFAC model and EPA's MOVES models.[9-11] The microtrip approach is the most wide-ranging for developing driving schedules. A microtrip is defined as a portion of the driving activity curve that starts and ends with zero vehicle speed.[11] Numerous microtrips configurations are tested and a series of them are selected to represent the driving cycle activity data. However, this common methodology only incorporates driving activities, such as speed and time and does not incorporate road grade characteristics into the driving cycles.

Road grade is an important factor affecting emissions. Several studies found that road grade has a significant effect on fuel consumption and emissions in light duty vehicles.[12-14] Cocker (2004a, 2004b) made comparisons of PM and NO_X emissions using a Freightliner tractor between uphill and downhill driving.[15, 16] The study showed that average PM and NO_X emission rates were larger in uphill (171 mg/mi and 24.4 g/mi, respectively) than in downhill (134 mg/mi and 18.4 g/mi, respectively). This study also found that the average NO_X emission factor in EMFAC (13.4 g/mi) was much lower by ~50% than any driving cycles tested in this study such as ARB transient and cruise modes, hot UDDS, and uphill-downhill chase experiments.

The MOVES model predicts emissions using its own default driving cycles. Therefore, modeling emissions using the default driving cycles may result in either overestimation or underestimation in different terrain even with the same average speed. In this study, characteristics of driving cycle in hilly terrain were analyzed using on road driving data of HHDV. The on road driving in hilly terrain can provide different driving patterns that the current default driving schedules do not represent.

1.2 OBJECTIVE

The default driving schedules show a lack of driving patterns that are representative of roads in hilly terrain. The objectives of this study were: (1) to demonstrate how two models, MOVES and MOBILE6.2, estimate heavy-heavy duty vehicle emissions differently by comparing emission estimates using a Pittsburgh case study involving the modal shift in freight transport to show the impacts from the transition of the models from MOBILE6.2 to MOVES2010a; (2) to assess characteristics of driving cycles of heavy-heavy duty trucks in hilly terrain based on real-world drivng activity data; (3) to construct driving cycles of heavy-heavy duty trucks in hilly terrain and compare calculated emissions with emissions caluclated using the MOVES default driving schedules using the model’s operating mode approach. The proposed methodology can be applied in other areas to develop operating mode distribution for estimating emissions and fuel consumption. The developed operating mode distributions in hilly terrain provide additional driving characteristics that the current MOVES model does not include in the default driving schedules.

1.3 OVERVIEW

- Chapter 2 describes the background of the MOVES model and literature review on driving cycle, operating mode, road grade effects on emissions.
- Chapter 3 includes emission estimate comparisons of MOBILE6.2 and MOVES2010a for diesel trucks based on a case study of a modal shift in freight

transportation from Pittsburgh to demonstrate how the two models predict emissions differently.

- Chapter 4 provides analyses of the on road driving data in hilly terrain and methodology of emission estimates using a driving cycle and the results of the anlayses on characteristics of driving cycles of heavy-heavy duty vehicles in hilly terrain. This chapter also includes developing operating mode distributions to reflect driving activity in hilly terrain that can be used in the modeling. Evaluation of the MOVES default driving cycles on freeways is presented as well.
- Chapter 5 provides summaries of the two studies in chapters 3 and 4 and recommendation.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 MOVES MODEL

MOVES2010 is a computer modeling tool that was designed to estimate emissions from on-road or highway vehicles. It is used for evaluating State Implementation Plans (SIPs), transportation conformity analyses, $PM_{2.5}$ hot spot and project level analyses, and the benefits from different mobile source control strategies. The MOVES2010a model was written in Java^{TM} computer code and designed to work with databases which require an external database management system.[17] The MySQL database management system (a subsidiary of Oracle) is included with the MOVES2010a model for this purpose. It is used for the principal user inputs and outputs and for the internal working storage locations for MOVES2010a. A large amount of experimental vehicle data were collected and analyzed since the release of MOBILE6.2[18], which was EPA's previous model that was released 2004 and that was used to simulate vehicle exhaust emissions.

A central concept for MOVES2010a is operating mode. MOVES2010a defines emission rates by speed and power-based operating modes. MOVES2010a subdivides vehicle activity into operating modes that differentiate emissions. Operating modes represent ranges of vehicle speed and vehicle specific power (VSP). The VSP parameter is a function of speed, acceleration and road grade. It also takes vehicle weight, rolling resistance, and aerodynamic drag into account. VSP is in units of kW/tonne, indicating the vehicle tractive power normalized to its weight. There are 17 and 23 operating mode bins for running (travel) energy consumption and outputting exhaust emissions, respectively.[19] Activity based effects on energy and emissions are accommodated in operating mode bins.

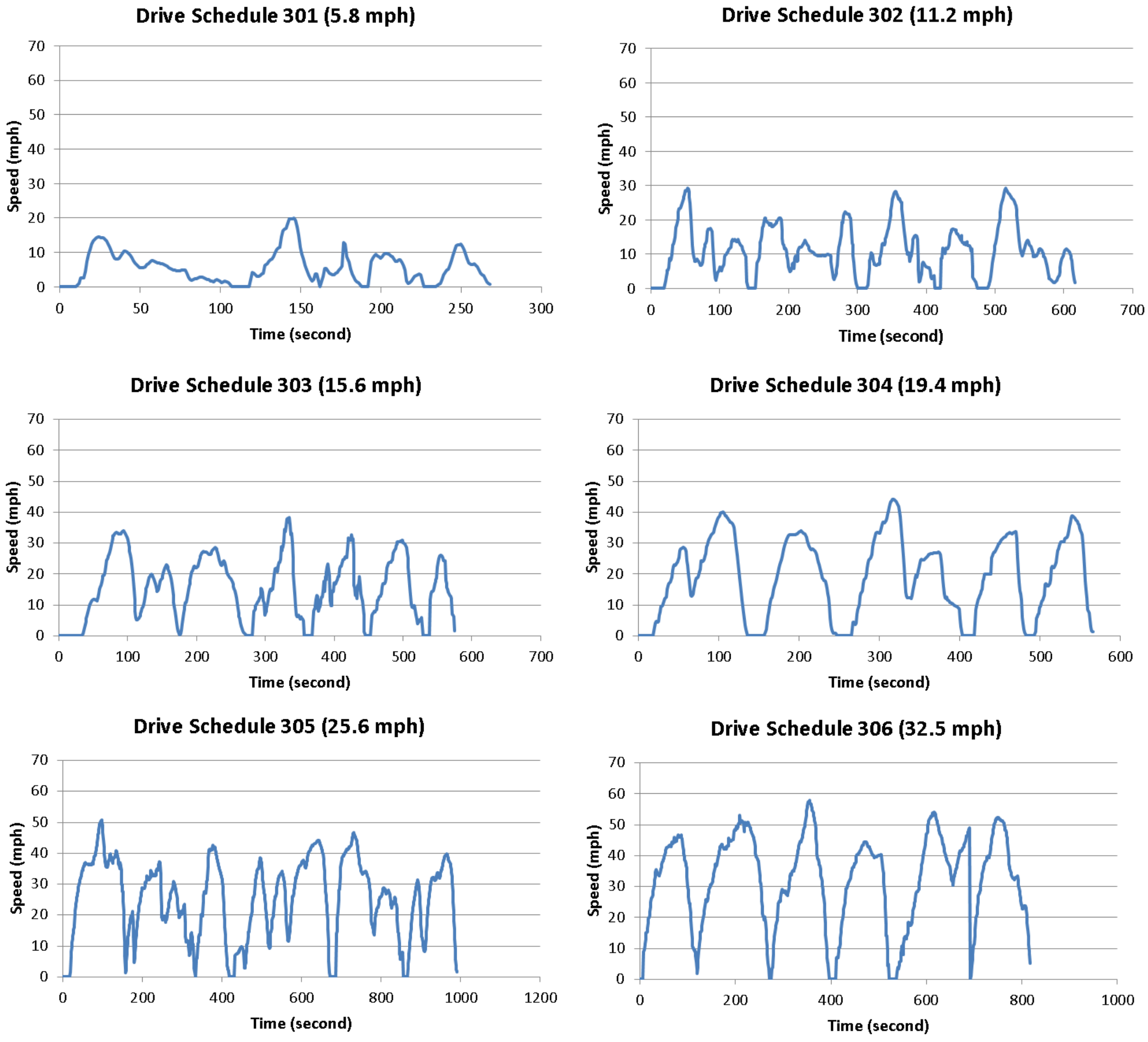
On-road emissions can be analyzed at multiple scales: national level, county level, and project level using different input data.[17] The national scale uses default vehicle fleet and activity data. The county scale uses county level vehicle fleet and activity data supplied by the user and is intended for SIP or regional conformity analyses. The project scale is the finest level, allowing the user to model the emissions effects from a group of roadway links. Project level analysis is limited to one hour of the day. This scale calculates emissions for the user's defined roadway links. The project scale can also be used for quantitative PM hot-spot analyses.[20] PM hot-spot analyses are required for the areas designated as nonattainment areas for PM national ambient air quality standards (NAAQS). EPA has released draft conformity guidance on how to quantify the local air quality impacts of certain transportation projects on the $PM_{2.5}$ and PM_{10} NAAQS.[20]

2.1.1 Three Options in MOVES as an Input for Speed in Project Scale

For project level modeling, depending on the information available for each roadway link, one of three options (an operating mode distribution, a driving schedule or an average speed) can be used as an input to describe the speed, acceleration and power of the vehicles being modeled. When more than one of three options are entered for a given link, the user-supplied operating mode distribution has calculating priority over the driving schedule, which has calculating priority over the average link speed.[17] Both operating mode distribution and link driving schedules inputs are used only in the project scale. The operating mode distribution is required when modeling any non-running emission process such as engine start operation and extended idling in a parking lot. The link driving schedules define the speed in miles per hour and grade in percent as a function of time in seconds on a given roadway link. Use of a link average speed input in the project level requires an average link speed and an average link road grade. If the average speed option is chosen, MOVES selects two default driving schedules based on the average speed and uses an interpolation algorithm to produce a default operating mode distribution for a created new driving cycle for that average speed. Operating modes are "modes" of vehicle activity which have a distinct emission rate. Operating modes are distinguished by Vehicle Specific Power (VSP) and instantaneous speed.[17]

2.1.2 MOVES2010a Default Driving Schedules for HHD

A driving schedule is a series of data points with speed versus time. MOVES2010a has 12 default driving schedules for HHD vehicles: 6 for non-freeways and 6 for freeways.[10] Figure 1 and Figure 2 show the plots of the default driving schedules for HHD vehicles and their associated average speed on non-freeways and freeways, respectively. As shown in the figures, driving schedules in MOVES2010 for non-freeways involve frequent stops. Driving schedules with higher average speed such as 59.7 mph and 71.7 mph do not involve lower speed. For example, speeds for driving schedule 354 (59.7 mph) range from 50 mph to 70 mph. Driving schedule 399 represents ramps.



Drive Schedule 301 (5.8 mph)

Drive Schedule 302 (11.2 mph)

Drive Schedule 303 (15.6 mph)

Drive Schedule 304 (19.4 mph)

Drive Schedule 305 (25.6 mph)

Drive Schedule 306 (32.5 mph)

Figure 1. MOVES Default Driving Schedules for HHD Vehicles on Non-Freeways

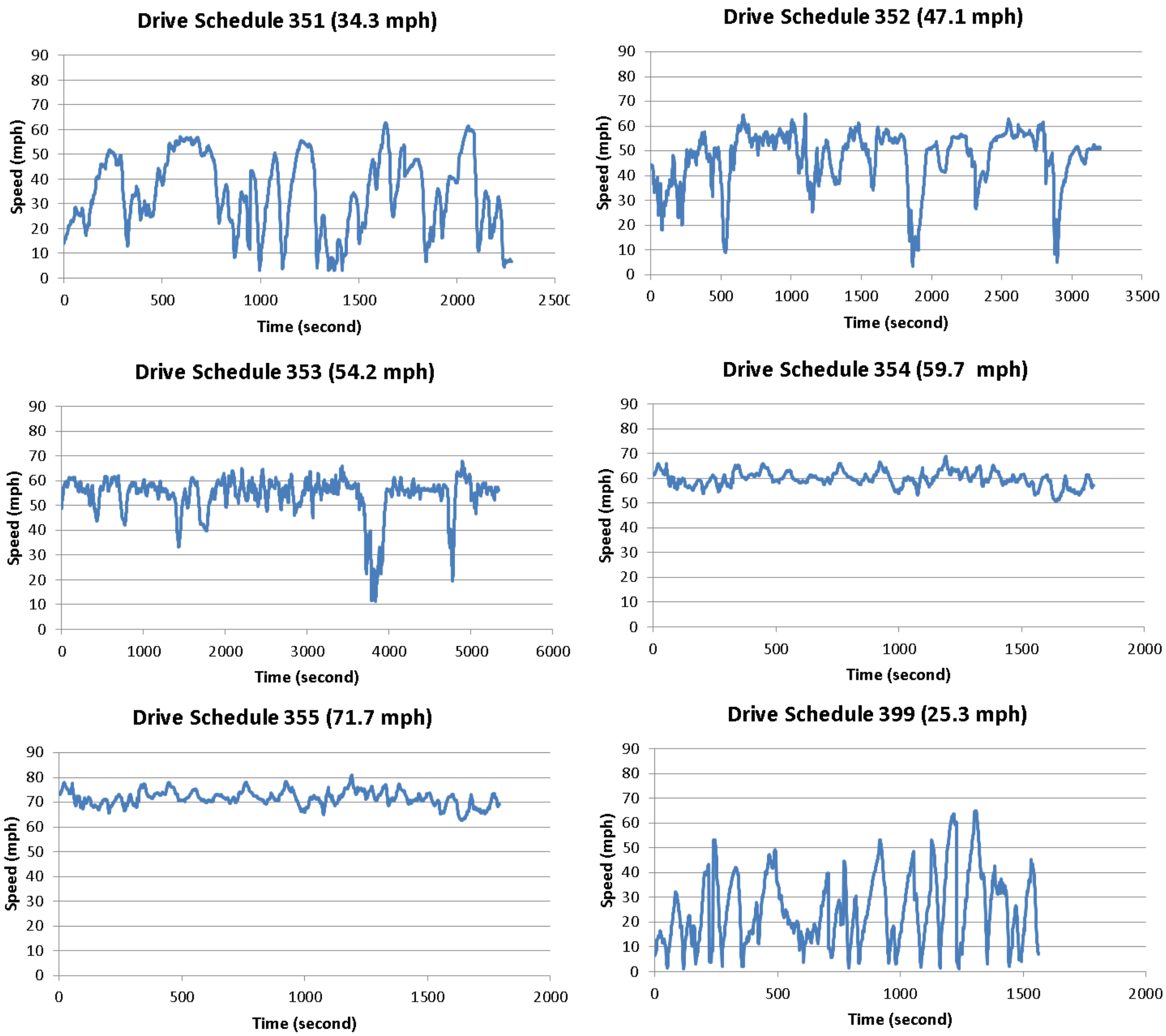


Figure 2. MOVES Default Driving Schedules for HHD Vehicles on Freeways

CHAPTER 3

RESEARCH PART I

Emission Estimate Comparisons of MOBILE6.2 and MOVES2010a using Project Scale for Combination Diesel Trucks with a Case Study of a Modal Shift in Pittsburgh

3.1 INTRODUCTION

MOVES2010a has different inputs and more capabilities than does MOBILE6.2. MOVES2010a inputs include vehicle types, facility types, vehicle population, etc. MOVES2010a can simulate more emission processes than MOBILE6.2, such as extended idle, well-to-pump, etc.[19] Emission estimates are improved in MOVES2010a, compared to MOBILE6.2. For example, MOBILE6 sensitivity analyses demonstrated that input parameters that have a major effect on nitrogen oxides (NO_X) emissions from light duty gasoline vehicles (LDGV) are average speed, min/max temperature command, and registration distribution.[21] In the case of heavy duty diesel vehicles (HDDV), average daily temperature does not affect NO_X emissions, while average speed has an effect on NO_X emissions.[21] Furthermore, MOVES2010a has the capability to estimate $PM_{2.5}$ and PM_{10} from HDDV, accounting for speed variations. Since the application of MOBILE6.2 for PM at the project level was limited, qualitative analyses, not quantitative analyses, were required by the conformity rule for $PM_{2.5}$ and PM_{10} hot-spot analyses when using this model in the past.[22] Quantitative hot-spot analyses for certain transportation projects in $PM_{2.5}$ and PM_{10} nonattainment and maintenance areas can now be supported by project level emission estimates with MOVES2010a.[20]

Emissions affected by speed are modeled differently in MOBILE6.2 and MOVES2010a. In MOBILE6.2, speed correction factors (SCF) are used to adjust emissions resulting from differences in driving behavior.[23] The SCFs are applied to pollutants such as total hydrocarbons (THC), CO, and NO_X, and have different coefficient values for each pollutant. However, there are no SCFs for PM emissions. On the other hand, MOVES2010a uses operating mode, which is defined in terms of instantaneous vehicle speed and Vehicle Specific Power (VSP).[19] Emissions are stored by operating modes. MOVES2010a can estimate emissions using any driving patterns as well as average speeds. Using average speeds, the model calculates operating mode distribution by using a pair of driving schedules, one of which has a slightly higher average speed and one of which has slightly lower average speed than the average.[19]

MOVES2010a has capabilities to calculate inventory (i.e., emissions as mass) as well as emission rates (i.e., mass per unit of activity), while MOBILE6.2 generates only emission factors in grams per mile. The benefit of the inventory option in MOVES2010a is that the model does not require post-process to calculate emissions outside the model.

The default vehicle miles traveled (VMT) data in MOVES were collected from different sources: Federal Highway Administration's Highway Statistics for base year VMT; Department of Energy's Annual Energy Outlook to forecast VMT growth and vehicle sales growth.[24] Use of the default data in the model may not represent local emissions. With county domain/scale, users can supply local data for activity and fleet inputs. With project domain/scale, the model runs at the link level with user-supplied data.

A comparison of MOVES2010 to MOBILE6.2 performed by the EPA using local data for several selected counties showed that in general volatile organic compounds (VOCs) emissions from MOVES2010 are lower compared to emissions from MOBILE6.2, while both NO_X and PM emissions are higher when all vehicle types were considered.[22] Claggett showed that MOVES2010 estimates higher emissions for NO_X, $PM_{2.5}$, and diesel PM and lower emissions for CO and VOCs than MOBILE6.2, even though emission results from MOVES2010 and MOBILE6.2 are different in many respects.[25] However, these results were based on composite emissions for all vehicle types. Since MOVES2010a is capable of modeling speed effects on HDDV emissions, it is interesting to find out how emission estimates of HDDV emissions using the MOVES2010a model are different from using the MOBILE6.2.

The objective of this part of the dissertation research was to show the impact on predicted emissions from the transition of MOBILE6.2 to MOVES2010a. Emission estimates from the two models were calculated using a case study that involved the modal shift from barges to trucks due to the temporary closure of waterway locks in the Pittsburgh area. Detailed information about the case study is described in the following section. A comparison between MOBILE6.2

and MOVES2010a was made in: 1) VMT, 2) emission estimates for all vehicle types and HDDV with 2008 national county database (NCD), and 3) emission estimates for increased heavy truck volumes from the case study. To date, few applications of the MOVES2010a model have been published. The analyses demonstrated how the two models estimate emissions differently by focusing on HDDV using project domain/scale. This study can assist other modelers to understand the application of the MOVES2010a model for PM project level analyses for heavy duty trucks and other purposes.

3.2 BACKGROUND

3.2.1 Case Study Area

The city of Pittsburgh is the location of the case study area. It is located where the Allegheny River and the Monongahela River merge to form the Ohio River. Inland waterways are important freight transportation systems in this area. Emsworth, Dashields, and Montgomery (EDM) are three of the six major lock and dam facilities on the Ohio River in the Pittsburgh District. Figure 3 shows the study area and locations of the EDM locks and dams, including the river and roadway links along the river in Allegheny and Beaver Counties. Truck routes were identified for the transportation of each commodity. The line in red, shown in the figure, indicates the truck routes that include 44 (road) links associated with the study area. Based on the diversion of commodities and routing of trucks, the study area was limited to the Pittsburgh area.

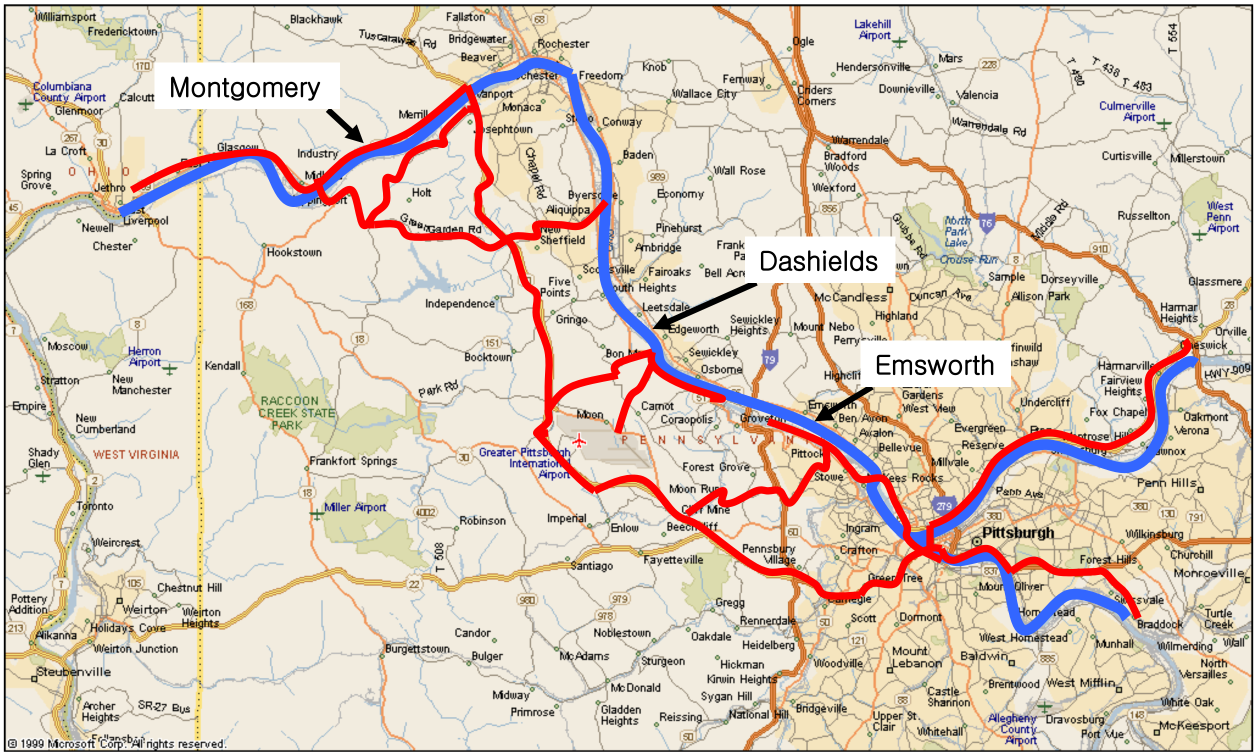


Figure 3. Study Area

3.2.2 Data Source

The University of Tennessee (UT) Center for Transportation Research (CTR) developed Origin-Destination (O-D) pairs with the information of the commodity type and annual tonnage for each commodity flow.[26] The O-D pairs are shown in Table 1. From field interviews, the CTR determined origins and destinations for the commodities shipped to or from each terminal. To prepare for possible lock outages, alternative truck routes for some truck movements were provided by the freight companies. The MapQuest program was used to verify established routes. The CTR staff visited Pittsburgh and drove each route to verify that it was reasonable. The affected transportation network was divided into a number of links within the study boundary. The road types used in the study included portions of river and urban arterials, freeways, expressways, bridges, and tunnels. The route segments were portions of Pennsylvania routes 22, 28, 30, 51, 60, 65, 68, 168, 279, and 837; interstate highways 279 and 376; and named roads including Shipping Port Road, Green Garden Road, Mill Street, Kennedy, Aliquippa, Franklin

Street, Braddock Avenue, Carston Street, West End Bridge, McKeesport Bridge, and access roads, Fleming Bridge, Neville Road, University Avenue, Fairhaven Run, Cleaver, Beaver, and Montour Roads.

The longest link was 13.83 miles while the shortest link was 0.11 miles. The link most heavily impacting traffic congestion by the truck diversion was Carston Street. It was a narrow urban arterial road located near the water terminals. Moreover, the interstate highways coming into or leaving the Pittsburgh City limits, roads in the industrial area along the rivers, and bridges across the rivers would be significantly impacted by additional truck traffic.

Table 1. O-D Pairs with Commodity Type and Annual Tonnage for Each Commodity Flow

Sequence	Commodity	Origin	Destination	Shipment from the note (tons/yr)
1	Ferrous Scrap	3100 Grand Ave, Neville Island, PA	13th st & Braddock Ave, Braddock, PA	42,716
2	Flat Rolled Steel	13th st & Braddock Ave, Braddock, PA	2217 Michigan Ave, East Liverpool, OH	168,034
3	Manufactures of Metal	Vandergrift, PA	2217 Michigan Ave, East Liverpool, OH	150,000
4	Pig Iron	2701 Route 68, Industry, PA	100 River Rd, Brackenridge, PA	49,500
5	Pig Iron	2701 Route 68, Industry, PA	1 5th st, New Kensington, PA	49,500
6	Petroleum Coke	16th & Nevada St, Wellsville, OH	100 River Rd, Monaca, PA	17,642
7	Jet Fuel	Hwy 68, Midland, PA	Pittsburgh International Airport, Pittsburgh, PA	357,060
8	Salt, Steel Rod & pipe, Aggregate, Grain, Lime, Coking Coal	401 Pennsylvania Ave, Weirton, WV	McKeesport, PA	61,659
9	Pig Iron	2701 Route 68, Industry, PA	700 Riverside Dr, Freeport, PA	18,757
10	Pig Iron	2701 Route 68, Industry, PA	100 River Rd, Brackenridge, PA	12,264
11	Pig Iron	2701 Route 68, Industry, PA	1 5th st, New Kensington, PA	12,264
12	Pig Iron	2701 Route 68, Industry, PA	681 Andersen Dr, Pittsburgh, PA	48,191
13	Crushed Stone	100 River Rd, Monaca, PA	819 Pennsylvania Ave, Coraopolis, PA	177,650
14	Crushed Stone	16th & Nevada st, Wellsville, OH	700 Riverside Dr, Freeport, PA	20,205
15	Gypsum	2701 Route 68, Industry, PA	1 Woodlawn Rd, Aliquippa, PA	354,943
16	Crushed Stone & Limestone Flux	100 S 3rd st, Pittsburgh, PA	3500 Neville Rd, Neville Island, PA	620,828
17	Sand & Gravel	819 Pennsylvania Ave, Coraopolis, PA	2220 Second Ave, Pittsburgh, PA	28,357
18	Petro-coke, Asphalt	3801 23rd st Southwest, Canton, OH	Clairton, PA	168,951
19	Petroleum Products	425 River Rd, East Liverpool, OH	700 Riverside Dr, Freeport, PA	23,959
20	Foodwaste, Animal Feed	2217 Michigan Ave, East Liverpool, OH	700 Riverside Dr, Freeport, PA	30,000
21	Coal	2701 Route 68, Industry, PA	200 Neville Rd, Neville Island, PA	813,463
22	Coal	Jackson st, East Liverpool, OH	(151-227) Porter st, Springdale, PA	479,129
23	Coal	Jackson st, East Liverpool, OH	Schenley, PA	110,781

3.3 METHODS

To quantify the increase in truck emissions due to the modal shift, commodity movement and new truck volumes for each O-D pair were estimated. Annual emissions were estimated for all vehicle types in 2008 as well as heavy heavy-duty diesel vehicles using both MOBILE6.2/NMIM and MOVES2010a. From the field interviews by CTR and tabulations from the Waterborne Commerce Statistical Center database, it was learned that 4.4 million annual tons of commodities could be potentially diverted to truck transportation. The assumption of the duration of the lock outages in this study was 60 days.

3.3.1 Estimates of New Truck Volumes due to Lock Closure

Commodity type and annual tonnage with O-D pairs shown in Table 1 were used to estimate diverted truck traffic volumes from barges. For some commodities, origins and destinations were not known and excluded in this analysis. Therefore, total commodities used in the analysis were 3.8 million annual tons. The commodities were aggregated into 23 distinctive origin-destination pairs including three for coal movements and the others for non-coal movements. Truck loads by commodity were assumed to be 23.5 tons. All truck movements were doubled to represent round trip.

To estimate increased truck volumes on each road network segment, the following steps were taken: 1) identify an annual tonnage of each diverted commodity between an O-D pair, 2) convert the annual tonnage to annual truck movements for each O-D pair, 3) assign annual trucks on each segment of the road for each O-D pair and sum the annual trucks on each segment to obtain the total truck volume, 4) convert annual truck volumes for each segment to hourly truck volumes by assuming that diverted truck traffic distribute uniformly between 6 a.m. and 6 p.m.(daylight) and between 6 p.m. and 6 a.m. (nighttime). As an example of the estimates of truck volumes, flat rolled iron and steel of 168,034 annual tons were assigned to trucks loaded at 23.5 tons per truck for shipment during daytime hours. This was equivalent to 14,300 truck movements per year, or 4 truck movements per hour during daytime hours.

3.3.2 2008 Emission Estimates Using MOBILE6.2/NMIM for All Vehicles and Heavy Heavy-Duty Diesel Vehicles

Annual on-road emissions in Allegheny and Beaver Counties for 2008 were calculated for all vehicle types and Heavy Heavy-Duty Diesel Vehicle (HHDDV) using MOBILE6.2/NMIM. NMIM develops estimates of emission inventories for on-road vehicles and non-road equipment, incorporating EPA's MOBILE6 and NONROAD models.[27] For a comparison with the emissions estimated using the MOVES2010a model, MOBILE6.2/NMIM was run for emissions for 2008 with National County Database (NCD) inputs. NCD12012010, which was used for version one estimates of the EPA's 2008 National Emission Inventory (NEI), included all NCD inputs submitted by November 2010 by state and local agencies.[28] In MOBILE6.2/NMIM, HDDVs are classified as following:[27]

1) 2BHDDV: Class 2B Heavy-Duty Diesel Vehicles (8,501 through 10,000 lbs gross vehicle weight rating (GVWR)),
2) LHDDV: Light Heavy-Duty Diesel Vehicles (10,001 through 19,500 lbs GVWR),
3) MHDDV: Medium Heavy-Duty Diesel Vehicles (19,501 through 33,000 lbs GVWR),
4) HHDDV: Heavy Heavy-Duty Diesel Vehicles (33,001 + lbs GVWR),
5) Buses: all diesel transit and school buses.

In this study, HHDDV in MOBILE6.2/NMIM was selected for a comparison with diesel fueled combination trucks in MOVES2010a.

For HHDDV emission estimates from added truck volumes, MOBILE6.2 was run to obtain emission factors for HDDV8A (Class 8A Heavy Duty Diesel Vehicles with 33,001-60,000 lbs. GVWR) and HDDV8B (Class 8B Heavy-Duty Diesel Vehicles with >60,000 lbs. GVWR), which are equivalent to HHDDV, for each speed range from 2.5 to 62.5 mph in 5 mph increments. HDDV8A and HDDV8B emission factors were averaged and used for HHDDV emission factors. Heavy truck emissions from added truck volumes were derived as follows:

$$EM = \sum_{speed=i}^{n} (EFi * VMTi) \qquad \text{Equation (1)}$$

where, EM = emissions (grams)

i = 2.5 to 62.5 mph in 5 mph increments

EF = emission factor (grams/mile)

VMT = vehicle miles traveled (miles)

Inputs to the model included national average age mix of HDDV8A and HDDV8B, minimum/maximum temperature of 66/85 F degrees, humidity of 75 grains per pounds, gasoline Reid Vapor Pressure (RVP) of 7.8 pounds per square inch (psi), and diesel sulfur content of 43 parts per million (ppm).[29]

3.3.3 2008 Emission Estimates Using MOVES2010a for All Vehicles and Combination Diesel Trucks

Annual on-road emissions in Allegheny and Beaver Counties for 2008 were calculated for all vehicle types and diesel fueled combination short-haul and long-haul trucks using MOVES2010a. For a comparison with MOBILE6.2/NMIM, MOVES2010a was run with a county domain/scale with local input data, which were converted from 2008 NCD in MOBILE6.2/NMIM. Those inputs included age distribution, average speed distribution, road type distribution, vehicle type VMT, and meteorology data. Defaults were used for source type population, fuel supply and formulation.

Emissions from increased truck volumes were calculated for each roadway link for daytime and nighttime separately, using a project domain/scale in MOVES2010a. In order to model effects of vehicle power, speed, and acceleration, MOVES2010a has three options: average speed, operating mode distribution, and link driving schedule.[30] In the first study of the dissertation, the average speed option was used. As inputs to the model, truck average speeds, increased truck volumes, and link length for each road link were used. These inputs are listed in Table 2. Average road grade was assumed to be zero to be consistent with estimates using MOBILE6/NMIM, which does not support road grade effects. Combination long-haul truck was selected for a vehicle type to calculate emissions from the added truck volumes. Evaluated pollutants included PM_{10}, $PM_{2.5}$, NO_X, VOCs, CO, carbon dioxide (CO_2), and ammonia (NH_3).

Table 2. Link Summary: Truck Volumes, Average Speed, and Distance for Each Link

	Route	From	To	Route type	Lanes per dir	1-way miles	New non-coal trucks		New coal trucks		Avg. Speed
							per hr-day	per hr-night	per hr-day	per hr-night	
1	68	168 bridge	intermediate point	river arterial	1	1.14	14	3	14	14	39.64
2	68	intermediate point	Rt 60, exit 13	river arterial	1	3.80	12	8	14	14	39.65
3	68	168 bridge	Pa line	river arterial	1	2.38	15	4	14	14	21.58
4	68	pa line	East Liverpool/Bushwick Ave	river arterial	1	11.02	14	4	14	14	30.01
5	168	68	Shippingport Road	Bridge	1	1.01	19	1	0	0	39.65
6	Shippingport Road	168 bridge	Green Garden	rolling/curves	1	2.69	19	1	0	0	43.60
7	Green Garden	Shippingport	Rt. 60, Ex 10	rolling/curves	1	5.04	18	0	0	0	47.55
8	Pa 18	Shippingport	Rt. 60, Ex 12	rolling/curves	1	5.94	1	1	0	0	47.55
9	Mill St/Kennedy/Aliquippa	Rt. 60 Ex 10	mid-pt.	flat	2	2.41	9	0	0	0	31.95
10	Franklin St. Aliquippa	Mid-pt.	Rt. 51	flat	1	1.17	9	0	0	0	27.76
11	Rt. 60	Ex 13	Ex 12	freeway bridge	2	1.10	12	8	14	14	62.34
12	Rt. 60	Ex 12	Ex 10	freeway	2	8.51	17	8	14	14	62.30
13	Rt. 60	Ex 10 Green Garden	Ex 9	freeway	2	3.00	26	8	14	14	62.30
14	Rt. 60	Ex 9 Gringo	Ex 8 60 split	freeway	2	2.15	26	8	14	14	62.09
15	Rt. 60	Ex 8 split	Ex 6 I-576 airport	freeway	2	3.21	21	8	14	14	62.15
16	Rt. 60	Ex 6	Ex 2 Montour	freeway	2	4.96	20	8	14	14	60.58
17	Rt. 60	Ex 2	Rt 22 Moon	freeway	2	1.56	20	8	7	7	57.55
18	22/30/279	Rt. 22	Ex 4A Greentree	freeway	2	7.00	21	8	7	7	46.50
19	I-279	Ex 4A	Ex 5A Rt 19	freeway	2	0.79	19	8	7	7	54.45
20	I-279	Ex 5A	End of tunnel	freeway/tunnel	2	1.94	19	8	7	7	16.87
21	I-279 to I-376	Fort Pitt Tunnel East End	North End Ft. Pitt Bridge to I-376	freeway/bridge	2	0.54	19	8	7	7	8.19
22	I-279	North End of Ft. Pitt Bridge	Ft. Duquene Bridge to I-279	freeway/bridge	2	0.54	8	5	7	7	41.05
23	Pa 279	Ft. Duquene Bridge	Ex 28 split	expressway	2	1.41	8	5	7	7	43.60
24	Pa 28	Ex 28 split	Ex 11	freeway	2	13.83	8	5	7	7	61.69
25	I-376	Ft. Pitt Bridge	Ex 1C	freeway	2	1.00	11	3	0	0	62.02
26	I-376	Ex 1C	Ex 7 Braddock	freeway	2	5.91	10	3	0	0	50.05
27	837-Carston	3 street	Intermediate Point	urban arterial	1	1.00	6	3	0	0	3.40
28	837-Carston	intermediate point	US 19 Westend Bridge	urban arterial	2	0.90	6	3	0	0	21.00
29	West End bridge	Rt. 51	Pa 65	bridge	2	0.42	15	0	0	0	62.28

3.3.4 PM and CO_2 Emission Calculations in MOVES2010a

PM emissions consist of exhaust emissions (organic carbon, elemental carbon, and sulfate particulate), brake-wear and tire-wear particulates. Processes for exhaust emissions include running exhaust, start exhaust, extended idle exhaust, and crankcase running, start, and extended idle exhaust. MOVES2010a uses the operating mode concept and provides unique emission rates for each mode.[19] PM emissions in the model are calculated with activity data by applying operating mode distributions, fuel adjustment, and temperature adjustment. For example, the first calculation for running exhaust emissions of organic carbon (OC) and elemental carbon (EC) $PM_{2.5}$ in the model is weight emission rates by operating mode as follows:[19]

$$OMBR = \sum_{OperatingModeBin=i}^{no.ofOperatingModebins} OMFi * MBRi \qquad \text{Equation (2)}$$

where, OMBR represents operating mode weighted mean base rate

OMF represents operating mode fraction

MBR represents mean base rate (in “EmissionRate” table in MOVES2010a default data).

i = operating mode bins, 1 to 23

PM_{10} emissions are ratios to $PM_{2.5}$ emissions. PM_{10} emissions are calculated as follows:[19]

$$EmissionQuantityofPM_{10} = EmissionQuantityofPM_{2.5} * PM_{10}EmissionRatio$$

Equation (3)

Atmospheric CO_2 emissions in the model are calculated as follows:[19]

$$AtmosphericCO_2 = TotalEnergy * OxidationFraction * CarbonContent * (44/12)$$

Equation (4)

3.4 RESULTS AND DISCUSSION

3.4.1 Truck Volume for Each Link

Truck volumes for each link were estimated and used to quantify the impacts of a modal shift on truck emissions. Estimated truck volumes for day and night time are shown in Table 2. The results showed, for example, that truck volumes on link 1 for non-coal movement were 14 trucks and 3 trucks per hour for day and night, respectively. Hourly truck volumes for coal movement were 14 trucks each for both day and night times, respectively. The analysis showed that the modal shift would add 1,080 trips each day to the traffic. The average added hourly truck movement in the area was equal to 67 trips per daytime hour and 23 trips per nighttime hour.

3.4.2 2008 Emissions Estimated Using MOVES2010a and MOBILE6.2/NMIM

Annual on-road emissions for all vehicle types and HHDDV in Allegheny and Beaver Counties for 2008 were calculated using both MOVES2010a and MOBILE6.2/NMIM and compared to each other. There were discrepancies between default VMT in MOVES2010a and local VMT in 2008 NCD. Default total VMT of 2008 in MOVES2010a was 27% higher than VMT in 2008 NCD in NMIM for both counties and 41% higher for default VMT of combination diesel trucks. For emission estimates, VMT from 2008 NCD was converted to a format of MOVES2010a. The total VMT used in the two models was the same: 9,227 million miles per year (Allegheny County) and 1,434 million miles per year (Beaver County). However, the VMT of diesel fueled combination short-haul and long-haul trucks in MOVES2010a were approximately 2% higher than HHDDV in MOBILE6.2/NMIM. This is because the two models use different vehicle classifications. MOBILE6.2/NMIM uses vehicle classifications according to the EPA emission classifications while MOVES2010a uses source (or vehicle) types that are subsets of the Highway Performance Monitoring System (HPMS). A mapping scheme provided by the EPA was used to transform VMT from MOBILE6.2 vehicle types to MOVES source types.[30] Table 3 shows the VMT mapping scheme. As shown in the table, 90% of the HDDV8A and HDDV8B VMT were assigned to diesel fueled combination short-haul and long-haul trucks. Furthermore, 38% of each of HDDV6 (class 6 heavy-duty diesel vehicle with 19,501 – 26,000 lbs. GVWR) and HDDV7 (class 7 heavy-duty diesel vehicle with 26,001 – 33,000 lbs. GVWR) were also assigned to combination trucks. It should be noted that in this dissertation research, HHDDV (HDDV8A and HDDV8B) were compared with combination diesel trucks.

Figure 4 shows the percent difference in 2008 emission estimates between the two models for all vehicle types as well as combination diesel trucks (MOVES2010a) versus HHDDV (MOBILE6.2/NMIM) in Allegheny and Beaver Counties. There were differences in the percent change between the two models in both counties. However, overall patterns were similar. Using the same total VMT in both models, MOVES2010a estimated CO, NO_X, PM_{10}, $PM_{2.5}$, and VOCs emissions from all vehicles higher than MOBILE6.2/NMIM except for NH_3 and CO_2 in both counties. When emissions were compared for only combination diesel trucks in MOVES2010a with HHDDV in MOBILE6.2/NMIM, emission estimates of all pollutants using MOVES2010a were higher than using MOBILE6.2/NMIM except for NH_3 in both counties. The biggest differences were seen in $PM_{2.5}$ emissions. MOVES2010a estimated $PM_{2.5}$ from combination diesel trucks at approximately 178% and 197% higher than MOBILE6.2/NMIM for Allegheny and Beaver counties, respectively.

Table 3. VMT Mapping from MOBILE6.2 Vehicle Types to MOVES Source Types

MOBILE6.2 Vehicle Type	Combination short-haul truck	Combination long-haul truck	Single unit short-haul Truck	Single unit long-haul truck	Refuse truck	Motor home	Total
20 HDDV6	0.27	0.11	0.55	0.05	0.01	0.01	1
21 HDDV7	0.27	0.11	0.55	0.05	0.01	0.01	1
22 HDDV8A	0.42	0.48	0.08	0.01	0.01	0	1
23 HDDV8B	0.42	0.48	0.08	0.01	0.01	0	1

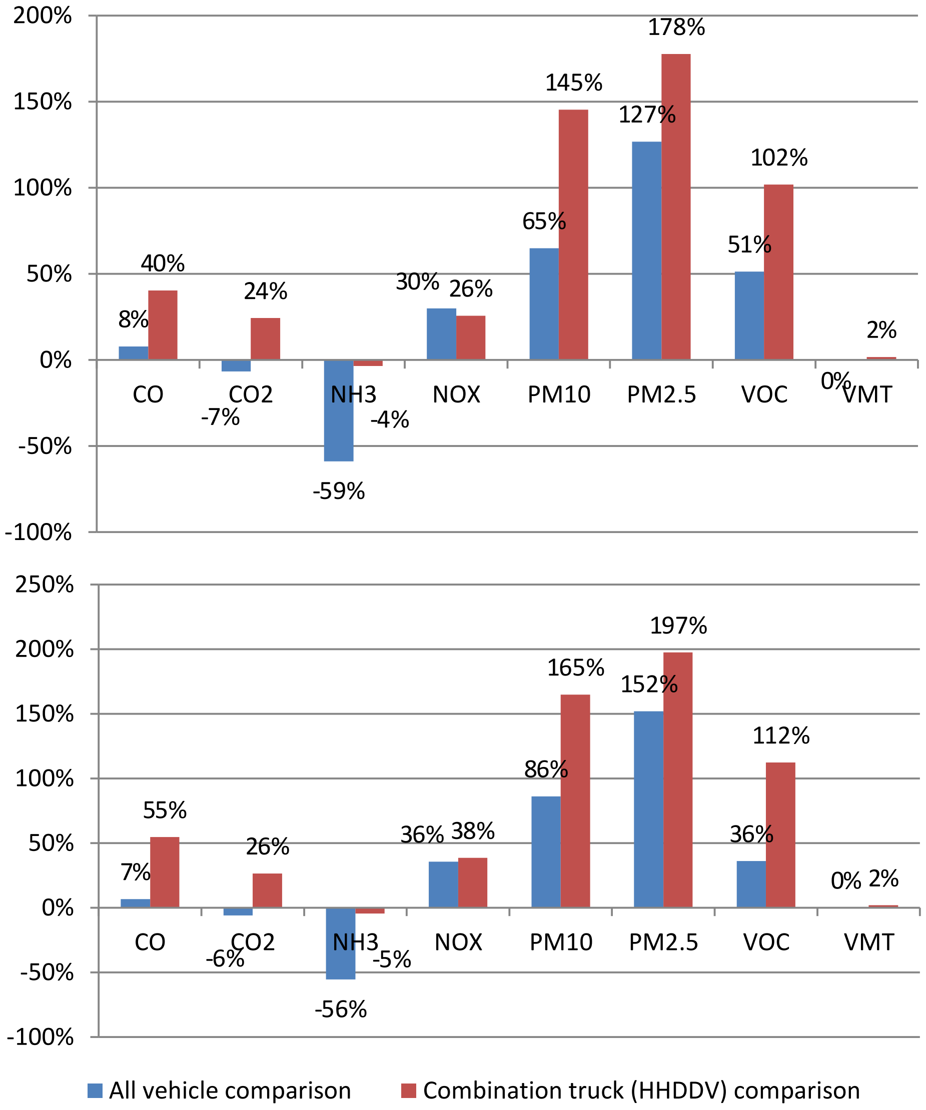


Figure 4. MOVES2010a Emissions in Percent Difference, Compared with MOBILE6.2/NMIM Emission Estimates for 2008: (a) Allegheny County and (b) Beaver County

3.4.3 Emissions from Diverted Trucks Estimated Using MOVES2010a and MOBILE6.2/NMIM

Truck emissions due to diverted trucks were estimated using both models. The diverted total cargo volumes were approximately 3.8 million tons per year. With the cargo volumes, the estimated increase of daily truck volumes were 1,080 trucks with 45,497 miles per day of VMT.

The results of emission estimates from the increased truck volumes using the two models were compared and summarized in Table 4. Using the same VMT and truck volumes, MOVES2010a estimated more emissions for CO by 101%, CO_2 by 32%, NO_X by 36%, PM_{10} by 250%, $PM_{2.5}$ by 293%, and VOCs by 110% than MOBILE6.2. However, MOVES2010a estimated NH_3 4% lower than MOBILE6.2. In general, MOVES2010a estimated more emissions for diesel-fueled combination trucks than HHDDV from MOBILE6.2. $PM_{2.5}$ emissions showed the biggest difference, which was 293%.

Table 5 shows average daily emissions in 2008 for all vehicles and HHDDV for both models, as well as the increase in daily emissions from the additional trucks due to the modal shift in freight transportation. The percent increase in emissions compared with average daily emissions are also shown in the table. For both models, the estimated emissions increased from the higher truck volumes. For MOVES2010a, the range was 0.06% to 2.85% for all pollutants and it was 0.03% to 1.67% for all pollutants for MOBILE6.2/NMIM. When compared with 2008 total combination truck emissions, increased combination truck emissions estimated using MOVES2010a accounted for 5.03% to 7.5% with 5.35% of VMT increase as compared to 4.68% to 5.51% increase with 5.44% using MOBILE6.2/NMIM.

Table 4. Heavy Duty Truck Emission Estimates for All Links Estimated Using Both Models

Model	VMT (miles/day)	CO	CO_2	NH_3	NO_X	PM_{10}	$PM_{2.5}$	VOCs
					(tons/day)			
MOVES2010a	45,497	0.226	106	0.001	0.890	0.052	0.048	0.040
MOBILE6.2	45,497	0.112	80	0.001	0.657	0.015	0.012	0.019
% difference	0%	101%	32%	-4%	36%	250%	293%	110%

Table 5. Increase in Emissions from Additional Trucks, Compared with Annual Daily Average Emissions for 2008 Estimated Using Both Models

	CO	CO_2	NH_3	NO_X	PM_{10}	$PM_{2.5}$	VOCs	VMT (miles/day)
				(tons/day)				
MOVES2010a								
All vehicles	409	13,951	1.26	55.8	2.04	1.67	32.0	29,206,925
Combination diesel trucks	3.41	1,854	0.02	15.2	0.69	0.64	0.79	850,639
Additional Trucks	0.226	106	0.001	0.890	0.052	0.048	0.040	45,497
% increase compared with all vehicles	0.06%	0.76%	0.10%	1.60%	2.55%	2.85%	0.12%	0.16%
% increase compared with combination diesel trucks	6.62%	5.69%	5.44%	5.86%	7.50%	7.42%	5.03%	5.35%
MOBILE6.2/NMIM								
All vehicles	380	14,929	3.03	42.7	1.22	0.73	21.5	29,206,930
HHDDV	2.40	1,488	0.02	11.9	0.28	0.23	0.39	835,825
Additional Trucks	0.112	80	0.001	0.657	0.015	0.012	0.019	45,497
% increase compared with all vehicles	0.03%	0.53%	0.04%	1.54%	1.22%	1.67%	0.09%	0.16%
% increase compared with HHDDV	4.68%	5.36%	5.43%	5.51%	5.31%	5.29%	4.88%	5.44%

3.4.4 Speed Effects on Emissions from HHDDV in MOVES2010a and MOBILE6.2

MOVES2010a improved speed effects on PM, NH_3, and CO_2 emissions from HHDDV. The HHDDV mean base rates for running exhaust emissions for the three pollutants were plotted against operating modes. Emissions were plotted for all vehicle model years accounting for age based on the calendar year 2008. The results shown in Figure 5 (a) are the mean base rates of $PM_{2.5}$ (EC + OC) and NH_3 running exhaust emissions by operating mode for 2008; Figure 5 (b) presents the mean base rates of total energy consumption and CO_2. It should be noted that the mean base rates of CO_2 were calculated from total energy consumption as described in the methods section. As shown in Figure 5, $PM_{2.5}$ emissions in the model have age effects while NH_3 and CO_2 emissions do not. Fuel and temperature adjustments are applied to the mean base rates to calculate emission rates.

For a comparison with MOBILE6.2, MOVES2010a composite emission rates in grams per mile from combination long-haul trucks for year 2008 were calculated for each speed, which represented consistent speed over time. Figure 6 shows composite emission rates of $PM_{2.5}$ (EC + OC), CO_2, and NH_3 from HHDDV by speed, MOBILE6.2 versus MOVES2010a, for year 2008. As shown in Figure 6, MOBILE6.2 does not show any emission rate variations on HHDDV $PM_{2.5}$, NH_3, and CO_2, while MOVES2010a shows that emission rates are varied by speed.

From the results in the earlier section, MOVES2010a estimated NH_3 4% lower than MOBILE6.2 while the model estimated higher emissions for all other pollutants from HHDDV. The biggest difference between the estimates from the two models was seen in $PM_{2.5}$ emissions. This is because $PM_{2.5}$ emissions in MOVES2010a were always higher than in MOBILE6.2 as shown in Figure 6, unlike NH_3 and CO_2. Therefore, $PM_{2.5}$ emissions estimated using MOVES2010a would be always higher than MOBILE6.2. This big difference in $PM_{2.5}$ emissions was due to an improvement in MOVES2010a to account for speed and VSP effects on $PM_{2.5}$ emissions.

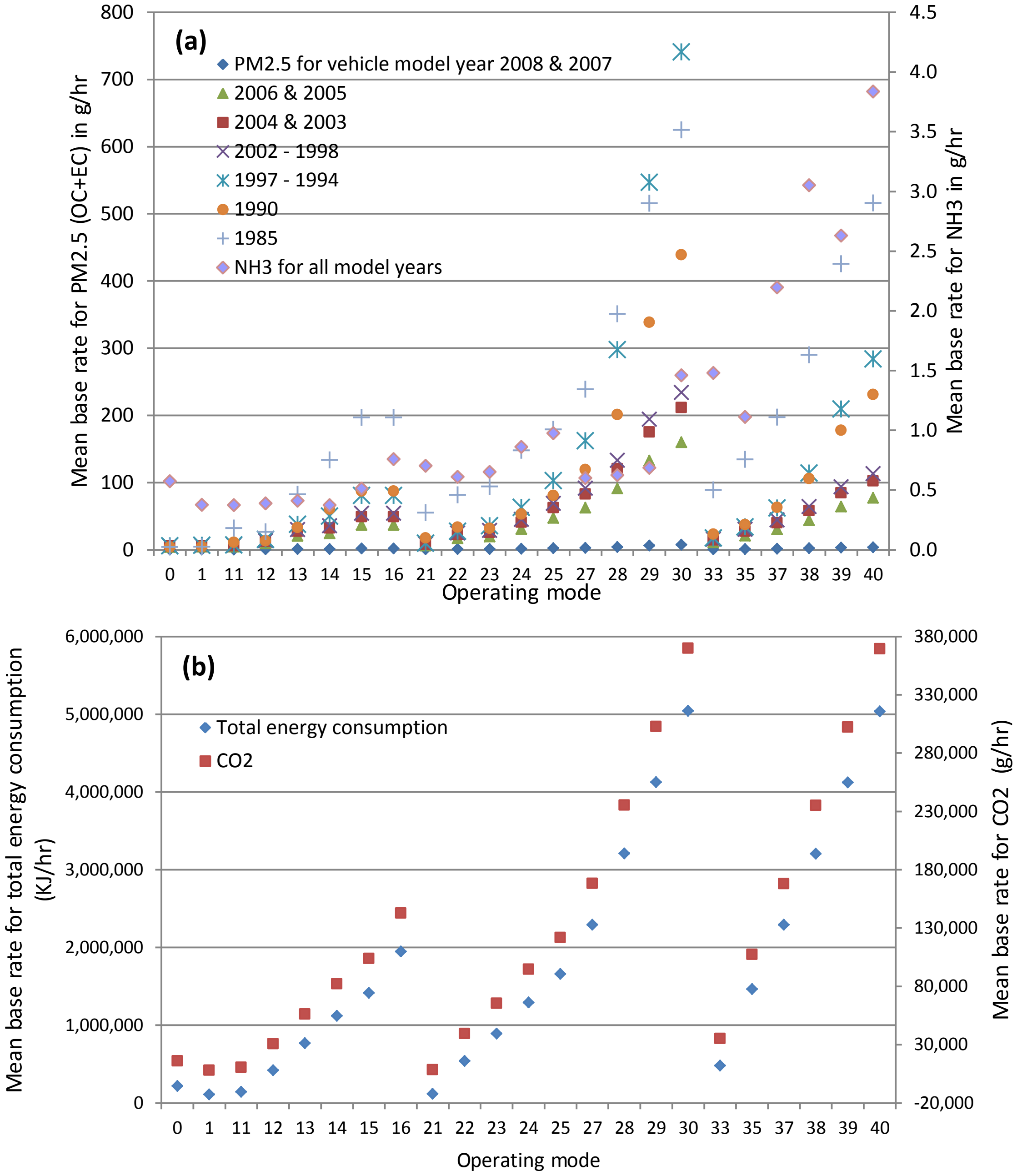


Figure 5. HHDDV Mean Base Rates for Running Exhaust Emissions by Operating Mode in MOVES2010a: (a) $PM_{2.5}$ (EC + OC) and NH_3 for Year 2008 and (b) Total Energy Consumption and CO_2 for All Model Year

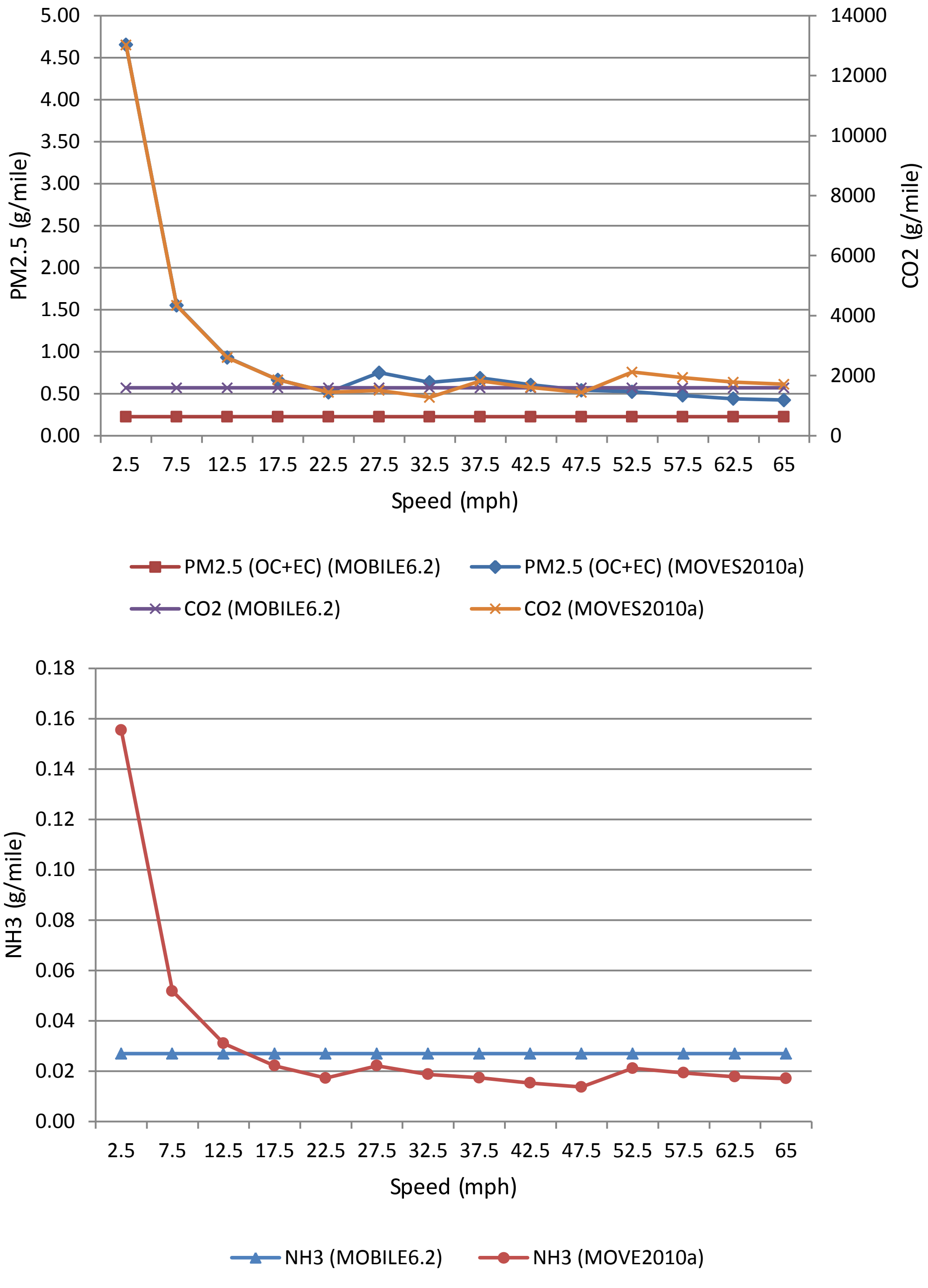


Figure 6. Composite Emission Factors by Speed for Pollutants: $PM_{2.5}$ (OC+EC), CO_2, NH_3 in 2008 for HDDV8A&HDDV8B from MOBILE6.2 Versus Combination Long-Haul Truck from MOVES2010a

3.5 CONCLUSION

This part of the dissertation research presented the impacts of the transition from MOBILE6.2 to MOVES2010a by comparing emission estimates from the two models. A case study of the modal shift from barges to trucks due to the temporary closure of the waterway locks in the Pittsburgh area was used for the demonstration. The 2008 NCD, were used to drive both models. County inputs for MOVES2010a were converted from 2008 NCD in MOBILE6.2/NMIM. The results showed that emission estimates for all vehicle types using MOVES2010a were higher than emissions estimated using MOBILE6.2/NMIM for CO, NO_X, PM_{10}, $PM_{2.5}$, and VOCs while MOVES2010a estimated lower emissions for CO_2 and NH_3 than MOBILE6.2/NMIM. The biggest differences were seen in $PM_{2.5}$ emissions. MOVES2010a estimated $PM_{2.5}$ from all source types approximately 127% and 152% higher than MOBILE6.2/NMIM for Allegheny and Beaver Counties, respectively. From EPA's comparisons using local data for several counties, NO_X and PM emissions from all vehicle types estimated using MOVES2010 were higher than MOBILE6.2, while VOCs emissions were lower.[22] However, in our analyses with local inputs of Allegheny and Beaver Counties in Pennsylvania, MOVES2010a estimated higher emissions for all three pollutants: NO_X by 30%, PM_{10} by 65%, $PM_{2.5}$ by 127%, and VOCs by 51% for Allegheny County and NO_X by 36%, PM_{10} by 86%, $PM_{2.5}$ by 152%, and VOCs by 36% for Beaver County.

Overall, the results showed that emissions for combination diesel trucks estimated using MOVES2010a were higher for CO, CO_2, NO_X, PM_{10}, $PM_{2.5}$, and VOCs than HHDDV emissions estimated using MOBILE6.2/NMIM except for NH_3. The same results were found in the emissions estimated with the same VMT and truck volumes from the added trucks due to the modal shift using project domain/scale in the model. In general, MOVES2010a estimated more emissions for diesel-fueled combination trucks than HHDDV from MOBILE6.2. It should be noted that in the present analyses, road grades were not used. In general, when adding road grades into the links, predicted emission estimates may actually show a higher increase using the MOVES2010a model.

There is room for improvement in MOVES2010a. There were discrepancies between default VMT in MOVES2010a and local VMT in 2008 NCD. The default VMT in the model should be updated based on the national emission inventory. One of downsides of the model is run time to compute all pollutants with all processes. To generate emission inventory, modelers need to be aware of the long modeling run time. This should be improved in the future version of the MOVES model.

In summary, the MOVES2010a model estimated emissions differently, compared to MOBILE6.2/NMIM. Overall, MOVES2010a estimated higher emissions for all pollutants except for NH_3 from HHDDV, compared with MOBILE6.2. PM emissions estimated using MOVES2010a seem to have the biggest difference, compared with MOBILE6.2, since MOVES2010a accounts for speed variations on PM emissions and the emission rates from MOVES2010a were higher for all speeds than MOBILE6.2. Results may be different from this study for other areas with different fleet and traffic characteristics. However, the differences in predicted emissions between the two models will have important implication for SIP, regional and/or other transportation conformity analyses because MOVES2010a is now the required mobile emission source model.

CHAPTER 4

RESEARCH PART II

Characteristics of Real World Driving Cycles for Heavy Duty Trucks in Hilly Terrain and Analyses of the Driving Cycles with Calculated Emissions

This chapter discusses the analysis of real-world driving data in hilly terrain and the general methodology of emission estimates using a driving cycle and the results of the anlaysis on characteristics of driving cycles of heavy-heavy duty vehicles in hilly terrain. This chapter also includes an evaluation of the MOVES default driving cycles on freeways.

4.1 METHODOLOGY

This section describes the data source used in the analysis, explains the key concept in the MOVES model, and presents the operating mode approach to evaluate and develop driving schedules for heavy duty trucks in hilly terrain.

4.1.1 Data Source

Truck speed and location data described in the FMCSA-RRR-09-056 project[31] were used for this study. HDD trucks were driven in East Tennessee along hilly terrain. The tested trucks included four truck manufacturing companies: Freightliner, International, Kenworth, and Volvo. Engine displacements were between 12.1 and 15.2 L. Engine horsepower ranged between 465 and 515 hp with 1,800 lb-ft of torque. Each truck hauled a 16.2 m (53 ft) long fully enclosed utility trailer which was pre-loaded with approximately 30,000 lbs of palletized top-soil.

The vehicles were driven on the route including portions of the rural interstates and rural highways. The route of the trips was approximately 260 km (160 mi): 120 km (75 mi) on the interstate (I-40); 80 km (50 mi) on US-27 and TN-68; 60 km (35 mi) on the interstate (I-75). Figure 7 shows the route of the trips. The route on I-40 starts at Knoxville, TN and ends at Crossville, TN. The region’s topography features a series of ridges and valleys. The road ascends the Cumberland Plateau, reaching about 1,900 feet (576 m) of altitude. The elevation of Knoxville is 886 feet (270 m). A total of 33 trips were made for the study. To obtain the speed-time data, HDD trucks were equipped with a Global Positioning System (GPS) data logger. The speed-time data were collected on weekdays and during off-peak hours. Location of the vehicles was identified using Geographic Information System (GIS) software. From this, the activity data along the I-40 corridor were extracted from the data for analysis.

The raw data were collected while conducting an in-cab study[31], and were used for this part of the dissertation research. The data were not recorded at every second. On average, they were recorded at every 3 seconds. Previous studies to develop driving cycles, however, were based on second-by-second speed data.[11] For this research, the raw data were reviewed for quality and used for further analysis.

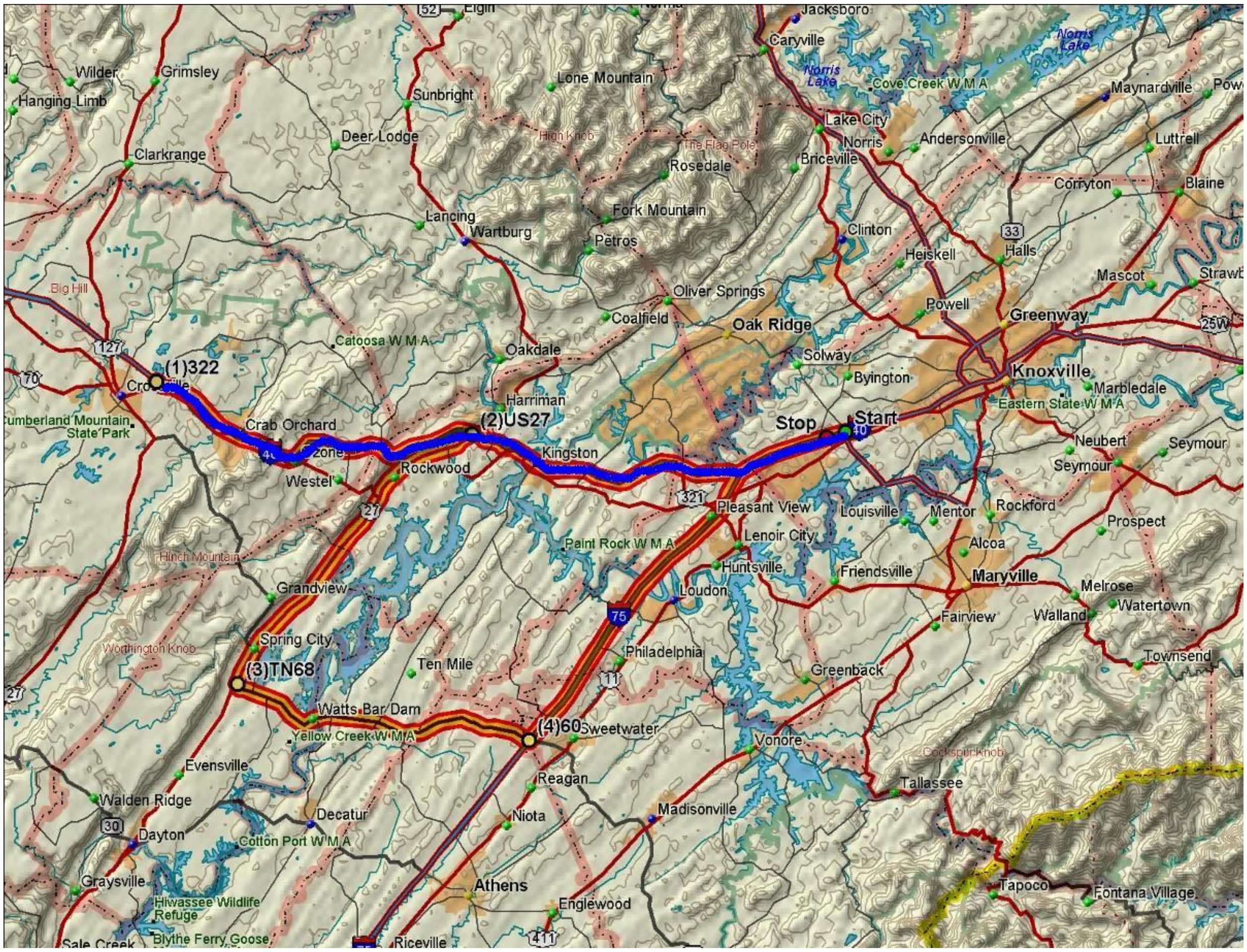


Figure 7. The Route, Showing I-40, US-27 & TN-68, and I-75

4.1.2 Data Processing

The frequency of the GPS record of the raw data was not 1 hertz (Hz). On average, they were recorded at every 3 seconds. Since the raw data were not recorded on consecutive seconds, in order to obtain a continuous speed flow with one second time steps, missing speed values at those time steps were populated using a linear interpolation method. Using latitude and longitude information, the locations were identified, and the trip was separated into different segments. In this part of the research, the first segment of the route, I-40, was chosen for analyses. The selected route for the analyses is highlighted in blue in Figure 7. From a total of 33 truck trips analyzed, 22 trips whose route includes the same portion on I-40 were chosen. The trips started between 9:30 AM and 3:10 PM. Sixteen out of 22 trips started between 9:30 AM and 11:30 AM.

A program was written to automatically insert the missing time and flag outliers of extreme speed. The program also populates missing speed values using a linear interpolation method. The cleaned data for each trip were used for further analysis.

4.1.3 Scaled Tractive Power for Heavy-Heavy Duty Vehicle and Operating Mode Approach

Zhai et. al computed correlation between several potential explanatory variables and emissions based on Spearman rank correlation coefficients and identified key variables affecting transit bus emissions.[32] Percent throttle, fuel consumption, torque, oil pressure, Vehicle Specific Power (VSP), and acceleration were correlated with diesel transit buses. Because variables such as percent throttle and torque were not available from travel activity data without access to engine data, VSP was chosen and used in developing emissions models.[32] In MOVES, emission rates are stored in each operating mode as a mean base rate. Adjustment factors are then applied to get emissions. The MOVES model calculates emissions for a driving cycle by calculating a weighted average of emissions by operating mode. If the operating mode distribution for a driving cycle is defined, emissions for the driving cycle can be determined. Therefore, in this study, operating mode was used to analyze and develop driving cycles.

The vehicle activity data (speed versus time) were used to estimate operating mode distributions and emissions were estimated based on MOVES mean base rate for each operating mode. The detailed methodology is described in the following section. VSP, Scaled Tractive Power (STP), and operating mode are explained in detail in this section.

4.1.3.1 Vehicle Specific Power (VSP)

Vehicle specific power (VSP, kW/tonne) is used in the MOVES model to determine emission rates. VSP is defined as vehicle tractive power per vehicle mass (kW/tonne) and is a function of speed, acceleration, and road grade taking into account aerodynamic drag, and tire rolling resistance. VSP that was introduced for the first time is expressed as follows:[33]

$$\mathbf{VSP = 0.278\boldsymbol{v}(0.305\boldsymbol{a} + 9.81\boldsymbol{r} + 0.132) + 0.0000065\boldsymbol{v}^3} \qquad \text{Equation (5)}$$

where, VSP = vehicle specific power (kW/ton)

v = vehicle speed (km/h)
a = vehicle acceleration (km/h per s)
r = road grade (%)
9.81 = acceleration due to gravity, m/s^2
0.132 = rolling resistance term coefficient
0.0000065 = drag term coefficient

The VSP was developed based on light duty vehicles. In several studies, VSP for transit buses were estimated based on the vehicle's typical coefficient values and expressed as follows:[34, 35]

$$\mathbf{VSP} = \boldsymbol{v} \times (\boldsymbol{a} + \mathbf{g} \times \mathbf{sin}(\boldsymbol{\theta}) + \boldsymbol{\psi}) + \boldsymbol{\zeta} \times \boldsymbol{v}^{\mathbf{3}} \qquad \text{Equation (6)}$$

where, VSP = vehicle specific power (kW/ton)
v = vehicle speed (m/s)
a = vehicle acceleration (m/s^2)
g = 9.81 m/s^2, acceleration due to gravity
$\theta =$ road grade (dimensionless)
$\psi =$ rolling resistance term coefficient (0.0092)
ζ = drag term coefficient (0.00021)

In the MOVES model, VSP for light duty vehicles is calculated as follows:[36]

$$\mathbf{VSP}_{\boldsymbol{t}} = \frac{\mathbf{A}\mathbf{v}_t + \mathbf{B}\mathbf{v}_t^2 + \mathbf{C}\mathbf{v}_t^3 + \mathbf{m}\mathbf{v}_t\mathbf{a}_t}{\boldsymbol{m}} \qquad \text{Equation (7)}$$

where, VSP = vehicle specific power in kW/metric ton
v_t = speed at time t (m/sec)
a_t = acceleration at time t (m/sec^2)
A = rolling resistance (kW-sec/m)
B = rotating resistance ($kW\text{-}sec^2/m^2$)
C = aerodynamic drag ($kW\text{-}sec^3/m^3$)
m = weight (metric ton)

4.1.3.2 Scaled Tractive Power (STP)

In the MOVES model, while VSP is defined for light duty trucks, STP is defined for heavy duty trucks. STP represents the vehicle's tractive power, scaled by a scaling factor to fit existing MOVES operating mode definitions for light duty vehicles. While STP is similar to VSP, it is not normalized by vehicle mass. STP is estimated in terms of a vehicle's speed and mass, as shown in the following equation:[37]

$$\mathbf{STP}_t = \frac{\mathbf{A}\mathbf{v}_t + \mathbf{B}\mathbf{v}_t^2 + \mathbf{C}\mathbf{v}_t^3 + \mathbf{m}\mathbf{v}_t\mathbf{a}_t}{f_{scale}} \qquad \text{Equation (8)}$$

where, STP_t = scaled tractive power at time t in kW

v_t = speed at time t (m/sec)

a_t = acceleration at time t (m/sec^2)

A = rolling resistance (kW-sec/m)

B = rotating resistance (kW-sec^2/m^2)

C = aerodynamic drag (kW-sec^3/m^3)

m = mass (metric ton)

f_{scale} = 17.1, scaling factor (aka fixed mass factor)

Road load coefficients A, B, and C vary for different vehicle types. Road load coefficients for heavy duty trucks used in this study were MOVES default coefficients for combination long haul truck. The values are 2.08126, 0, 0.00418844 for A, B, and C, respectively. They are approximately 0.00676 for rolling resistance coefficient, 10.5 m^2 for frontal area, 0.65 for aerodynamic drag coefficient. The vehicle mass used in the study was 31.4 metric ton. These values defined in MOVES default are from average values in the vehicle category.

4.1.3.3 Operating modes

Operating modes are the key concept in the MOVES model. For heavy duty trucks, operating modes are defined by a combination of Scaled Tractive Power (STP) and speed class. driving schedules are used to determine operating mode distribution, which is used to determine emissions. Emission rates of pollutants in grams per hour in MOVES are stored in each operating mode for fuel type/engine type/model year group/regulatory class/age group. Model year group varies by pollutant-process.[38]

For running exhaust emissions, there are 23 operating modes, including 21 operating modes for coast and cruise, one operating mode for idle (#1), and one operating mode for deceleration/braking (#0). Table 6 shows 23 operating modes for HHD vehicles.[37] STP, ranging from 0 to over 30, represents cruise/acceleration. STP, where below 0, represents coasting. Deceleration/Braking is defined at $a_t \leq -2.0$ mph/s or ($a_t < -1.0$ mph/s and $a_{t-1} < -1.0$ mph/s and $a_{t-2} < -1.0$ mph/s). Idling is defined at -1.0 mph $\leq v_t < 1.0$ mph.

In MOVES, modeling using a project scale option limits to one hour driving activity. In this case, the operating mode approach used in this research can be applied. The advantage of the operating mode approach is that it can combine all of the driving characteristics which may not be included when developing a synthetic driving cycle from a number of driving activities.

Table 6. 23 Operating Modes for Running Exhaust Emissions for HHD Vehicles

STP class in scaled kW	Description		Speed (mph)		
			1-25	25-50	50 +
	Deceleration/Braking	0			
	Idling	1			
<0	Coast		11	21	33
0-3	Cruise/Acceleration		12	22	
3-6	Cruise/Acceleration		13	23	
6-9	Cruise/Acceleration		14	24	35
9-12	Cruise/Acceleration		15	25	
12-15	Cruise/Acceleration		16	27	37
15-18	Cruise/Acceleration				
18-21	Cruise/Acceleration			28	38
21-24	Cruise/Acceleration				
24-27	Cruise/Acceleration			29	39
27-30	Cruise/Acceleration				
30 +	Cruise/Acceleration			30	40

4.1.4 Algorithm to Calculate Running Exhaust Emissions for HHD Vehicles

Composite emissions were estimated for each of the 22 trips on the freeway using MOVES's approach.

4.1.4.1 Using a driving cycle

Based on second-by-second driving cycle data, total trip-based emissions were calculated as follows:

1. Calculate STP in units of scaled kW for each second using Equation (8).
2. Determine operating mode for each second based on STP and speed as shown in Table 6.

3. Calculate operating mode fractions for the driving cycle as:

$$\boldsymbol{F\_OM_i = \frac{noOM_i}{noSEC}} \qquad \text{Equation (9)}$$

where, F_OM = operating mode fraction
i = operating mode (0, 1, 11, 12, ……, 40)
noOM = number of operating mode
noSEC = total seconds for the driving cycle

4. Each operating mode fraction is multiplied by emission rate for that operating mode and summed as:

$$\boldsymbol{ER = \sum_{i=1}^{23}(F\_OM_i \times ER_i)} \qquad \text{Equation (10)}$$

where, ER = emission rate in g/hr
i = operating mode (0, 1, 11, 12, ……, 40)

4.1.4.2 Using an average speed

Speed profiles on road link were categorized by mean speed, and emissions were estimated using an average speed operating mode approach. Operating mode distributions were generated at the link level using the following methods.

In MOVES, there are limited default driving schedules as shown in the figures in Appendix A. MOVES Default HHD Vehicle Driving Schedule and Its Characteristics. Emissions can be estimated using an average speed option. An average speed which is not represented by the average speed from the default driving schedules can be represented by a pair of two default driving schedules. In order to calculate emissions using an average speed, two driving schedules are selected and used: one has a slightly higher average speed and the other has a slightly lower average speed than the average.[38] Total trip-based emissions using an average speed are calculated as follows:

1. Determine two driving schedules where the average speed lies in between: lower speed driving schedule and higher speed driving schedule.

2. Calculate STP on a second by second basis for each driving schedule.
3. Determine operating mode for each second.
4. Determine operating mode fractions for each driving schedule.
5. Determine fractions for the two driving schedules for the average speed as:

$$\boldsymbol{LF = \frac{(H - average\ speed)}{(H - L)}} \quad \text{Equation (11)}$$

$$\boldsymbol{HF = 1 - LF} \quad \text{Equation (12)}$$

where, LF = lower speed driving schedule fraction

HF = higher speed driving schedule fraction

H = average speed for higher speed driving schedule

L = average speed for lower speed driving schedule

6. Weight the operating mode fractions for the average speed using the calculated fractions from above:

$$\boldsymbol{F\_OM\_N_i = F\_OM\_L_i \times LF + F\_OM\_H_i \times HF} \quad \text{Equation (13)}$$

where, F_OM_N = new operating mode fraction for the average speed

i = operating mode (0, 1, 11, 12, 13, ………., 40)

F_OM_L = operating mode fraction for lower speed driving schedule

F_OM_H = operating mode fraction for higher speed driving schedule

7. Calculate emissions using operating mode fractions and emission rates for each operating mode using Equation (10).

Using the travel activity data set (with speed data), emissions based on the operating mode approach were calculated for 22 trips. The emissions that were estimated using the method described above were analyzed using an appropriate statistical method and compared with MOVES default driving schedules.

4.1.5 Road Grade

There are several methods that can be used to estimate road grade.[39] Those methods include design drawing data, traditional surveying such as direct on-road measurement, analysis of GPS data, and mobile mapping systems such as light detection and ranging. Boriboonsomsin and Barth (2009) discussed several methods to obtain road grade in their study.[14] Zhai et al. (2008) calculated road grades in percent based on the difference in elevation and distance between the two points.[40] The study by Wanglund (2009) estimated road grade by the ratio of vertical velocity to forward velocity, which is identical to the ratio of differentiated altitude to travel distance. In this study, road grade in percent was estimated by the ratio of the difference in elevation to the distance between the two points from the GPS data.

Road grade was filtered using a moving average approach. First if the calculated road grade is greater than the absolute value of 6%, the grade was replaced with the absolute value of 6. According to “a policy on design standards-interstate system” by the American Association of State Highway and Transportation Officials (AASHTO), maximum grade is 6%.[41] In order to smooth the road grade, the moving average was taken from 5 second grades with 2 seconds forward and backward of logged data. This filtered grade data is then used to reconstruct the elevation. This approach eliminates unrealistic grade values due to GPS errors and results in a smoothed grade profile, not exceeding a 6% limit.

STP including grade function is expressed as:[24]

$$\mathrm{STP_t} = \frac{\boldsymbol{Av_t + Bv_t^2 + Cv_t^3 + mv_t\,(a_t + g \cdot sin\theta)}}{\boldsymbol{f_{scale}}} \qquad \text{Equation (14)}$$

where, $\mathrm{STP_t}$ = scaled tractive power at time t in kW

v_t = speed at time t (m/sec)

a_t = acceleration at time t (m/sec^2)

A = rolling resistance (kW-sec/m)

B = rotating resistance (kW-sec^2/m^2)

C = aerodynamic drag (kW-sec^3/m^3)

m = mass (metric ton)

f_{scale} = 17.1, scaling factor (aka fixed mass factor)

g is gravitational acceleration

$\sin\theta$ is grade expressed as a fraction

Here, acceleration due to road grade is expressed as:

$$\boldsymbol{a_t + g \cdot sin\theta} \qquad \text{Equation (15)}$$

4.1.6 Two Scenarios for the Trip Data

Grade effects on emissions from the driving cycles in hilly terrain were analyzed using two different road grades: (1) grades that correspond to the terrain and (2) zero grade. Average road grade of the trip was also calculated and used for the MOVES driving schedules to compare emissions. The driving cycles of the 22 trips were compared between the two scenarios. To compare the means of the two scenarios, T-tests were made. The null hypothesis was that the means of the two groups are not significantly different.

4.2 RESULTS AND DISCUSSION

Characteristics of driving cycles on the freeway in hilly terrain were compared with the MOVES default driving schedules using emission rates stored in the MOVES model. The operating mode distribution was derived for the 22 trips. Emission rates (mean base rates) for a 2005 model year, 0-3 year old heavy-heavy duty vehicle were obtained from the MOVES input database and used throughout this part of the dissertation research. Operating mode bins for running exhaust emissions used in MOVES are listed in Table B- 1in Appendix B. Operating Mode and Mean Base Rate for Running Exhaust Emissions for HHD Vehicles in MOVES. The mean base rates for running exhaust emissions of NO_X, $PM_{2.5}$, CO, THC, and total energy consumption are shown in Table B- 2 to Table B- 6 in Appendix B. Operating Mode and Mean Base Rate for Running Exhaust Emissions for HHD Vehicles in MOVES.

4.2.1 Characteristics of Driving Cycles of 22 Trips

Table 7 summarizes the 22 trips. The average distance and total time of travel were 48.09 ± 0.19 miles and 2,770 ± 73 seconds, respectively. Graphs of the driving cycles for each trip are presented in Appendix C. Driving Cycles for 22 Trips for the Study: separate plots of speed versus time and acceleration versus speed are shown. Altitude change over distance for Trip 1 is shown in Figure 8; speed and both filtered and raw altitude are shown in the figure.

Among the 12 MOVES default driving schedules for HHD vehicles that were shown in Figure 2, driving schedules with high average speeds on freeways are the driving schedules 354 and 355 with average speeds of 59.7 ± 3.05 mph and 71.7 ± 3.05 mph, respectively. Figure 9 shows the driving cycle of Trip 1 and two MOVES default driving schedules (354 and 355). These two default driving schedules show similar patterns with respect to the magnitude of speed changes relative to the different average speeds. However, the driving cycle of Trip 1 show a wider fluctuation of speed ranges than the two MOVES default driving schedules.

Trips in hilly terrain illustrated in Appendix C. Driving Cycles for 22 Trips for the Study also show a wide fluctuation of speed ranges, compared to the two MOVES driving schedules (354 and 355) with similar average speeds. From the summary of the trips in Table 7, standard deviations of the speeds ranged from 3.9 to 6.4 mph, comparing with 3.1 mph for the two MOVES driving schedules. This indicates that the trips made in hilly terrain would have different driving characteristics from the MOVES driving schedules. Acceleration-speed profiles for the MOVES driving schedules are shown in Figure A- 3 and Figure A- 4 in Appendix A. MOVES Default HHD Vehicle Driving Schedule and Its Characteristics, and trips in hilly terrain are shown in Figure C- 4 to Figure C- 6 in Appendix C. Driving Cycles for 22 Trips for the Study. The acceleration-speed profile and speed-time profile for Trip 1 are shown in Figure 10. Based on the speed-time and acceleration-speed profiles, trips in hilly terrain involve more acceleration and braking operation than the MOVES driving schedules, and the driving cycles in hilly terrain look different from the MOVES default driving schedules.

Figure 10 shows the actual driving characteristics of Trip 1. The characteristics analyzed here include operating mode distribution, acceleration distribution, and various STP distribution using different bin categories as well as STP distributions according to the MOVES STP bin definition.

Table 7. Summary of 22 Trips

Trip	Distance (mile)	Total Time (second)	Average speed (mph)
1	48.09	2,712	63.9 ± 5.4
2	48.15	2,834	61.1 ± 5.8
3	48.13	2,781	62.3 ± 6.2
4	47.98	2,895	59.8 ± 5.4
5	48.20	2,827	61.4 ± 4.7
6	48.20	2,751	62.9 ± 5.4
7	48.53	2,747	63.1 ± 6.2
8	48.15	2,834	62.0 ± 5.3
9	48.00	2,782	62.2 ± 5.0
10	48.03	2,803	61.7 ± 6.4
11	47.98	2,745	63.0 ± 5.5
12	48.00	2,683	64.4 ± 5.3
13	47.80	2,729	63.1 ± 5.1
14	48.12	2,823	61.2 ± 5.2
15	48.50	2,902	59.6 ± 6.3
16	48.15	2,834	64.0 ± 4.8
17	47.99	2,719	63.6 ± 4.9
18	47.75	2,732	63.0 ± 3.9
19	47.88	2,786	62.0 ± 5.6
20	48.06	2589	66.9 ± 4.6
21	48.04	2,749	62.9 ± 5.2
22	48.25	2,688	64.6 ± 6.4
Average ± Stdev	48.09 ± 0.19	2,770 ± 73	

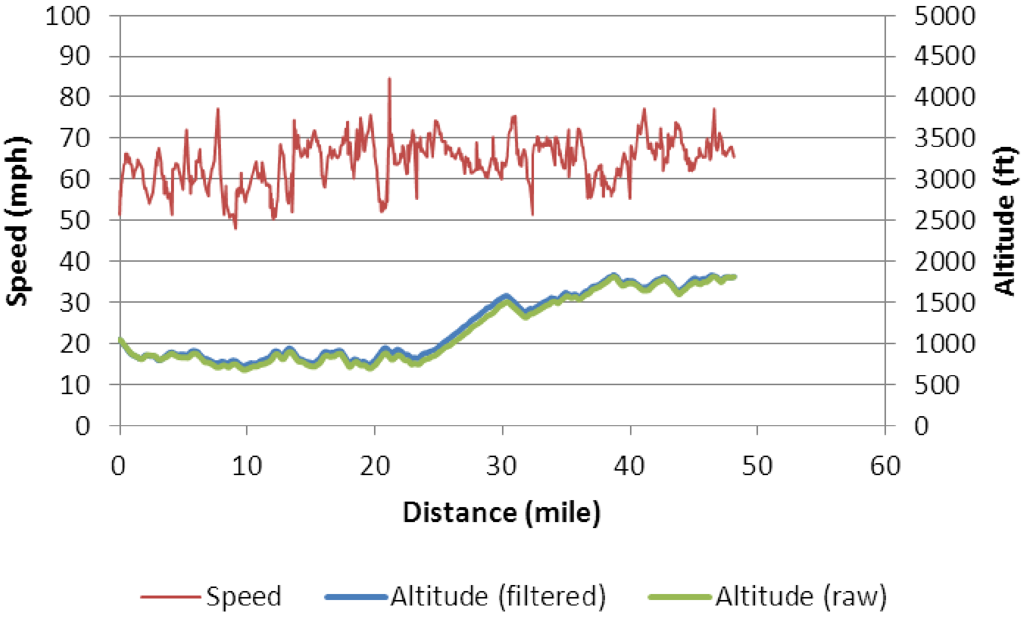


Figure 8. Speed and Altitude Change over Distance for Trip 1

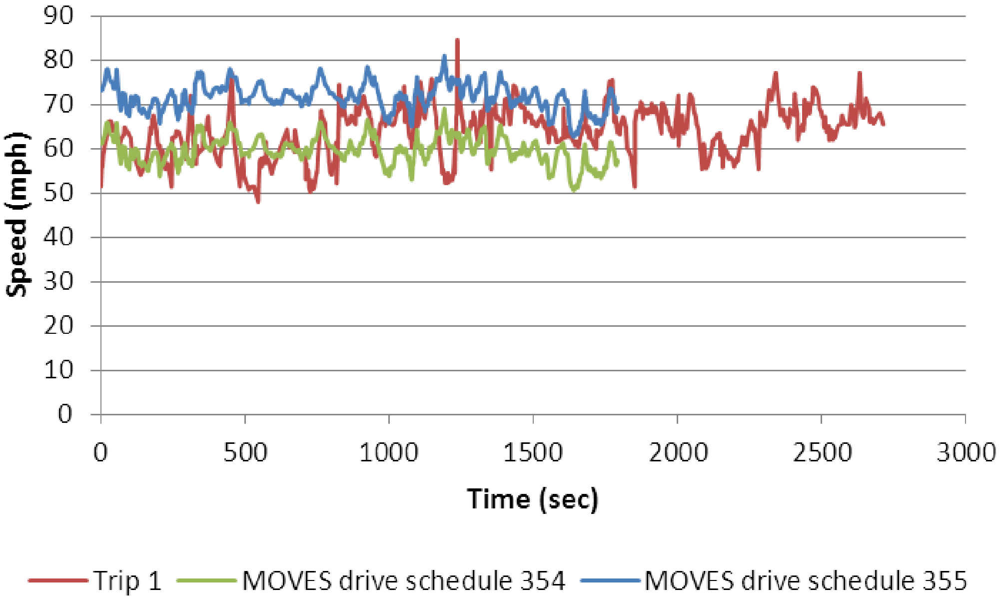


Figure 9. Speed Comparisons: Trip 1 (63.9 mph), MOVES Drive Schedule 354 (59.7 mph), and MOVES Drive Schedule 355 (71.7 mph)

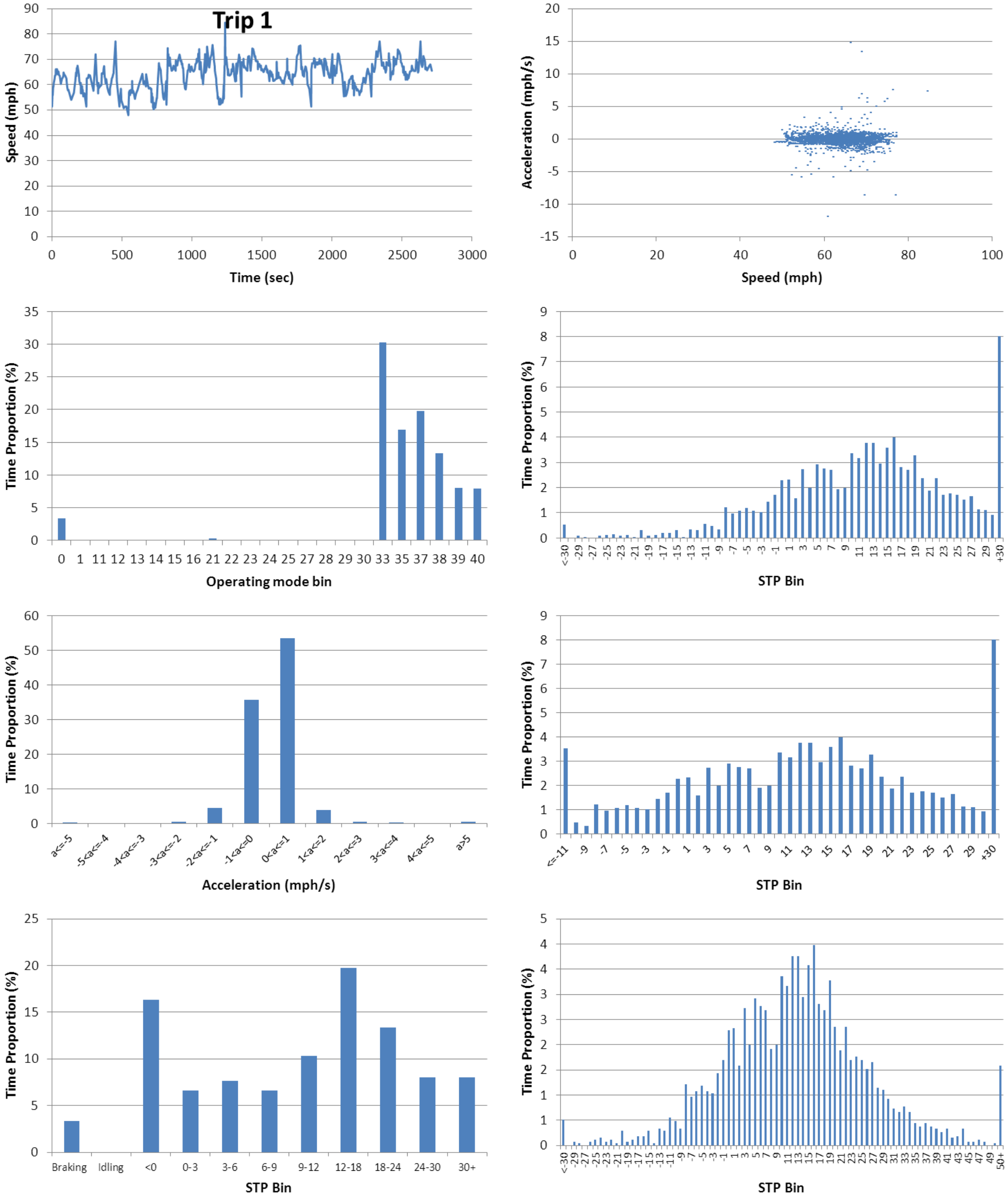


Figure 10. Characteristics of Trip 1 Driving Cycle

Various STP distribution plots were created as shown in Figure 10. Among the various STP distribution plots using different STP categories, the graph in the lower right hand corner, which extends bins up to 50 and 50+ with more STP bins than what MOVES defines in the model, shows a better normal distribution than other STP distributions. However, when considering MOVES STP bin category as described in Table 6, it did not provide any specific patterns.

Since the average speeds of the trips were over 60 mph, the majority of the time fell in the operating mode bins of 33, 35, 37, 38, 39, and 40. Deceleration/braking mode accounted for approximately 3 to 4% of the total time. Acceleration distributions showed that close to 90% of the time fell in between -1 mph/s to 1 mph/s. Similar characteristics were found in the other trips.

Figure 11 shows comparisons of STP bin distributions among Trip 1 with grades according to the terrain and two MOVES default driving schedules 354 and 355 with zero grade. As shown in Figure 11, Trip 1 accounted for more time proportions in STP bins of braking, <0, 24-30, and 30+, compared to the two MOVES default driving schedules. The MOVES driving schedule 355 with an average speed of 71.7 mph accounted for more time proportions in higher STP bins such as 9-12, 12-18, 18-24, 24-30, and 30+, compared to the MOVES driving schedule 354 with an average speed of 59.7 mph.

Figure 12 shows comparisons of operating mode bin distributions among Trip 1 and two MOVES default driving schedules 354 and 355. Trip 1 accounted for more time proportions in operating mode bins of 0, 39 and 40, compared to the two MOVES default driving schedules. The MOVES default driving schedule 355 showed more time proportions in operating mode bins of 37, 38, 39, and 40, compared to the MOVES default driving schedule 354.

STP distributions for the MOVES default driving schedules on freeways shown in Figure A-7 to Figure A- 11 in Appendix A. MOVES Default HHD Vehicle Driving Schedule and Its Characteristics show a bell-shaped type curve except for the last STP bin, which is STP greater than 30. In the case of the driving schedule 355 with an average speed of 71.7 mph, the STP bin greater than 30 shows close to 4%, compared to the smaller percentage with other default driving schedules.

STP bins were extended to 50 and greater than 50 in one group for the MOVES driving schedules 354 and 355 as well as Trip 1. Figure 13 shows STP distributions with extended STP bins for Trip 1 with grades and no grades as well as for the MOVES driving schedules 354 and 355. Both default driving schedules (354 and 355) with extended STP bins show normal distributions. The Gaussian function was fitted to each STP distributions for each driving cycle. The Gaussian function is expressed below and the coefficients for each case are tabulated in Table 8.

$$\mathrm{y} = \mathrm{y0} + \left(\frac{A}{w * \sqrt{\frac{\pi}{2}}} \right) * e^{-2 * \frac{(x - xc)^2}{w^2}} \qquad \text{Equation (16)}$$

where, y = the proportion of bins in percent

y0 = the bottom of the curve

A = contributes to the height of the curve’s peak

w = standard deviation which controls the width of the bell curve shape

x = STP bin

xc = mean, the position of the center of the peak

Table 8 shows the fitted Gaussian function. The Gaussian function achieved high R^2 from 0.87 to 0.91. STP distributions for Trip 1 has a spike of STP bin when it is above 50, compared to STP distributions for the two MOVES default driving schedules. This higher tractive power observed from the trip in hilly terrain could be explained by requirements of the higher tractive power to accelerate uphill. As shown in Figure 13, STP distributions for Trip 1 with grades show a widely spread pattern, compared to distributions for the driving cycle without considering grade.

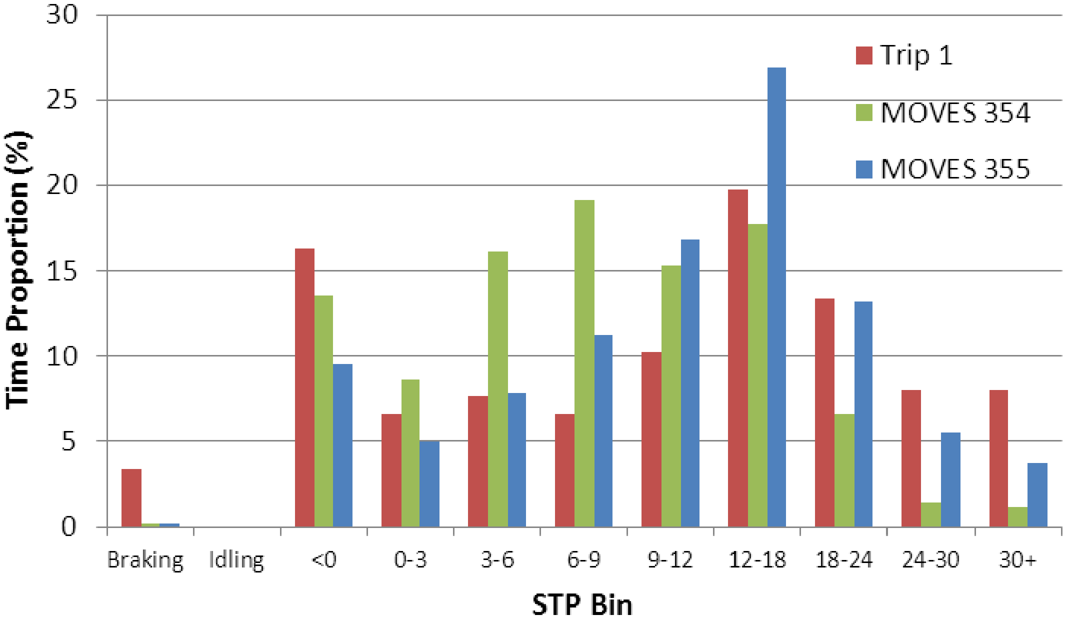


Figure 11. Comparison of STP Bin Distributions: Trip 1 (with Grades), and MOVES Default Driving Schedules 354 and 355 (No Grades)

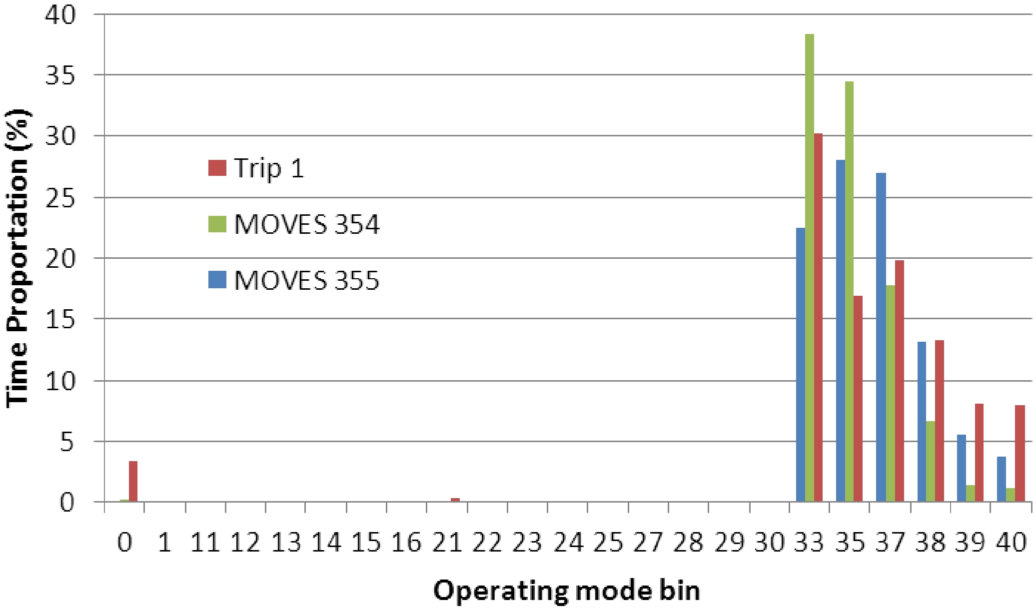


Figure 12. Comparison of Operating Mode Bin Distributions: Trip 1 (with Grades), and MOVES Default Driving Schedules 354 and 355 (No Grades)

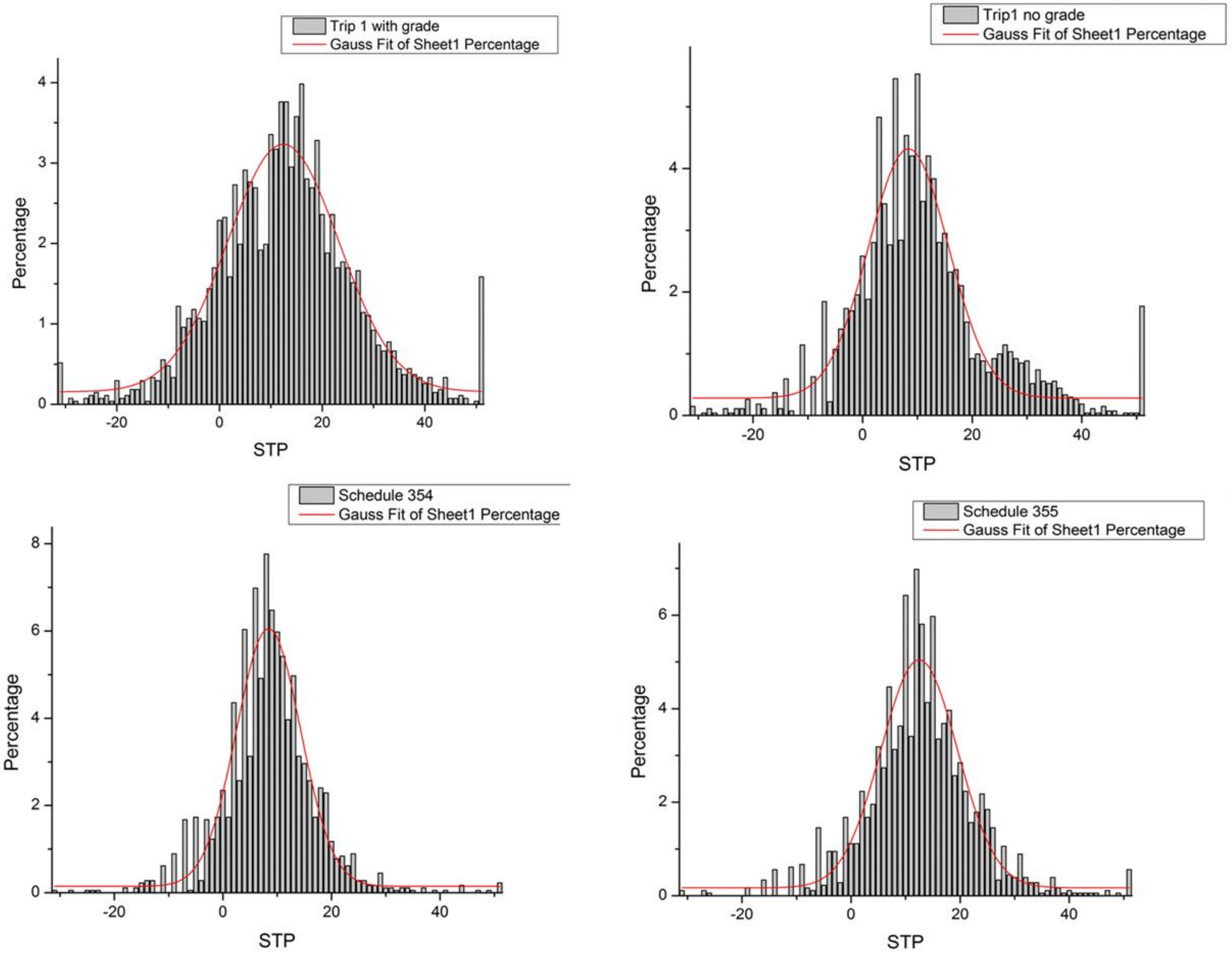


Figure 13. STP Distributions for Trip 1 with Grades and No Grades as well as for the MOVES Driving Schedules 355 and 354 with Extended STP Bins

Table 8. Gaussian Equation Fitted to the STP Distributions of Each Graph in Figure 13

Equation	$y=y0 + (A/(w*sqrt(\pi/2)))*exp(-2*((x-xc)/w)^2)$							
Model	Trip 1 with grade		Trip 1 no grade		Schedule 354		Schedule 355	
Reduced Chi-Sqr	0.12		0.25		0.33		0.30	
Adj. R-Square	0.91		0.87		0.91		0.89	
	Value	Standard Error	Value	Standard Error	Value	Standard Error	Value	Standard Error
y0	0.157	0.068	0.28	0.076	0.15	0.080	0.17	0.081
xc	12.41	0.391	8.37	0.358	8.41	0.251	12.49	0.316
w	21.69	1.033	14.64	0.816	11.83	0.550	14.02	0.712
A	83.65	4.709	74.06	4.310	87.50	4.076	85.58	4.497
sigma	10.85	0.517	7.32	0.408	5.91	0.275	7.01	0.356
FWHM*	25.54	1.217	17.24	0.960	13.93	0.648	16.51	0.838
Height	3.08	0.108	4.04	0.179	5.90	0.224	4.87	0.198

*FWHM: full width at half maximum

4.2.2 Grade Effects on Emissions in MOVES

The MOVES model can account for road grades as shown in Equation (14). To understand how the model handles the emissions as a function of grade, sensitivity analysis was performed for several constant speeds and road grades. Emission rates in unit of grams per mile were calculated using the MOVES model method for a 600 second (10 minute) driving episode at constant speeds from 10 mph to 70 mph on different road grades from -6% to 6% in 0.5% increments. Figure 14 andFigure 15 show the results of these analyses.

Figure 14 shows acceleration versus grade for several vehicle speeds. Acceleration affecting tractive power due to grades can be calculated using Equation (15). Note that the accelerations are identical for different speeds at the same road grade. This means that as road grade increases, acceleration is increased in order for the same speed to be maintained by the vehicle. Continuing with this approach, STP, THC, CO, NO_X, total energy consumption, and $PM_{2.5}$ (OC+EC) were calculated for those speeds. Figure 15 illustrates STP and the mean base rates for the several pollutants for the constant speeds at different grades. If one assumes that the vehicle is traveling at a constant speed on flat terrain, no acceleration or deceleration occurs in this driving episode.

The STP plot shown in Figure 15 indicates that the tractive power necessary to operate at higher speed requires more power than at lower speed. In terms of NO_X, $PM_{2.5}$, and energy consumptions at zero grade, a constant speed of 50 mph showed the lowest emissions and energy usage, compared with other speeds, while for THC and CO, the 70 mph speed had the lowest emissions. Based on the sensitivity analysis, unlike other pollutants, CO emissions decrease when grade increases from 0% to 2% at the constant speed of 70 mph. For other pollutants, when road grade increases in the positive direction, emissions increase in general. Overall, the graphs show that emissions and energy consumption, when driving uphill, increase dramatically compared to when driving downhill especially for NO_X and $PM_{2.5}$.

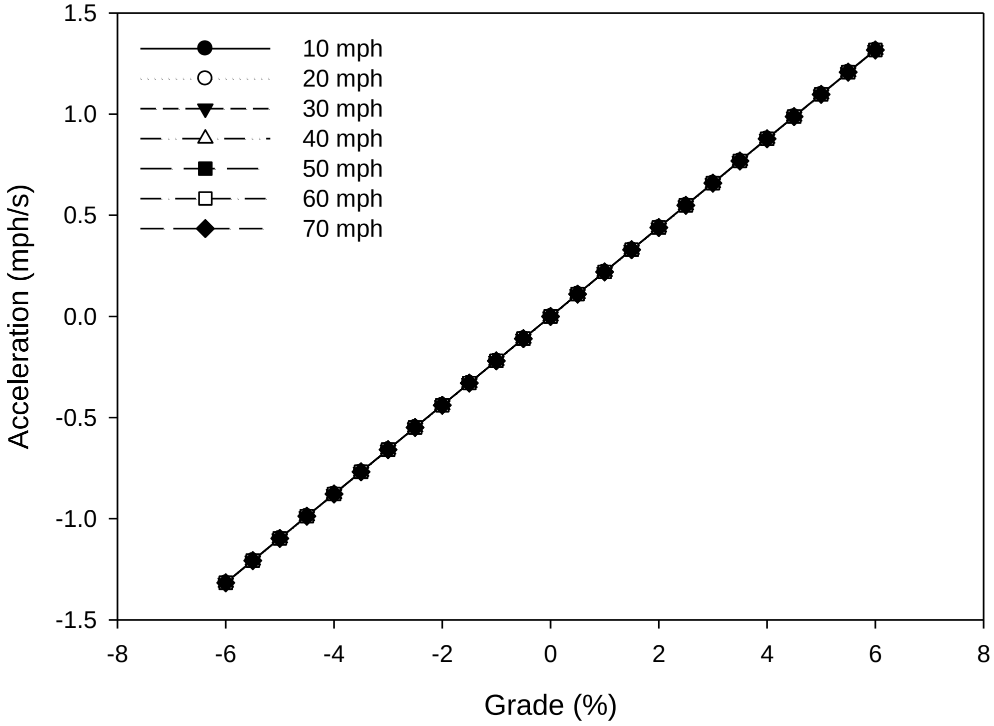


Figure 14. Grade Versus Acceleration at Several Constant Speeds

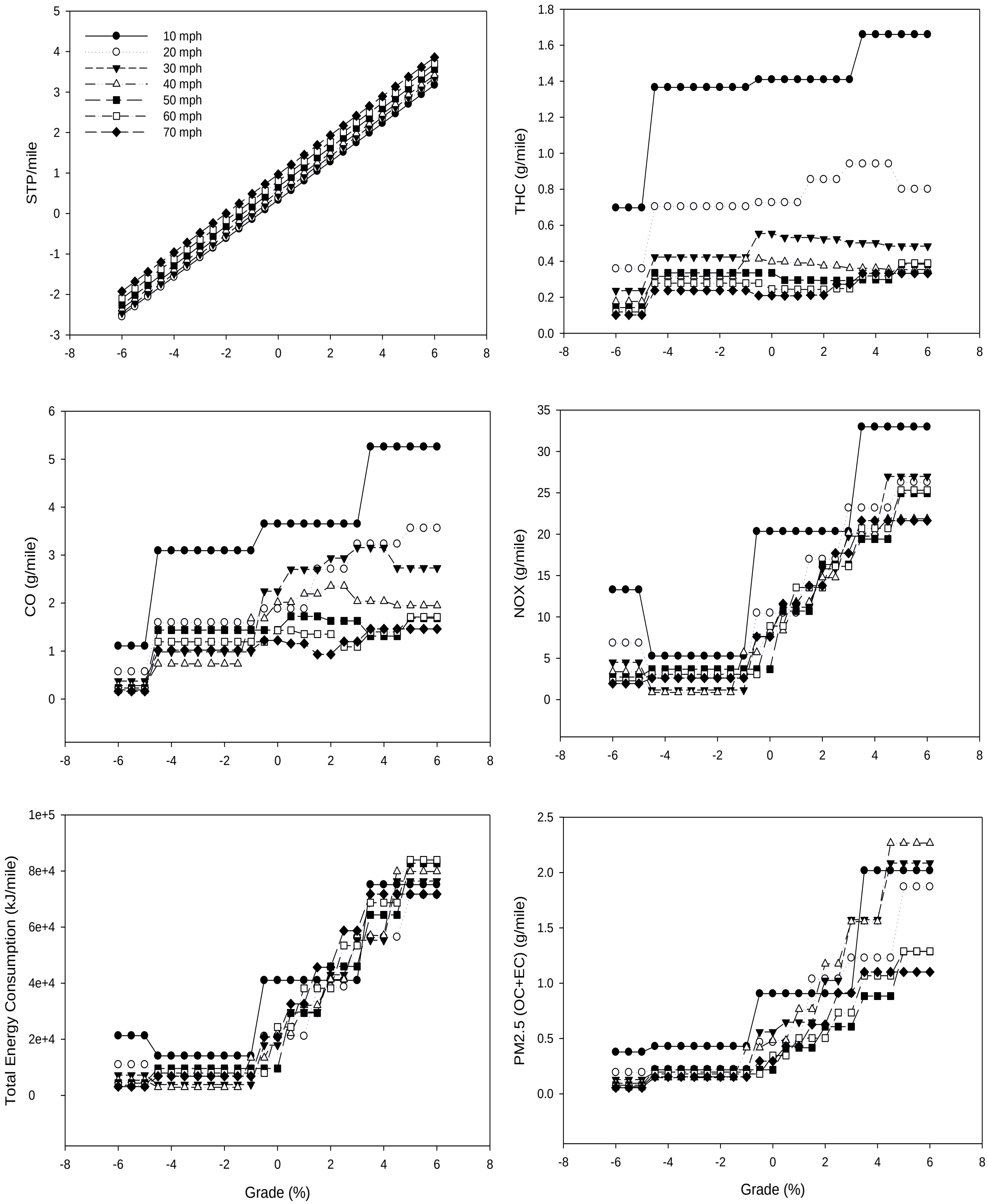


Figure 15. Grade Versus STP and Mean Base Rates for Several Pollutants

4.2.3 Emission Estimates for the Trips and Comparison of the Emissions with Grades and No Grades

4.2.3.1 Emission estimates for the trips with grades and no grades

Emissions for the trips were calculated using the algorithms explained in the section 4.1.4.1. Table 9 lists the summary of calculated emissions for each trip with road grades. Table 10 summarizes calculated emissions for each trip with no grades. Average emissions for the trips with road grades were 500.6 ± 8.2 g NO_X, 23.3 ± 0.5 g $PM_{2.5}$, 58.3 ± 1.4 g CO, and 12.4 ± 0.3 g THC. Average emissions for the trips with no grades were 437.0 ± 10.1 g NO_X, 19.9 ± 0.5 g $PM_{2.5}$, 59.4 ± 1.3 g CO, and 12.3 ± 0.3 g THC. Average energy consumption was 1,296,714 ± 33,123 kJ. Figure 16 and Figure 17 show box plots of operating mode distributions in percent for the 22 driving cycles with grades and no grades, respectively. A box plot is a schematic way to represent the distribution of data and identify outlier values. The bottom and top of the box represent the 25th and 75th percentiles, respectively. The two horizontal center lines inside the box represent the average and the median (50th percentile). When the average value equals the median value, only one line is visible inside the box which means that the data is not skewed. Whiskers are the two vertical lines that extend from both ends of the box and terminate in small horizontal lines. The whiskers represent the minimum and maximum values. Operating mode distributions of the driving cycles with road grades in Figure 16 showed different patterns, compared to Figure 17. Outliers also showed differently. Therefore, when applying road grades into the operating mode calculation, it is likely to change characteristics of the operating modes.

4.2.3.2 Comparisons of the emissions for the driving cycles with grades and no grades

Grade effects were analyzed using two scenarios to show how road grade affects emissions. The two scenarios are: 1) Driving cycles with 0% road grade, i.e., flat terrain, and 2) Driving cycles with road grades that correspond directly to the terrain. Based on the emissions calculated for the 22 trips for the two scenarios as shown in Table 9 and Table 10, means of the estimated emissions for the two groups were compared using t-tests.

Table 9. Summary of the Calculated Emissions for Each Trip with Road Grades

Trip	Overall emissions (in grams)				(in kJ)
	NO_X	$PM_{2.5}$ (EC+OC)	CO	THC	Total energy consumption
1	498.2	22.7	57.5	12.1	1,517,273
2	514.9	24.3	59.7	12.8	1,583,851
3	495.4	23.0	57.6	12.2	1,514,475
4	490.7	23.4	60.8	12.9	1,490,333
5	502.5	23.3	59.5	12.6	1,532,167
6	510.0	23.7	57.6	12.3	1,563,660
7	518.5	23.9	57.9	12.3	1,586,887
8	489.8	22.6	58.3	12.4	1,490,780
9	495.7	23.2	58.5	12.5	1,519,796
10	507.8	24.3	58.7	12.4	1,549,382
11	498.0	23.3	57.6	12.4	1,527,073
12	493.2	22.7	57.1	12.1	1,510,684
13	488.2	22.8	57.3	12.3	1,499,857
14	495.7	22.8	60.1	12.5	1,490,514
15	504.0	24.0	61.1	12.8	1,522,788
16	507.7	23.0	57.2	12.0	1,549,765
17	501.4	22.8	57.4	12.1	1,529,979
18	496.6	23.2	58.0	12.5	1,529,101
19	501.0	23.7	59.7	12.5	1,524,530
20	495.7	23.3	55.8	12.0	1,531,877
21	497.4	23.5	57.6	12.3	1,528,087
22	511.2	24.0	56.8	12.1	1,573,418
Average	500.6	23.3	58.3	12.4	1,530,285
± StDev	± 8.2	± 0.5	± 1.4	± 0.3	± 28,015
Min	488.2	22.6	55.8	12.0	1,490,333
Max	518.5	24.3	61.1	12.9	1,586,887

Table 10. Summary of the Calculated Emissions for Each Trip with No Grades

Trip	Overall emissions (in grams)				(in kJ)
	NO_X	$PM_{2.5}$ (EC+OC)	CO	THC	Total energy consumption
1	429.5	19.5	58.4	12.1	1,275,867
2	446.4	20.6	61.0	12.7	1,329,624
3	430.8	19.7	59.9	12.3	1,273,305
4	419.9	19.4	61.9	12.9	1,232,115
5	435.9	19.6	60.5	12.5	1,289,429
6	448.1	20.4	58.6	12.2	1,337,674
7	453.6	20.5	59.1	12.2	1,349,201
8	428.4	19.4	59.8	12.4	1,268,488
9	414.8	19.0	59.5	12.4	1,228,872
10	442.7	20.4	60.0	12.3	1,308,888
11	437.9	20.0	59.5	12.4	1,306,558
12	441.5	19.8	58.1	12.0	1,313,370
13	426.3	19.3	58.1	12.1	1,267,610
14	450.1	20.7	61.1	12.6	1,338,572
15	440.2	20.6	61.7	12.8	1,305,930
16	449.1	19.7	58.9	11.9	1,325,508
17	432.4	19.3	58.7	12.0	1,281,755
18	429.5	19.1	59.2	12.1	1,266,454
19	433.1	19.9	59.8	12.4	1,282,468
20	436.8	19.6	56.7	11.6	1,302,410
21	442.1	20.0	59.3	12.2	1,310,698
22	445.4	20.4	57.9	12.0	1,332,906
Average ± StDev	437.0 ± 10.1	19.9 ± 0.5	59.4 ± 1.3	12.3 ± 0.3	1,296,714 ± 33,123
Min	414.8	19.0	56.7	11.6	1,228,872
Max	453.6	20.7	61.9	12.9	1,349,201

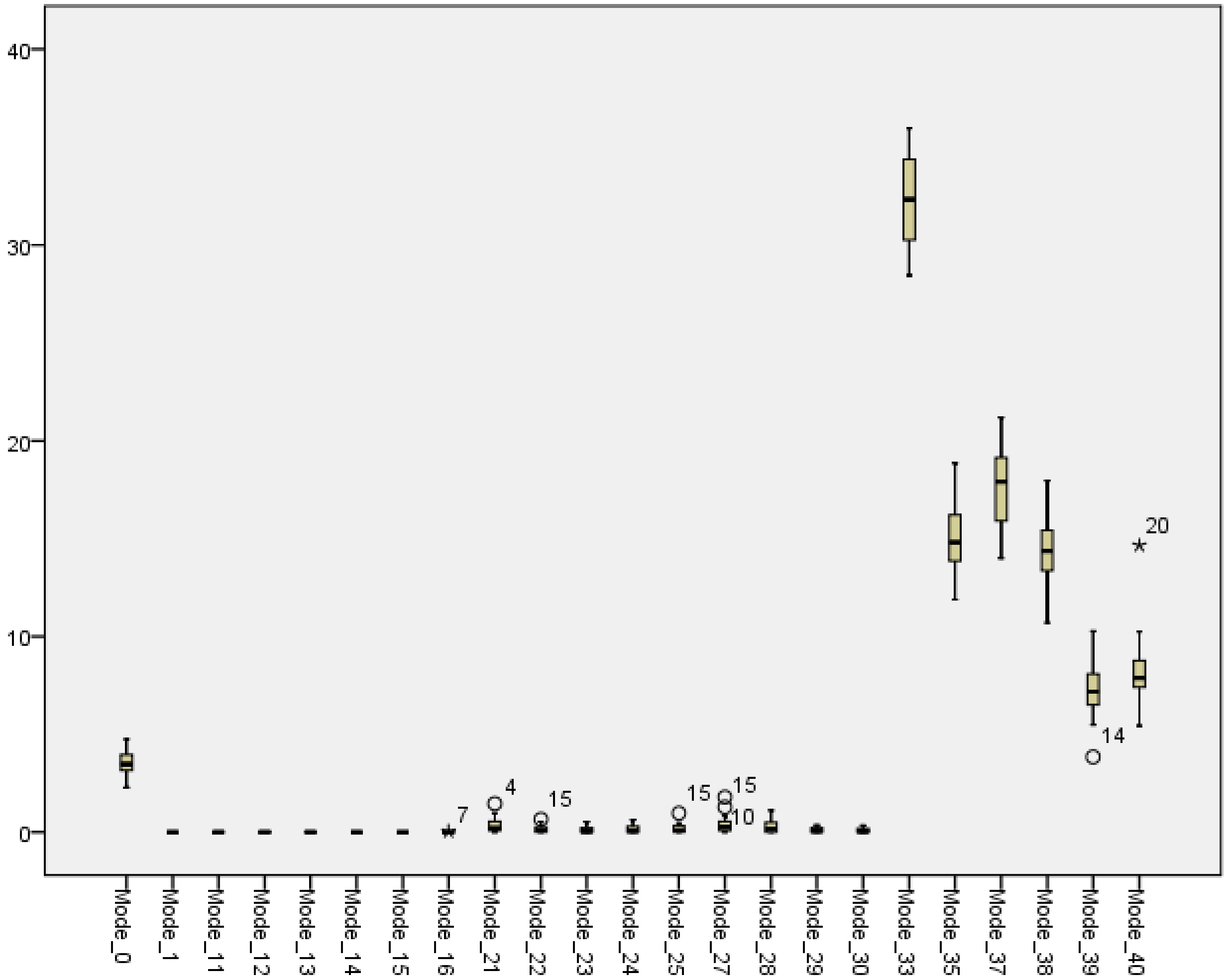


Figure 16. Box-Plot of Operating Mode Distributions in Percent for the Scenario – 22 Driving Cycles with Grades

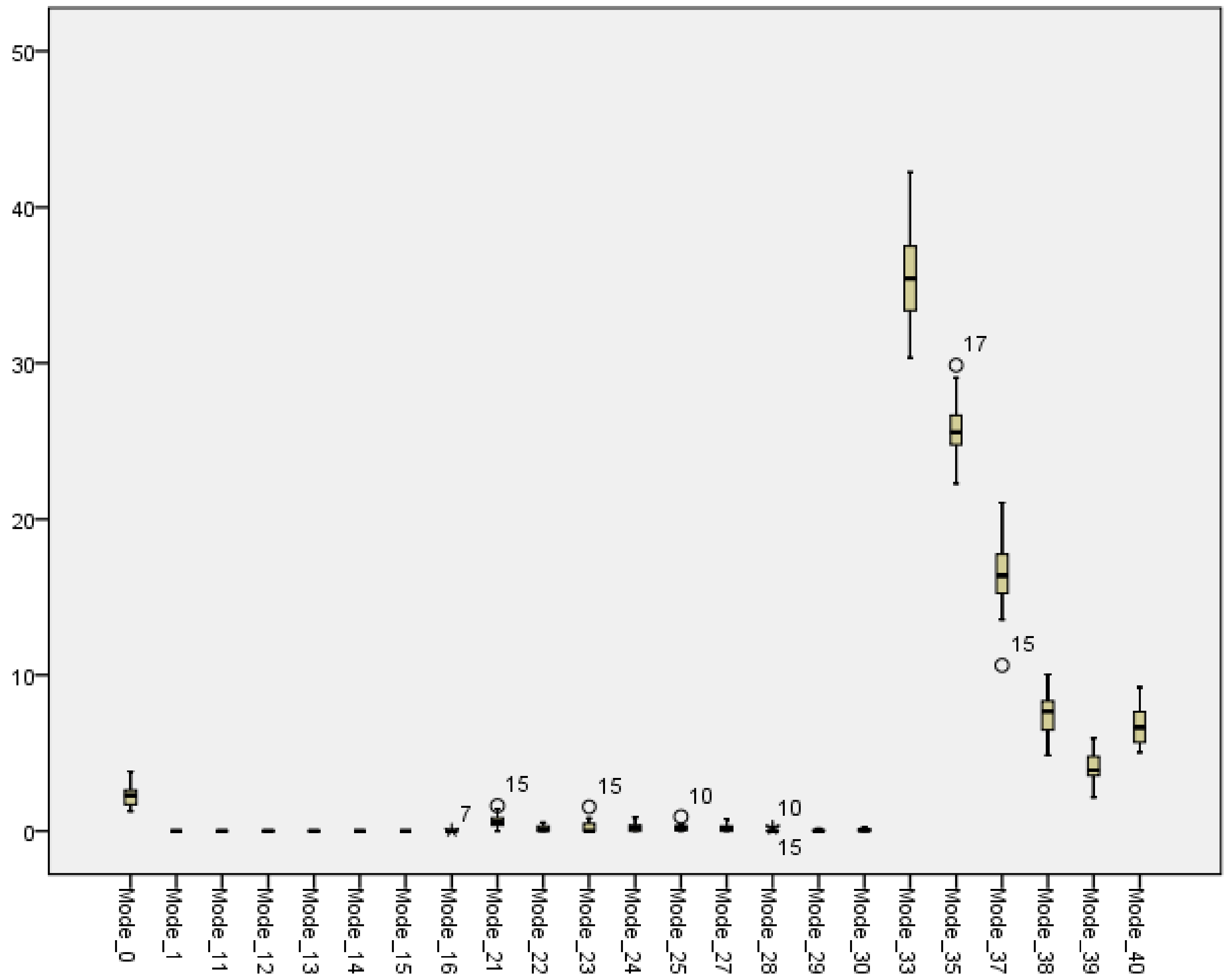


Figure 17. Box-Plot of Operating Mode Distributions in Percent for the Scenario – 22 Driving Cycles with No Grades

Table 11 shows mean emission and total energy consumption values, and standard deviations for the two Scenarios. Percent difference of the mean between the two scenarios was calculated and listed in Table 11. As shown, NO_X and $PM_{2.5}$ emissions and total energy consumption from the mean of the emissions for the driving cycles with grades were approximately 14.6%, 17.1%, and 18% higher than the mean for the driving cycles with no grades. THC emissions were only 0.8% different from each other. Driving cycles with grades resulted in higher NO_X and $PM_{2.5}$ emissions and total energy consumption, however, lower emissions in CO than driving cycles with no grades.

Table 12 shows t-tests to check equality of the means of emissions and total energy consumption from the two scenarios. Mean difference was based on subtraction the mean for the driving cycles with no grades from the mean for the driving cycles with grades. Therefore, it showed negative difference for NO_X and $PM_{2.5}$ emissions and total energy consumption. Based on the p values, the t-tests for CO, $NO_{X,}$ and $PM_{2.5}$ emissions and total energy consumption indicated that the difference between the mean values of the two scenarios was significant at $p <= 0.05$. No significant difference was seen for the calculated emissions for THC between the two scenarios. It is important to note that even though CO, $NO_{X,}$ and $PM_{2.5}$ emissions and total energy consumption were significantly different between the two scenarios, NO_X and $PM_{2.5}$ emissions and total energy consumption were higher for driving cycles with grades while CO emissions were higher for driving cycles with no grades.

Table 11. Descriptive Statistics of the Two Scenarios and Percent Difference

	Scenario (Driving Cycles)	N	Mean	Standard Deviation	Standard Error Mean	% difference (grades vs. no grades)
THC (grams)	no grades	22	12.3	.30943	.06597	
	grades	22	12.4	.25979	.05539	0.8
CO (grams)	no grades	22	59.4	1.28494	.27395	
	grades	22	58.3	1.36180	.29034	-1.9
NO_X (grams)	no grades	22	437.0	10.06111	2.14504	
	grades	22	500.6	8.18004	1.74399	14.6
$PM_{2.5}$ (grams)	no grades	22	19.9	.52776	.11252	
	grades	22	23.3	.53180	.11338	17.1
Total Energy Consumption (kJ)	no grades	22	1,296,713	33123	7061.808	
	grades	22	1,530,285	28015	5972.804	18.0

Table 12. T-Tests for Equality of Means of Emissions and Total Energy Consumption from the Two Scenarios

						95% Confidence Interval of the Difference	
	t	df	P value	Mean Difference	Std. Error Difference	Lower	Upper
THC (grams)	-1.156	42	.254	-.0996	.08614	-.27338	.07429
CO (grams)	2.930	42	.005	1.1696	.39918	.36397	1.97512
NO_X (grams)	-23.000	42	.000	-63.5855	2.76454	-69.16452	-58.00639
$PM_{2.5}$ (grams)	-21.723	42	.000	-3.4700	.15974	-3.79236	-3.14764
Total Energy Consumption (kJ)	-25.254	42	.000	-233572	9249	-252238	-214906

4.2.3.3 Comparisons of the characteristics of individual trip for the two scenarios

Figure 188 shows comparisons of the two scenarios depicting different conditions of road grades. Characteristics that were analyzed as shown in Figure 18 include time proportion distributions in percent for operating modes, STP bins for three different categories, and acceleration, as well as comparisons of emissions for each pollutant. STP bins defined in the MOVES model are up to 30 (in scaled kW) and 30 above is combined into one category. Additional comparisons for Trips 2 through 5 are included in Appendix D. Comparisons of Characteristics of Driving Cycles for Trips 2 through 5 for reference.

The analyses of the driving cycle with grades showed a larger percentage of time in the higher operating mode bins, higher STP bins, and deceleration/braking mode bin, compared to the percentage of those modes analyzed with the driving cycle with no grades. As shown in Figure 18, for the driving cycle with grades, a larger percentage fell into the higher operating modes such as modes 38, 39, and 40, compared to those with the driving cycle with 0% road grade. Similar patterns were seen for the STP bins. The driving cycle with grades spent a more time than the driving cycle with no grades at the STP bins greater than 15. The acceleration distribution graph showed that the drive cycle with grades involved a larger percentage of time in acceleration of 0 mph/s < a < 1 mph/s than acceleration of -1 mph/s < a < 0 mph/s. On the other hand, opposite characteristics were seen with the driving cycle with no grades. The overall terrain changes for this trip were uphill from a valley to a plateau. This could explain why the driving cycle of Trip 1 involves more acceleration of 0 mph/s < a < 1 mph/s than -1 mph/s <a < 0 mph/s.

Emission comparisons made for the two scenarios showed a good agreement with the descriptive statistics of the analyses described in section 4.2.3.2. Emissions of NO_X and $PM_{2.5}$ and total energy consumption for the driving cycle with grades were higher than for the driving cycle with no grades. On the other hand, THC and CO emissions do not show much difference between the two scenarios.

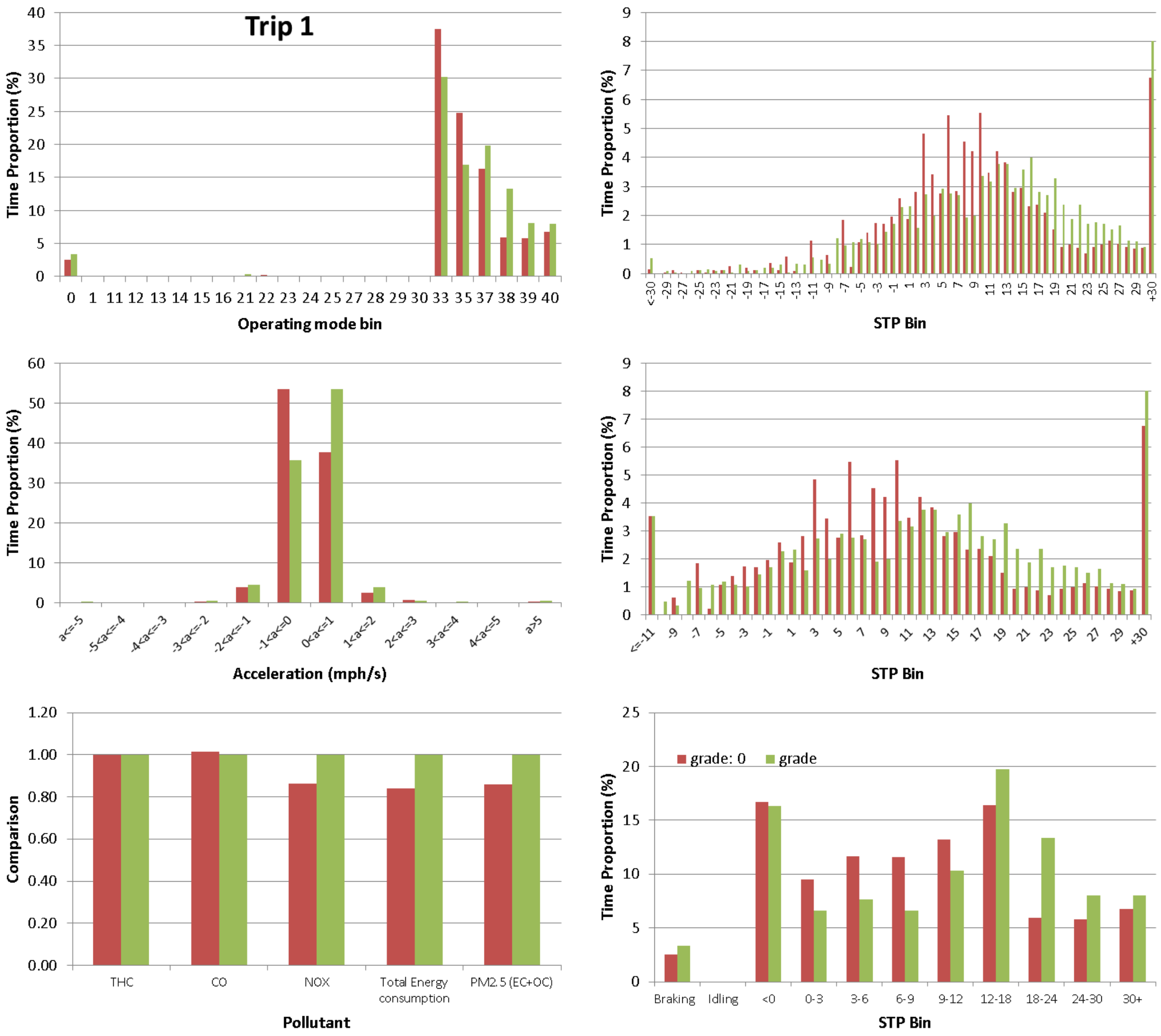


Figure 18. Characteristics Comparisons between the Driving Cycle with Grades and No Grades for Trip 1

4.2.4 Emission Estimates Using the MOVES Driving Schedules and Comparison of the Emissions with Grades and No Grades

The MOVES driving schedules were also analyzed, using constant grades at -0.3%, 0%, and +0.3%. Figure 19 shows the performance characteristics for the MOVES driving schedule 354 with an average speed of 59.7 mph. The characteristics include operating mode bin, STP bin, and acceleration. Analyses for the rest of the MOVES driving schedules on freeways are shown in Figure A- 12 to Figure A- 16 in Appendix A. MOVES Default HHD Vehicle Driving Schedule and Its Characteristics. As shown in Figure 19, a greater proportion of time fell into the higher operating mode bins as grades increased from negative to positive grades,. In terms of STP bins, at grades of -0.3%, more time fell into lower STP bins and at grades of +0.3%, more time fell into higher STP bins. Acceleration distributions for the driving schedule with no grades had higher percentages in acceleration of -1 mph/s < a < 0 mph/s than in acceleration of 0 mph/s < a< 1 mph/s. However, the reverse was true for the driving schedule with +0.3% grade.

Table 13 shows emission comparisons for the MOVES driving schedule 354 with three grades, -0.3%, 0%, and +3%. When the road grades increased from -0.3% to 0 then 0.3%, emissions of CO, NO_X and $PM_{2.5,}$ and total energy consumption increased. Emissions of NO_X and $PM_{2.5,}$ and total energy consumption were increased by approximately 9% to 12.6%. On the other hand, CO emissions increased by only up to 1%. When road grade increased, other pollutants increased. However, THC emissions were decreased slightly by 0.5 – 0.6%.

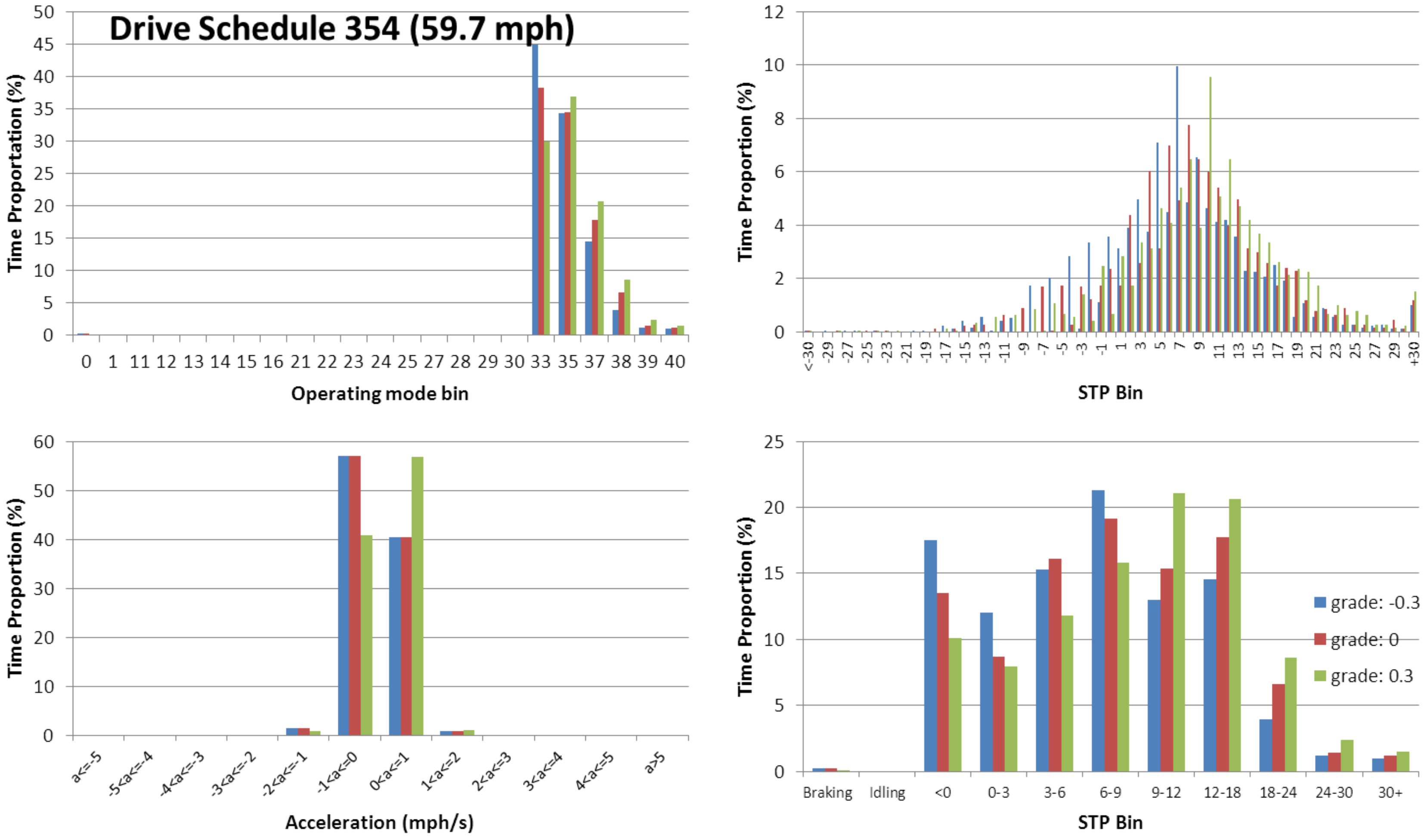


Figure 19. Comparisons of Characteristics of the Driving Schedule 354 with No Grade and Grades of 0.3% and -0.3%

Table 13. Emission Comparisons for the MOVES Driving Schedule 354 (with Average Speed of 59.7 mph) with Different Constant Road Grades

	Grades (%)	Rates (grams)	% increase*
THC	-0.3	7.82	
	0	7.77	-0.6
	0.3	7.73	-0.5
CO	-0.3	38.77	
	0	38.89	0.3
	0.3	39.28	1.0
NO_X	-0.3	224.57	
	0	247.96	10.4
	0.3	276.04	11.3
$PM_{2.5}$	-0.3	9.76	
	0	10.65	9.1
	0.3	11.74	10.2
Total energy consumption	-0.3	633,937 kJ	
	0	708,921 kJ	11.8
	0.3	798,038 kJ	12.6

* % increase is from -0.3% to 0% to +0.3%.

4.2.5 Comparisons of Emissions for the Same Average Speed with Different Road Grades Using the Driving Cycle of Trip 1 and the MOVES Default Driving Schedules

Comparisons were made between the calculated emissions for the driving cycle of Trip 1 with the average speed of 63.9 mph and the calculated emissions using the MOVES driving schedules for the same average speed. Figure 20 shows the comparisons for NO_X, $PM_{2.5}$, and total energy consumption at different grades using both MOVES driving schedules and Trip 1 driving cycle. The patterns were similar, as grades increased, emissions of NO_X and $PM_{2.5,}$ and total energy consumption increased for both MOVES driving schedules and Trip 1 driving cycle. Across the driving cycles with the same road grades, the Trip 1 driving cycle resulted in higher emissions and greater total energy consumption than the MOVES driving schedules.

When the emissions from the drive cycle of Trip 1 with grades were compared with the emissions from the same cycle with zero grade, NO_X emissions were 498 grams for grades, compared to 430 grams for no grades, which was 16% difference. There was 16.5% difference

(22.7 grams versus 19.5 grams) for $PM_{2.5}$ and 18.9% difference (11.3 grams versus 4.8 grams) for total energy consumption. Even with the same speed profile, if road grades were not included in the emissions modeling, there were about 16 to 19% difference in emission levels of NO_X and $PM_{2.5}$, and total energy consumption in this hilly terrain.

Figure 21 shows the comparisons for CO and THC as well as percent difference in emissions between the MOVES driving schedules with 0.3% grade and the driving cycle of Trip 1 with grades. As grades increased, emissions of NO_X and $PM_{2.5}$ and total energy consumption increased for both MOVES driving schedules and Trip 1 driving cycle. However, unlike NO_X, $PM_{2.5}$, and total energy consumption, CO emissions calculated using the Trip 1 driving cycle were lower than using the MOVES driving schedules for each road grade. Furthermore, the Trip 1 driving cycle with grades showed the lowest CO emissions among all cases. For THC emissions, emissions were not different from one another when using the Trip 1 driving cycle with different road grades. Using the MOVES driving schedules with different road grades, there was little change in THC emissions with decrease in emissions as grades increased. Based on the percent differences shown in Figure 21, total energy consumption and emissions of NO_X, $PM_{2.5}$, and THC were higher using the driving cycle of Trip1 with grades than using the MOVES driving schedules with 0.3% grade by 11%, 7.6%, 14%, and 3%, respectively. On the other hand, CO emissions were lower by 3.4%.

The results showed that emissions using Trip 1 with grades that correspond to the terrain were estimated 7.6%, 14%, and 3% higher for NO_X, $PM_{2.5}$, and THC than when using the MOVES default driving schedules for the same average speed with an average grade of 0.3%, and that total energy consumption was also estimated 11% higher. However, CO emissions were 3.4% lower when using the Trip 1 driving cycle with grades than when using the MOVES driving schedules with 0.3% grade.

Overall, total energy consumed and emissions for NO_X and $PM_{2.5}$ using the driving cycle of Trip 1 were higher than when estimated using the MOVES default driving schedules for the same average speed. For CO, however, the opposite effect was true. Emissions for the MOVES default driving schedules were higher than using the driving cycle for Trip 1.

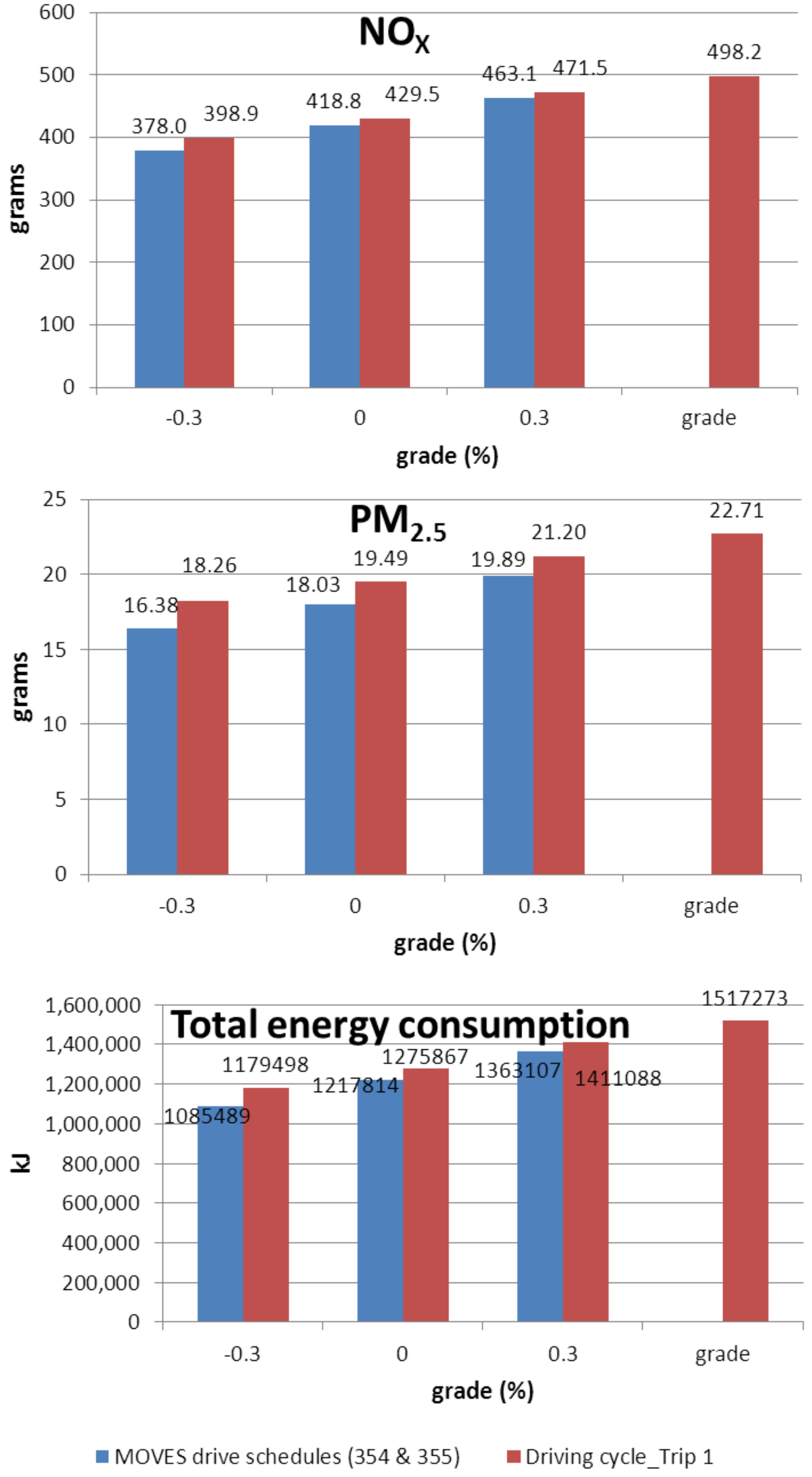


Figure 20. Comparisons for NO_X, $PM_{2.5}$, and Total Energy Consumption: MOVES Driving Schedules (354 & 355) Versus Trip 1 Driving Cycle for the Average Speed of 63.9 mph

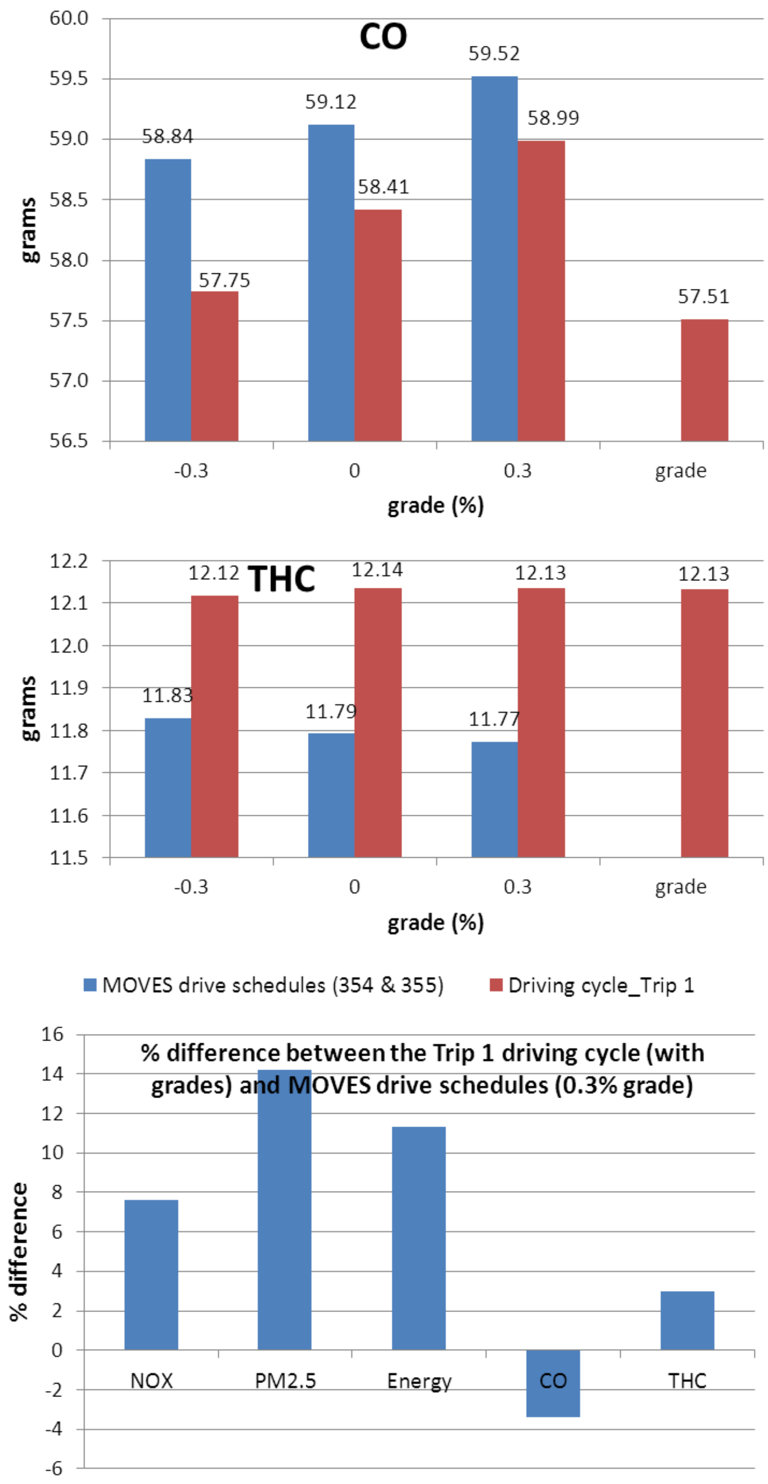


Figure 21. Comparisons for CO and THC: MOVES Driving Schedules (354 & 355) Versus Trip 1 Driving Cycle for the Average Speed of 63.9 mph, and % Difference in Emissions between the MOVES Driving Schedules with 0.3% Grade and Trip 1 Driving Cycle with Grades

4.3 CONCLUSIONS

This study examined the driving activity data for heavy duty trucks in hilly terrain. By applying a filtering algorithm, 22 vehicle speed and time profiles obtained from a GPS were used to construct a synthetic driving cycle for a hilly terrain section of the Federal Interstate. Data were analyzed to identify characteristics of typical driving episodes. Results showed that the range of speeds for the driving cycles in this hilly terrain was greater than the range of speeds for the two MOVES default driving schedules (identified by the numbers 354 and 355) that have average speeds of 59.7 ± 3.05 mph and 71.7 ± 3.05 mph, respectively.

Analyses of the operating mode distributions for the synthetic driving cycles, the majority of the synthetic driving cycles fell in the operating mode bins 33, 35, 37, 38, 39, and 40 since the average speeds of the synthetic driving cycles were over 60 mph. Deceleration/braking mode of the cycles accounted for approximately 3 to 4% of the total time for the synthetic driving cycle. This percentage is higher than the percentage of the deceleration/braking mode from the two MOVES default driving schedules. This is because the trips were made in the area which has grade changes along the terrain.

Examination of STP also showed that the synthetic driving cycles have different characteristics from the two MOVES default driving schedules. The Gaussian function was fitted to the synthetic driving cycles and the default driving schedules in MOVES. The STP for the synthetic driving cycles showed lower peak height and spread widely off the center, compared to the STP for the two MOVES driving schedules. This indicates that driving in hilly terrain requires a wide range of tractive powers, compared to the MOVES driving schedules. More time proportion in STP, which is greater than 30 in scaled kW, was seen in the synthetic driving cycles, compared to the two MOVES driving schedules.

Sensitivity analyses using emission and road grade effects in MOVES showed that as grade increased, NO_X and $PM_{2.5}$ emissions and total energy consumption rates increased. However, emissions of CO and THC showed different patterns. For example, at constant speed of 70 mph, CO emission rates at 2% grade were lower than at zero grade, and THC emission rates at 2%

grade were the same as at zero grade. For THC emissions at constant speeds of 30 mph and 40 mph, emission rates decreased as grade increased from zero to 6%.

Emission estimates for the two scenarios (synthetic driving cycles with grades and no grades) showed that CO, NO_X and $PM_{2.5}$ emissions and total energy consumption were significantly different from each other ($p <= 0.05$). However, THC emissions were not significantly different. This means that modeling emissions using road grade or zero grade will result in substantively different emissions for all pollutants except for THC.

Based on the speed-time and acceleration-speed profiles, the results of the analyses showed that trips in hilly terrain involved more acceleration and braking operations. The synthetic driving cycles in hilly terrain were different from the two MOVES default driving schedules. The synthetic driving cycles resulted in higher emissions than the MOVES default driving schedules. From comparisons of the characteristics of the trips that were used to generate the synthetic driving cycles and the MOVES driving schedules, it was demonstrated that the MOVES default driving schedules were not representative of actual driving patterns in hilly terrain. Regulatory agencies and/or air quality modelers that perform transportation conformity analyses should be aware of the importance of using the local driving operating modes instead of relying on the default driving schedules that are included in the model. Especially, when using the MOVES default driving schedules for the same average speed for driving in hilly terrain, emissions are most likely to be underestimated even without incorporating the road grades.

Emissions calculated for Trip 1 with grades were 7.6%, 14%, and 3% for NO_X, $PM_{2.5}$, and THC higher than when using the MOVES default driving schedules for the same average speed with an average grade of 0.3%. Total energy consumption was also estimated higher by 11%. On the other hand, CO emissions were 3.4% lower.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY

Two research works were presented in this dissertation. The first objective was to compare emissions from the newer mobile source emissions model, MOVES2010a, with the older model, MOBILE6.2. A case study from the Pittsburgh area was used to demonstrate this purpose. Baseline emission estimates for all vehicles and heavy-heavy duty diesel trucks were compared. Hourly truck volumes, VMT, and average speeds for each road link in the study area from the added truck volumes were used to evaluate increases in emissions using both models. The results showed that emission estimates for all vehicle types using MOVES were higher than emissions estimated using MOBILE6.2/NMIM for CO, NO_X, PM_{10}, $PM_{2.5}$, and VOCs except for CO_2 and NH_3. For HHDD vehicles, MOVES estimated higher emissions for all pollutants when compared to MOBILE6.2 except for NH_3 where emissions were lower for MOVES. The biggest difference from the two models was seen in PM_{10} and $PM_{2.5}$. It is important to note that these results may be different for other areas, which have different traffic characteristics such as vehicle population, VMT, speed, vehicle age distribution, etc.

The second objective was to evaluate the characteristics of synthetic driving cycles created from actual road data, and to compare MOVES default driving schedules with the driving cycles of HHDD vehicles in hilly terrain. This was accomplished using the operating mode approach based on MOVES. The driving activity data used in this study were GPS data based on the trips made in East Tennessee, with the elevation change of approximately 1000 ft. Based on the study, the following conclusions were reached:

1. It was found that driving characteristics in hilly terrain were different from the characteristics in the MOVES driving schedules in terms of speed range, scaled tractive power (STP) distributions, and acceleration distributions.
2. Based on the sensitivity analyses on grade effects in MOVES, NO_X and $PM_{2.5}$ emissions and total energy consumption rates increased as grade increased in general. However CO and THC emissions showed different patterns.

3. Emissions for the synthetic driving cycles with road grades and no grades showed that NO_X and $PM_{2.5}$ emissions and total energy consumption were different from each other. Percent difference in CO emissions was relatively smaller, compared to NO_X and $PM_{2.5}$ emissions and total energy consumption. However, THC emissions were not affected from the road grade changes.
4. From the comparisons of the two scenarios, the synthetic driving cycles with grades showed more time proportion in higher operating mode bins and STP bins, compared to the synthetic driving cycles with no grades. This resulted in higher NO_X and $PM_{2.5}$ emissions and total energy consumption from the synthetic driving cycles with grades than from the synthetic driving cycles with no grades.
5. Emissions calculated using the synthetic driving cycles with grades were 7.6%, 14%, and 3% for NO_X, $PM_{2.5}$, and THC higher than when using the MOVES default driving schedules for the same average speed (63.9 mph) with an average grade of 0.3%. Total energy consumption was also estimated higher by 11%. On the other hand, CO emissions were 3.4% lower.
6. MOVES default driving schedules were not representative of actual driving patterns in hilly terrain. In this terrain, using the MOVES default driving schedules, emissions for NO_X and $PM_{2.5}$ emissions and total energy consumptions are most likely to be underestimated.

5.2 RECOMMENDATIONS

This research compared the two mobile emission models, constructed synthetic driving cycles in hilly terrain and assessed the driving characteristics of HHDD vehicles. The research was, however, limited in certain aspects and the following recommendations are made for further study:

1. More research is needed to improve default driving schedules in MOVES for hilly terrain. Since this study was based on a single location. More research is needed for other hilly areas to develop additional (generic) driving cycles.

2. For better emission estimates and transportation policy, local travel agencies, Metropolitan Planning Organization (MPO), air quality modelers, and transportation policy makers may need to develop local specific traffic data, instead of using MOVES defaults.
3. CO and THC emissions from heavy duty trucks in MOVES were not affected significantly by road grade. At certain speeds, emission rates decreased slightly as road grade increased. Although these are not major air pollutants that contribute to total emissions from heavy duty vehicles, compared to light duty vehicles, more research is needed to improve MOVES emissions rates of CO and THC from heavy duty trucks, especially for the effect of road grade.
4. Emission comparisons in this research were made based on the MOVES mean base rates. For better model evaluations, more research is recommended for on-road measurements on emissions, engine performance and driving activity.
5. The research showed STP bins were extended to up to 50 and more for the truck driving cycles in hilly terrain. However, MOVES has only up to 30 bins and above 30 is grouped into a single bin. Additional STP bin categories, greater than 30, are needed to model emissions in greater detail for hilly terrain.
6. More operating mode categories may need to be developed to accommodate higher STP in hilly terrain. More emission rates for those additional operating mode categories need to be developed.

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APPENDICES

Appendix A. MOVES Default HHD Vehicle Driving Schedule and Its Characteristics

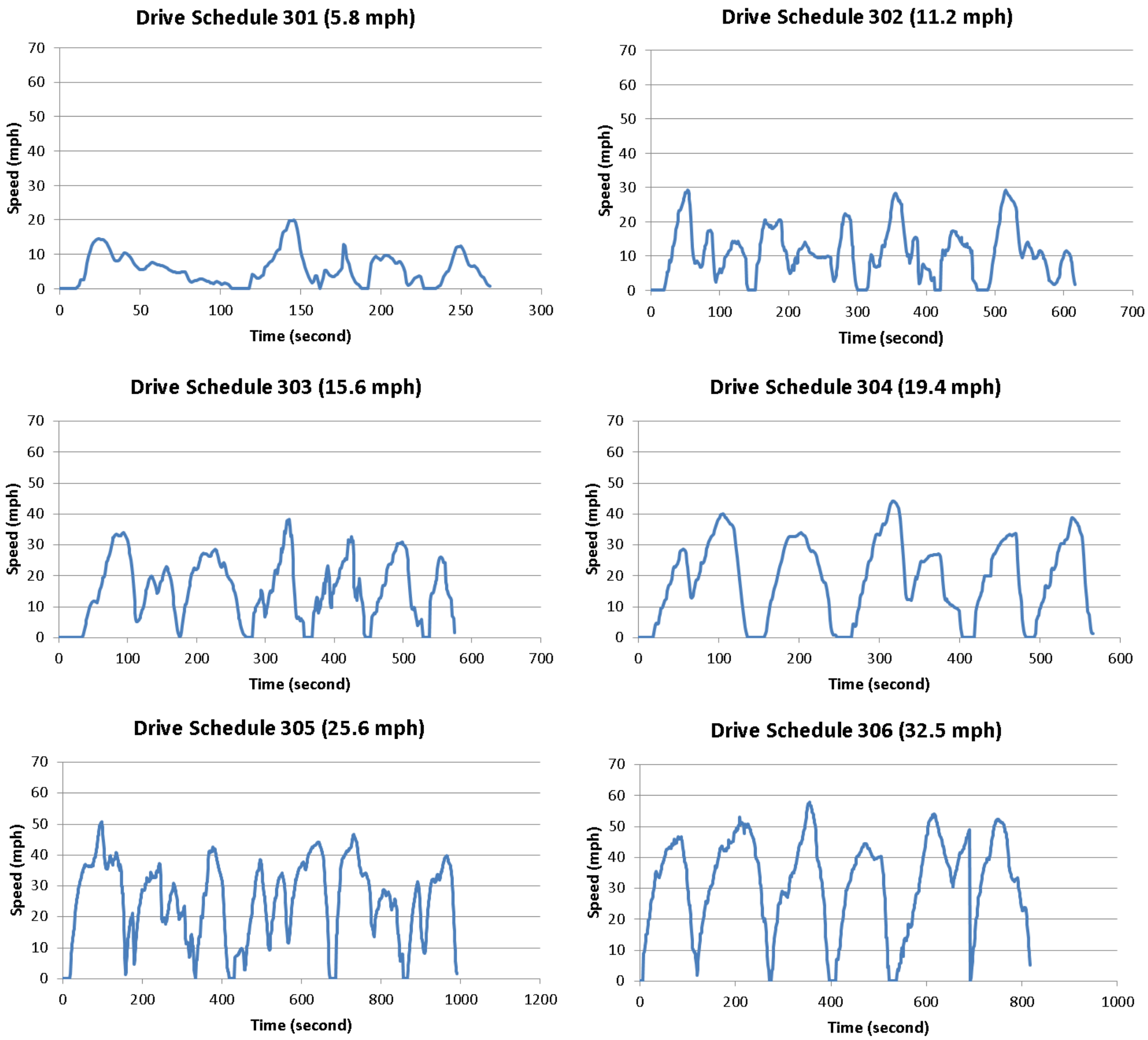


Figure A- 1. MOVES Default HHD Vehicle Driving Schedules for Non-Freeways

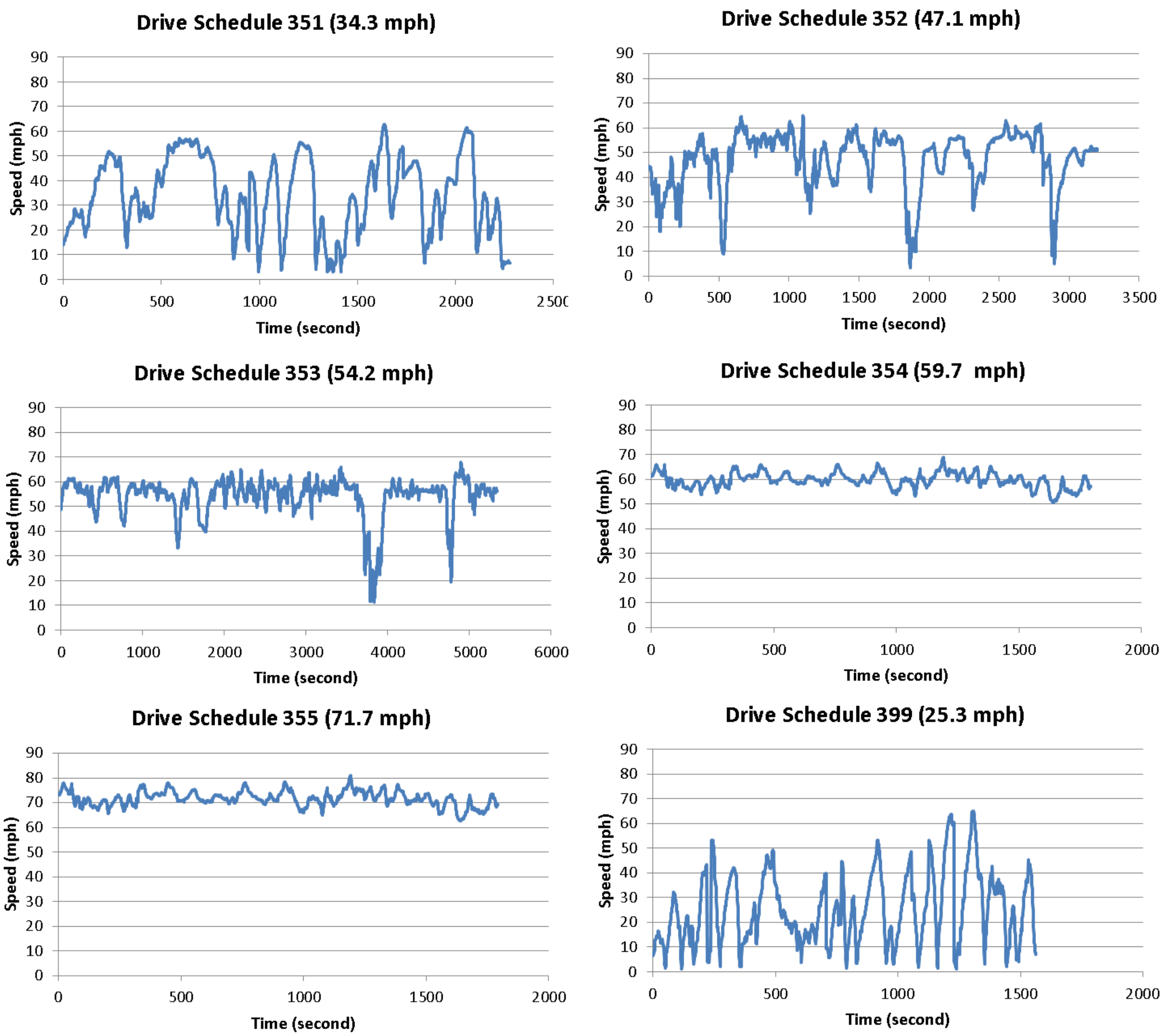


Figure A- 2. MOVES Default HHD Vehicle Driving Schedules for Freeways

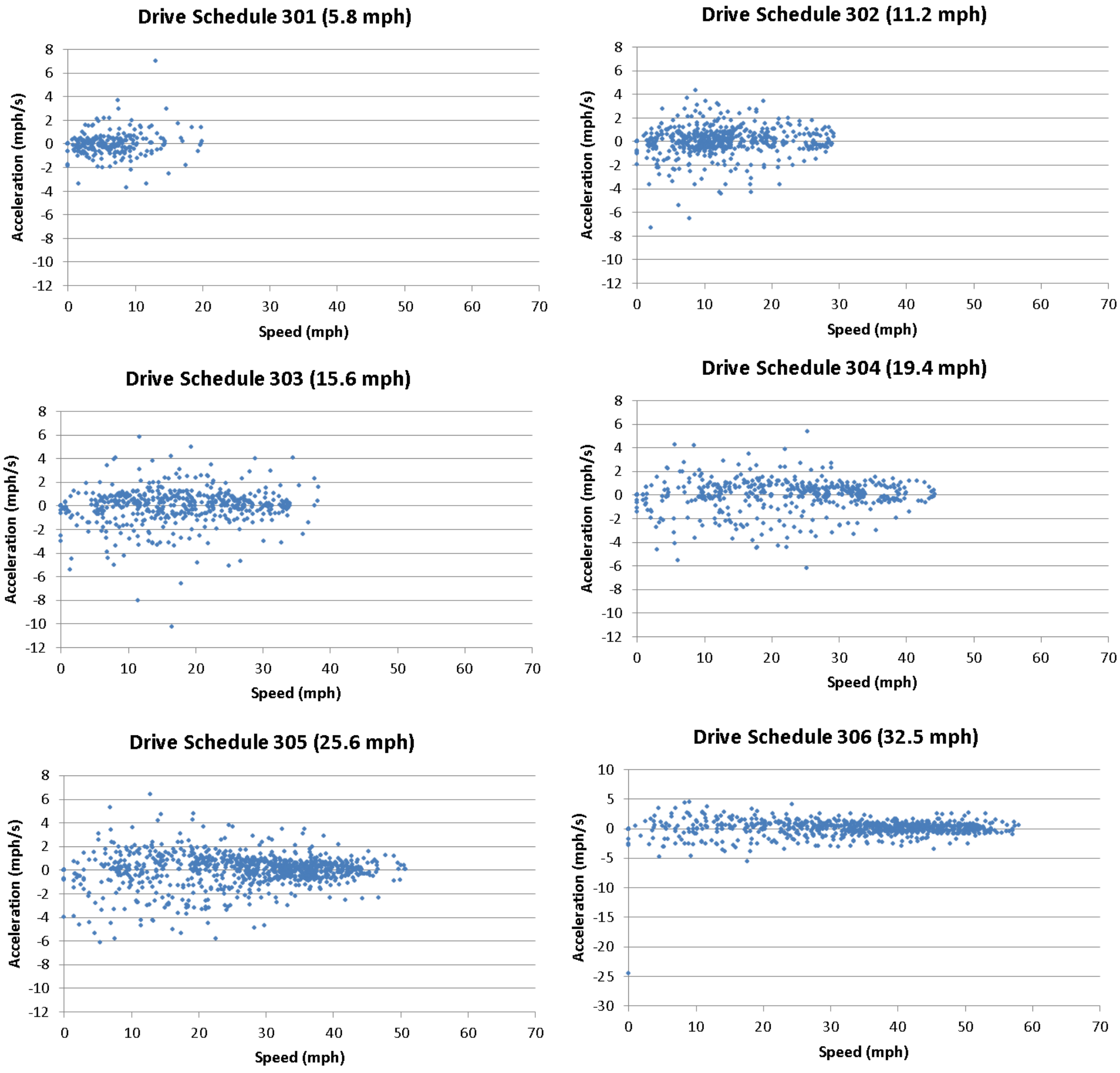


Figure A- 3. Acceleration Versus Speed for MOVES Default HD Vehicle Driving Schedules for Non-Freeways

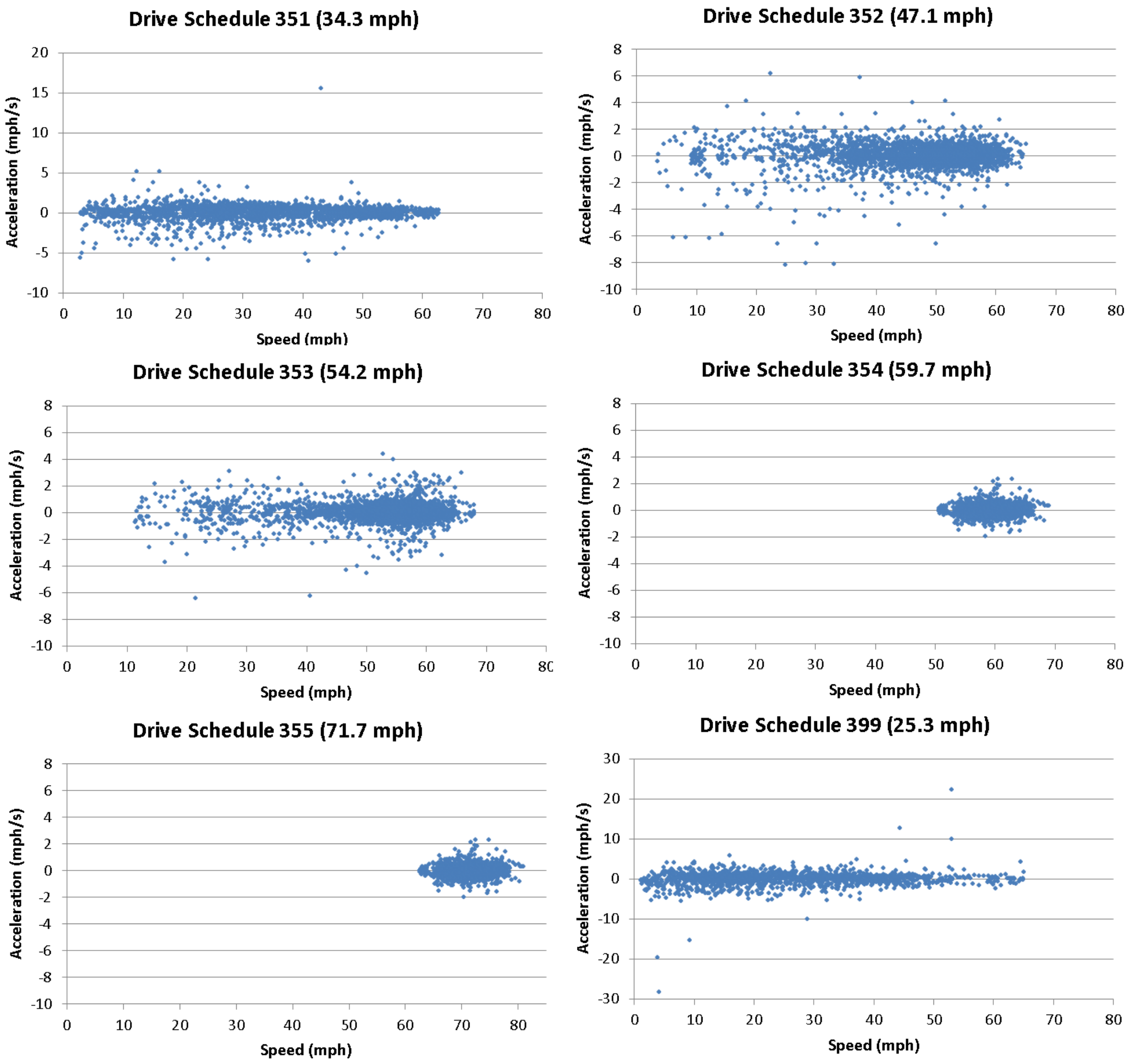


Figure A- 4. Acceleration Versus Speed for MOVES Default HD Vehicle Driving Schedules for Freeways

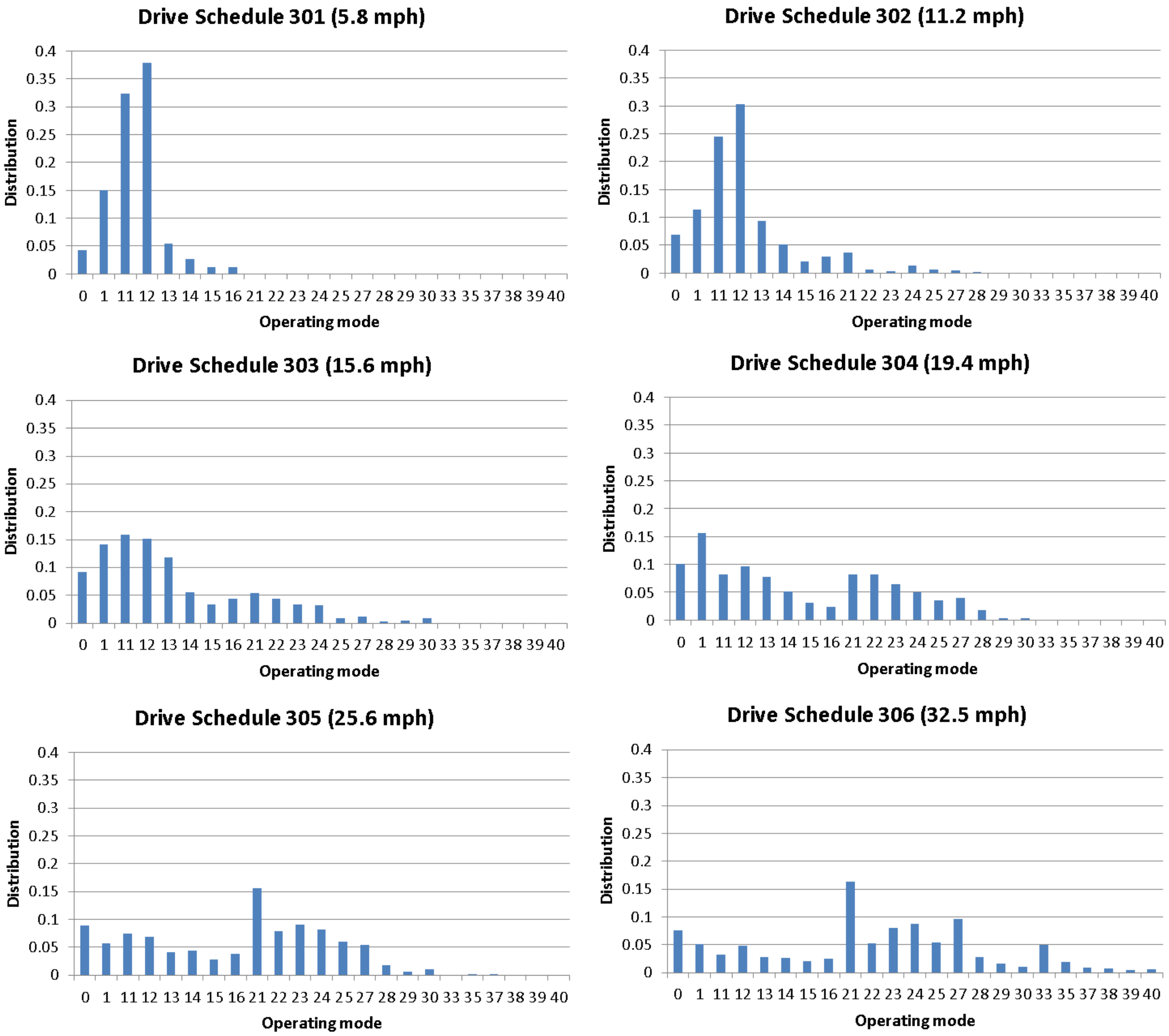
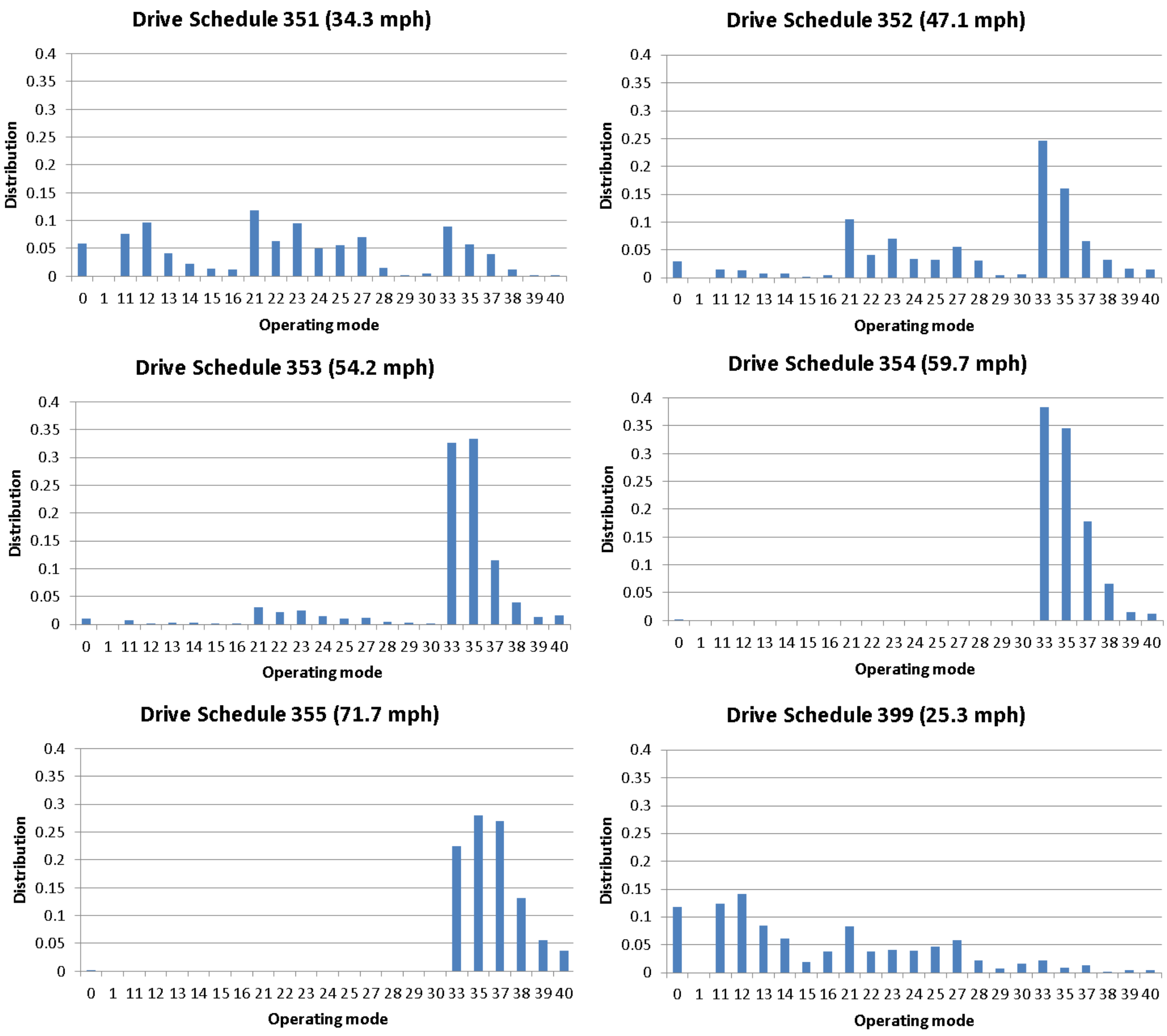


Figure A- 5. Operating Mode Distribution for MOVES Default HD Vehicle Driving Schedules for Non-Freeways


Drive Schedule 351 (34.3 mph)

Drive Schedule 352 (47.1 mph)

Drive Schedule 353 (54.2 mph)

Drive Schedule 354 (59.7 mph)

Drive Schedule 355 (71.7 mph)

Drive Schedule 399 (25.3 mph)

Figure A- 6. Operating Mode Distribution for MOVES Default HD Vehicle Driving Schedules for Freeways

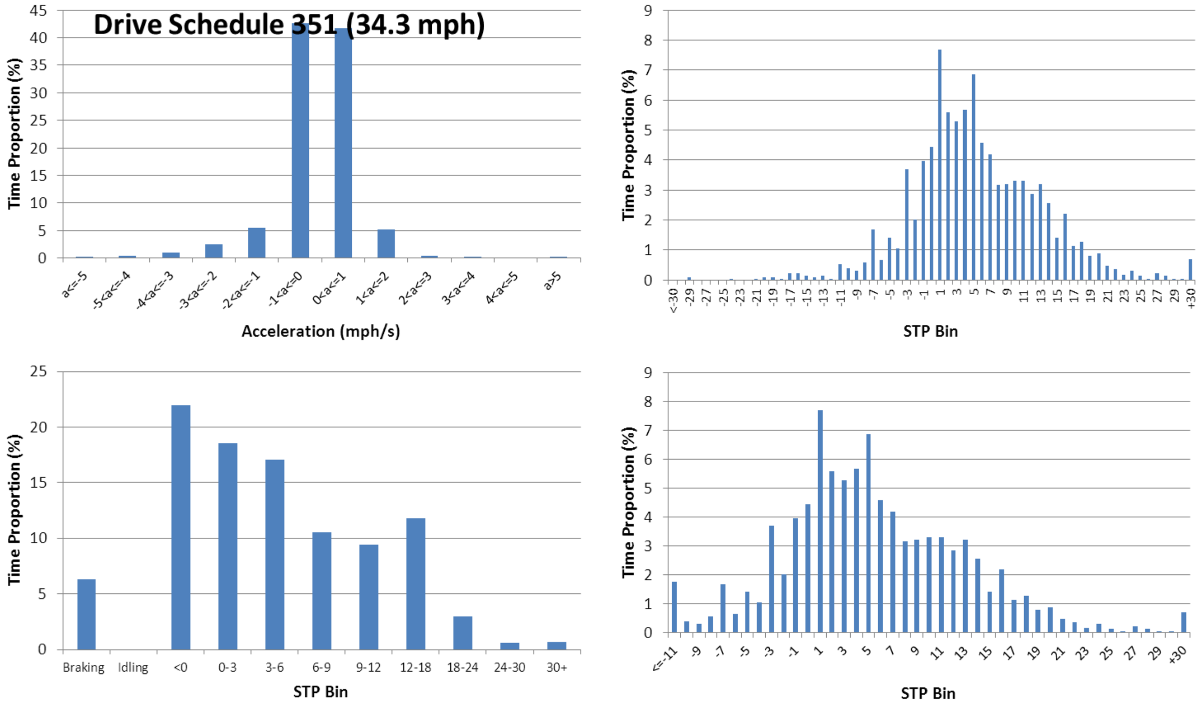


Figure A- 7. Characteristics of the MOVES Driving Schedule 351

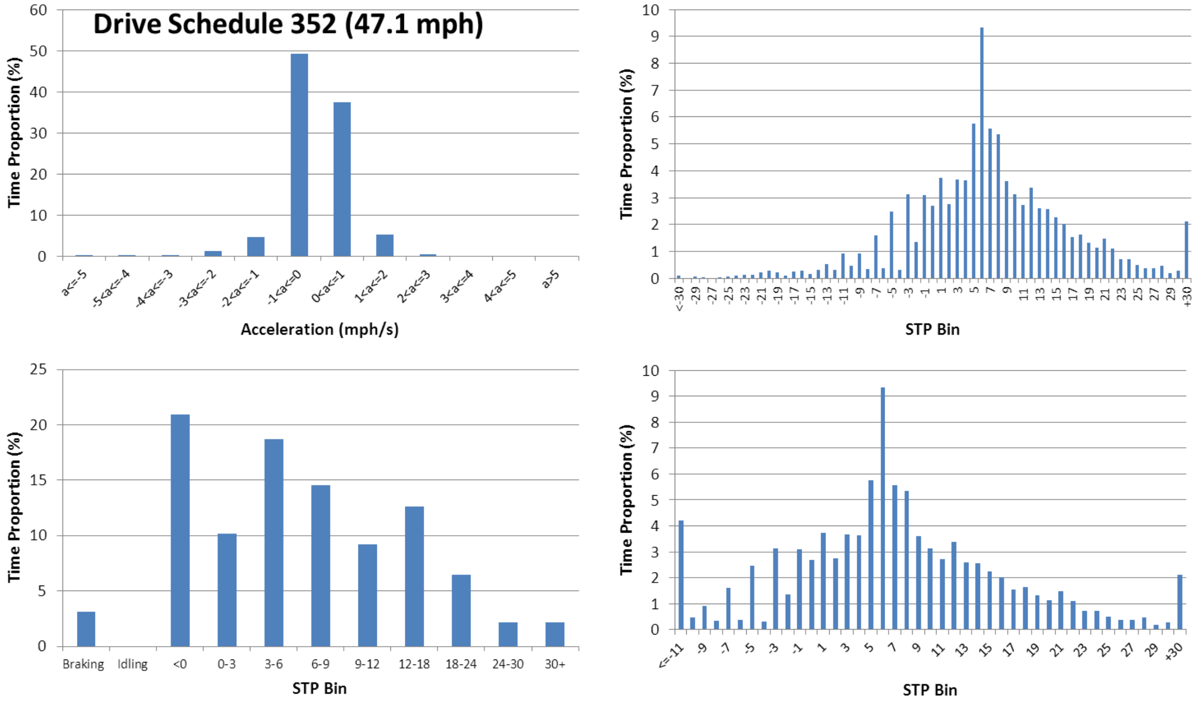


Figure A- 8. Characteristics of the MOVES Driving Schedule 352

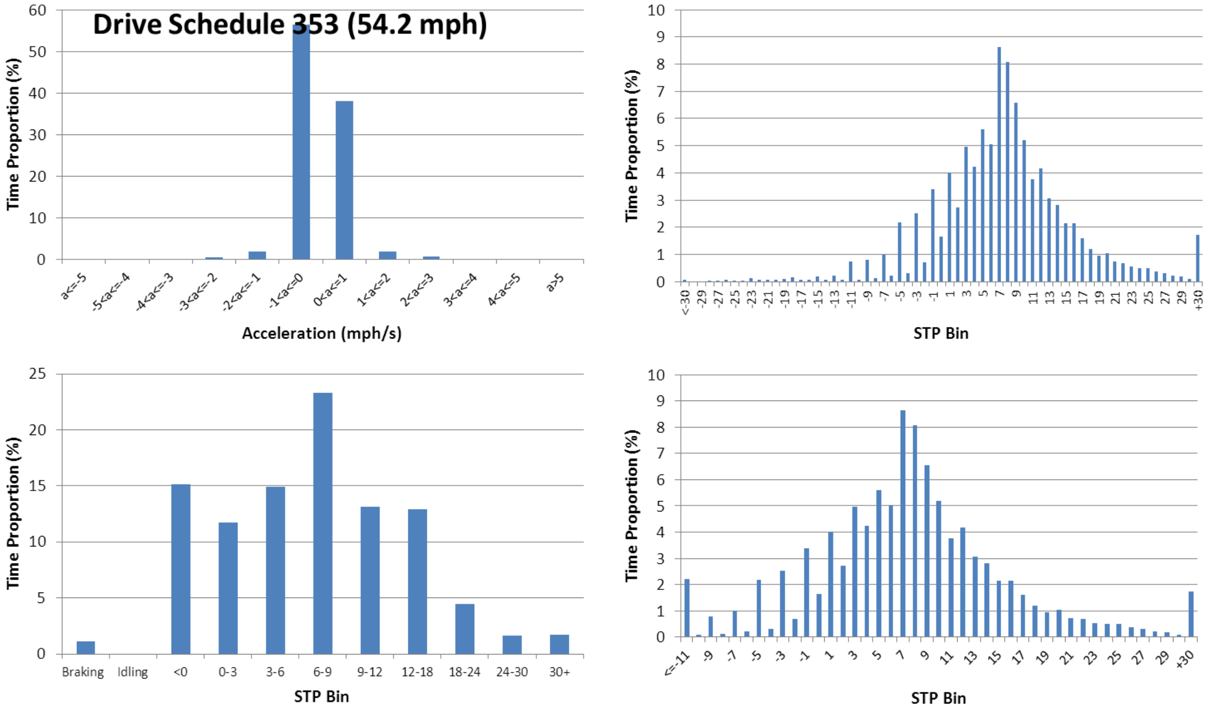


Figure A- 9. Characteristics of the MOVES Driving Schedule 353

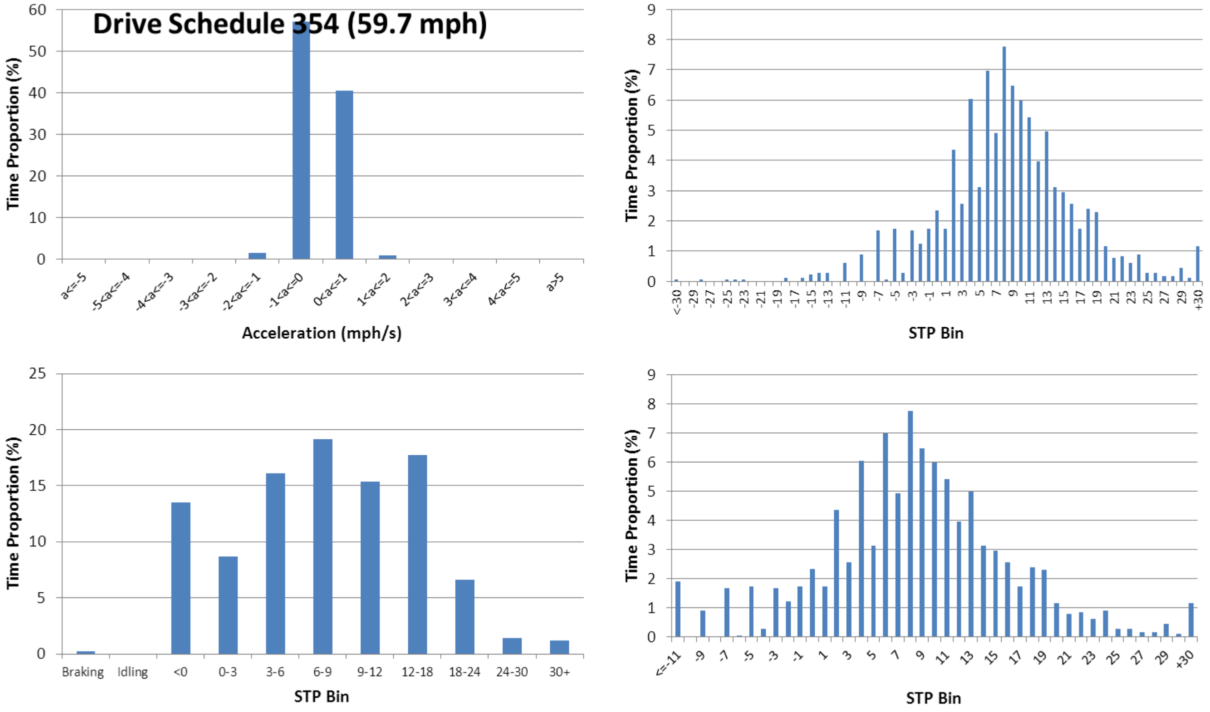


Figure A- 10. Characteristics of the MOVES Driving Schedule 354

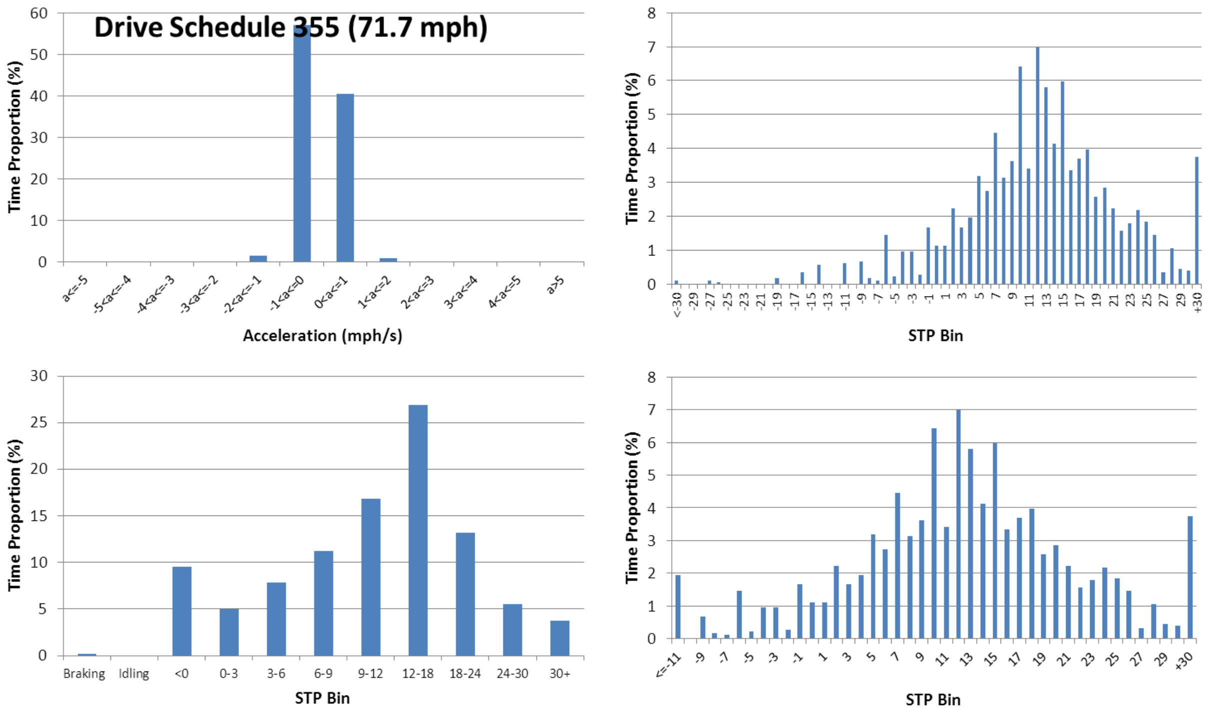


Figure A- 11. Characteristics of the MOVES Driving Schedule 355

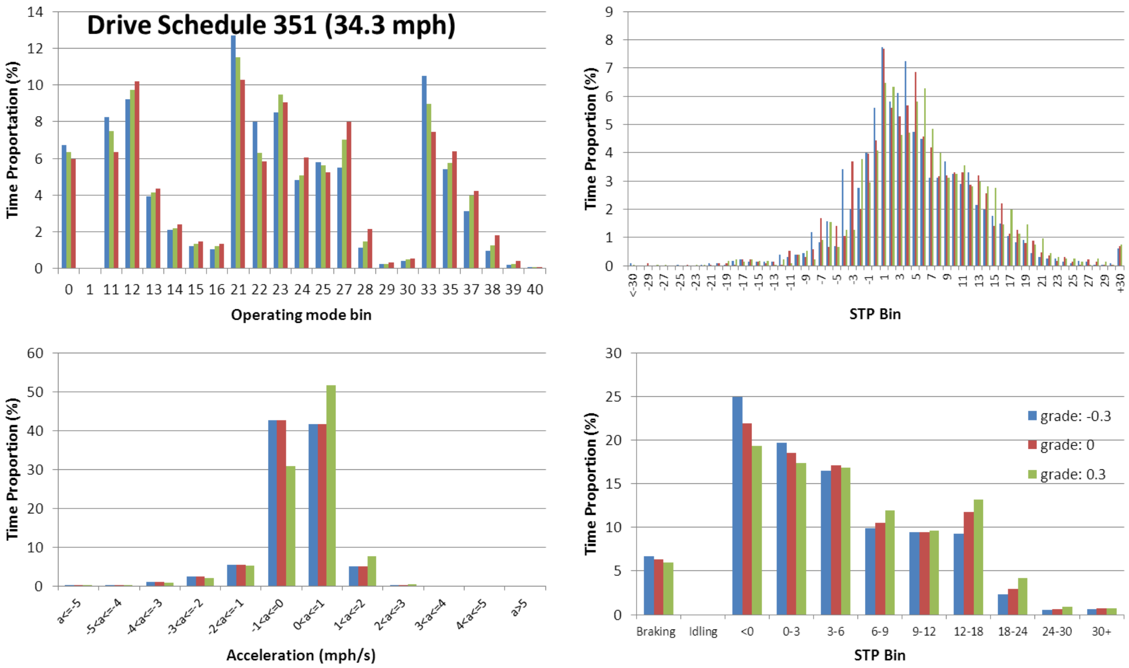


Figure A- 12. Comparisons of Characteristics of the Driving schedule 351 with No Grade and Grades of 0.3% and -0.3%

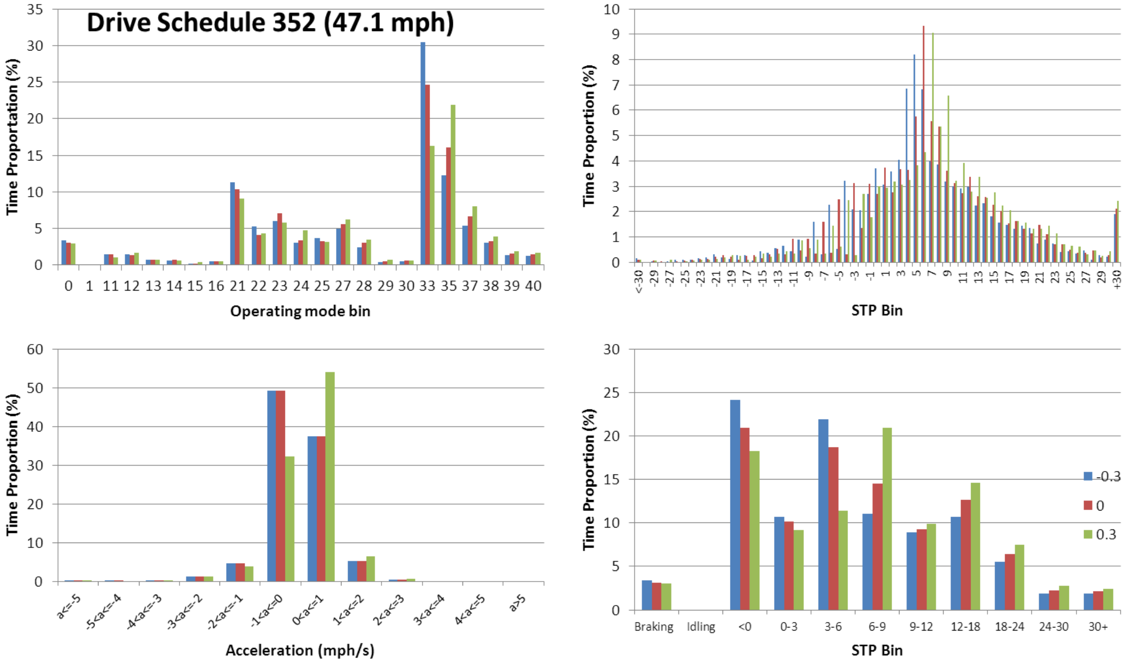


Figure A- 13. Comparisons of Characteristics of the Driving Schedule 352 with No Grade and Grades of 0.3% and -0.3%

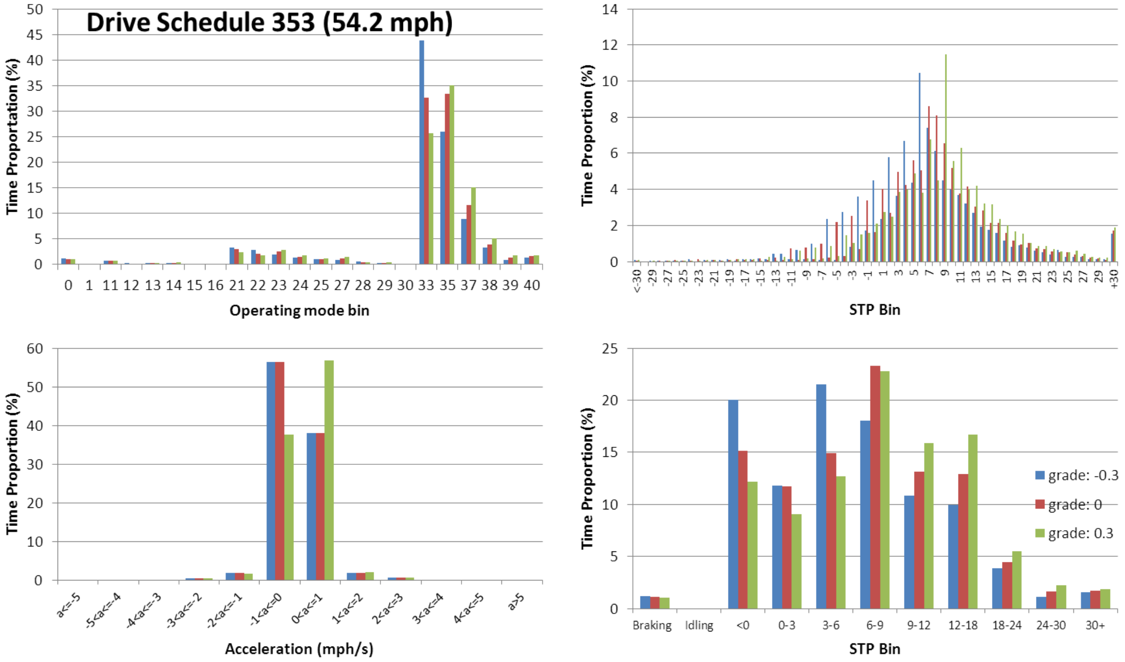


Figure A- 14. Comparisons of Characteristics of the Driving Schedule 353 with No Grade and Grades of 0.3% and -0.3%

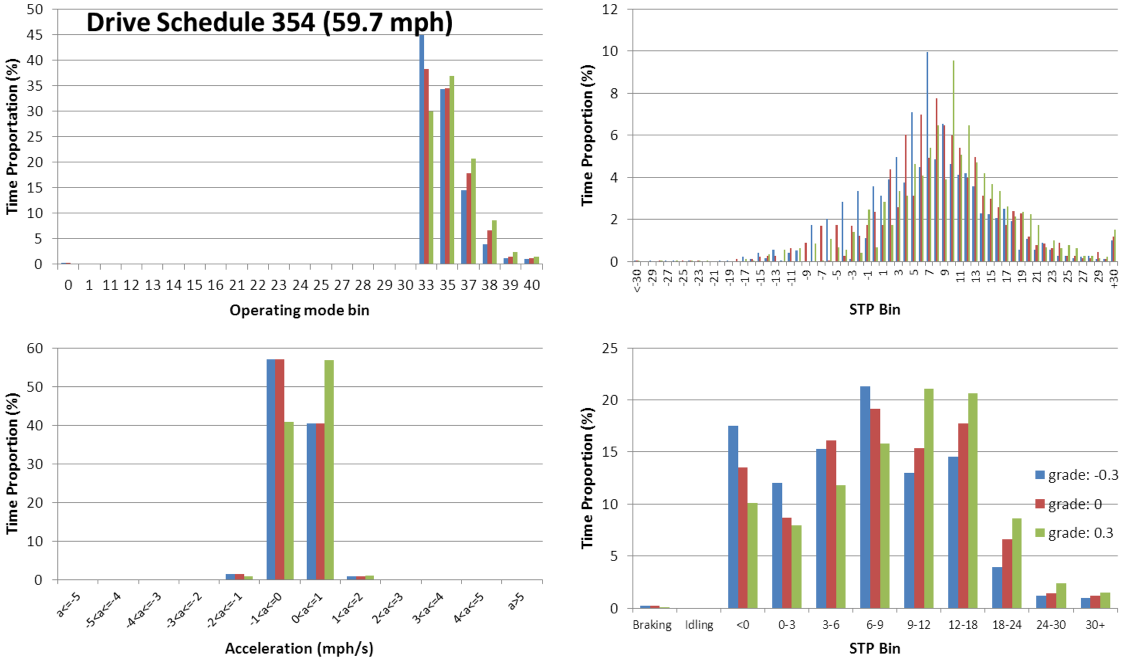


Figure A- 15. Comparisons of Characteristics of the Driving Schedule 354 with No Grade and Grades of 0.3% and -0.3%

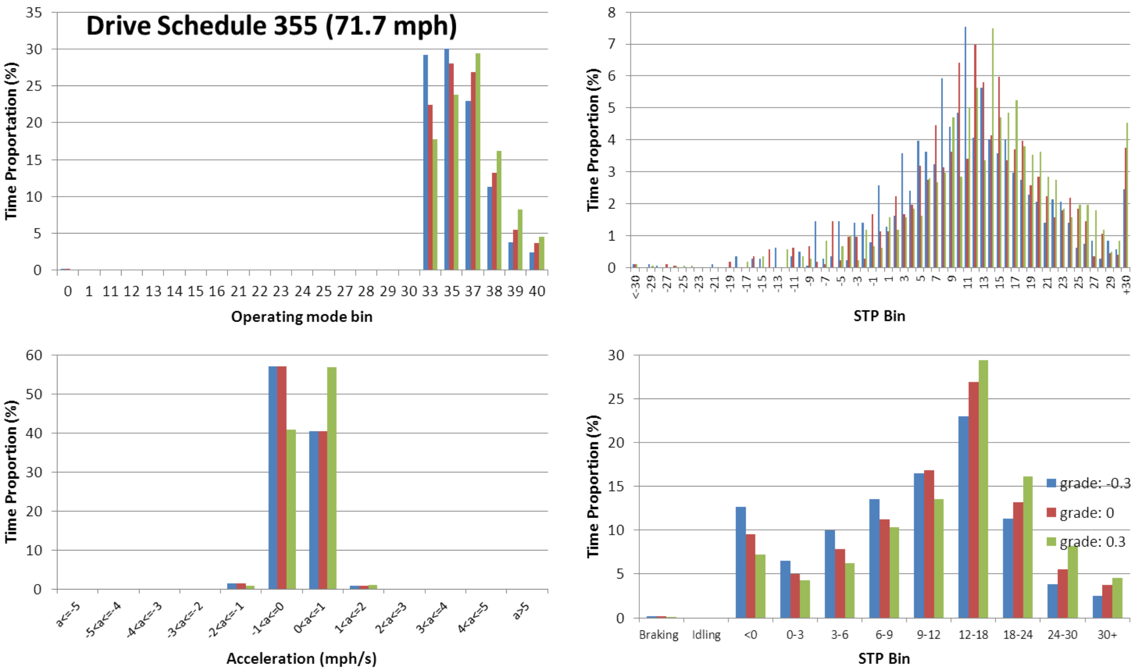


Figure A- 16. Comparisons of Characteristics of the Driving Schedule 355 with No Grade and Grades of 0.3% and -0.3%

Appendix B. Operating Mode and Mean Base Rate for Running Exhaust Emissions for HHD Vehicles in MOVES

Table B- 1. Operating Mode for Running Exhaust Emissions Based on Speed and STP in MOVES

STP (Scaled Tractive Power) (in scaled kW)		Speed (mph)		
		1-25	25-50	50 +
Braking	0			
Idling	1			
<0		11	21	33
0-3		12	22	
3-6		13	23	
6-9		14	24	35
9-12		15	25	
12-18		16	27	37
18-24			28	38
24-30			29	39
30 +			30	40

Table B- 2. NO_X Mean Base Rate in Grams Per Hour for Running Exhaust Emissions for Each Operating Mode for HHD Vehicle, 2005 Model Year, 0-3 Age in MOVES

STP (Scaled Tractive Power) (in scaled kW)		Speed (mph)		
		1-25	25-50	50 +
Braking	135.77			
Idling	53.84			
<0		53.71	34.77	183.14
0-3		207.43	229.04	
3-6		336.29	335.03	
6-9		458.90	474.39	533.46
9-12		520.39	592.83	
12-18		675.25	809.30	813.10
18-24			878.73	966.52
24-30			1129.79	1242.67
30 +			1380.86	1518.82

Table B- 3. $PM_{2.5}$ (EC+OC) Mean Base Rate in Grams Per Hour for Running Exhaust Emissions for Each Operating Mode for HHD Vehicle, 2005 Model Year, 0-3 Age in MOVES

STP (Scaled Tractive Power) (in scaled kW)		Speed (mph)		
		1-25	25-50	50 +
Braking	3.85			
Idling	4.21			
<0		4.38	5.90	10.79
0-3		9.24	16.77	
3-6		20.58	19.44	
6-9		24.33	30.73	20.77
9-12		37.05	47.21	
12-18		37.05	62.58	30.23
18-24			91.10	44.01
24-30			132.63	64.08
30 +			160.03	77.31

Table B- 4. Total Energy Consumption Mean Base Rate in kJ Per Hour for Running Exhaust Emissions for HHD Vehicle, 2005 Model Year, 0-3 Age in MOVES

STP (Scaled Tractive Power) (in scaled kW)		Speed (mph)		
		1-25	25-50	50 +
Braking	217,515			
Idling	107,131			
<0		143,758	115,944	478,338
0-3		418,318	537,678	
3-6		766,213	891,734	
6-9		1,118,100	1,290,650	1,462,710
9-12		1,413,980	1,659,570	
12-18		1,944,920	2,292,430	2,289,400
18-24			3,209,400	3,205,160
24-30			4,126,370	4,120,910
30 +			5,043,340	5,036,670

Table B- 5. CO Mean Base Rate in Grams Per Hour for Running Exhaust Emissions for HHD Vehicle, 2005 Model Year, 0-3 Age in MOVES

STP (Scaled Tractive Power) (in scaled kW)		Speed (mph)		
		1-25	25-50	50 +
Braking	11.20			
Idling	17.63			
<0		31.54	29.48	71.57
0-3		37.25	67.44	
3-6		53.63	81.07	
6-9		64.01	88.12	85.84
9-12		70.54	94.68	
12-18		83.89	81.98	81.08
18-24			78.33	65.29
24-30			100.71	83.94
30 +			123.09	102.60

Table B- 6. THC Mean Base Rate in Grams Per Hour for Running Exhaust Emissions for HHD Vehicle, 2005 Model Year, 0-3 Age in MOVES

STP (Scaled Tractive Power) (in scaled kW)		Speed (mph)		
		1-25	25-50	50 +
Braking	7.09			
Idling	5.54			
<0		13.94	12.70	16.71
0-3		14.38	16.62	
3-6		16.93	15.96	
6-9		18.64	15.71	14.73
9-12		15.85	15.07	
12-18		16.53	14.52	14.60
18-24			14.24	14.88
24-30			18.31	19.13
30 +			22.38	23.38

Appendix C. Driving Cycles for 22 Trips for the Study

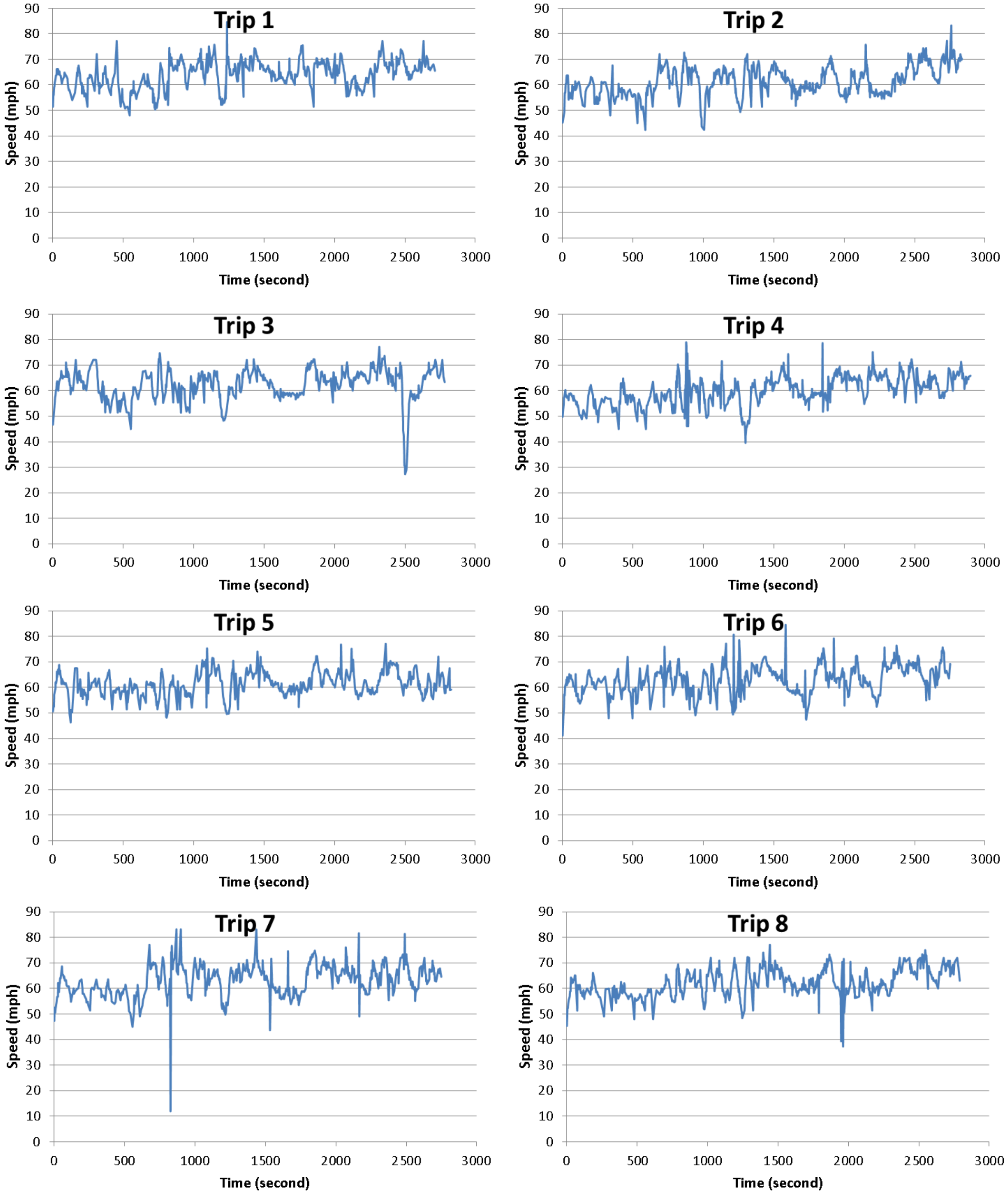


Figure C- 1. Driving Cycles for Trips 1 to 8

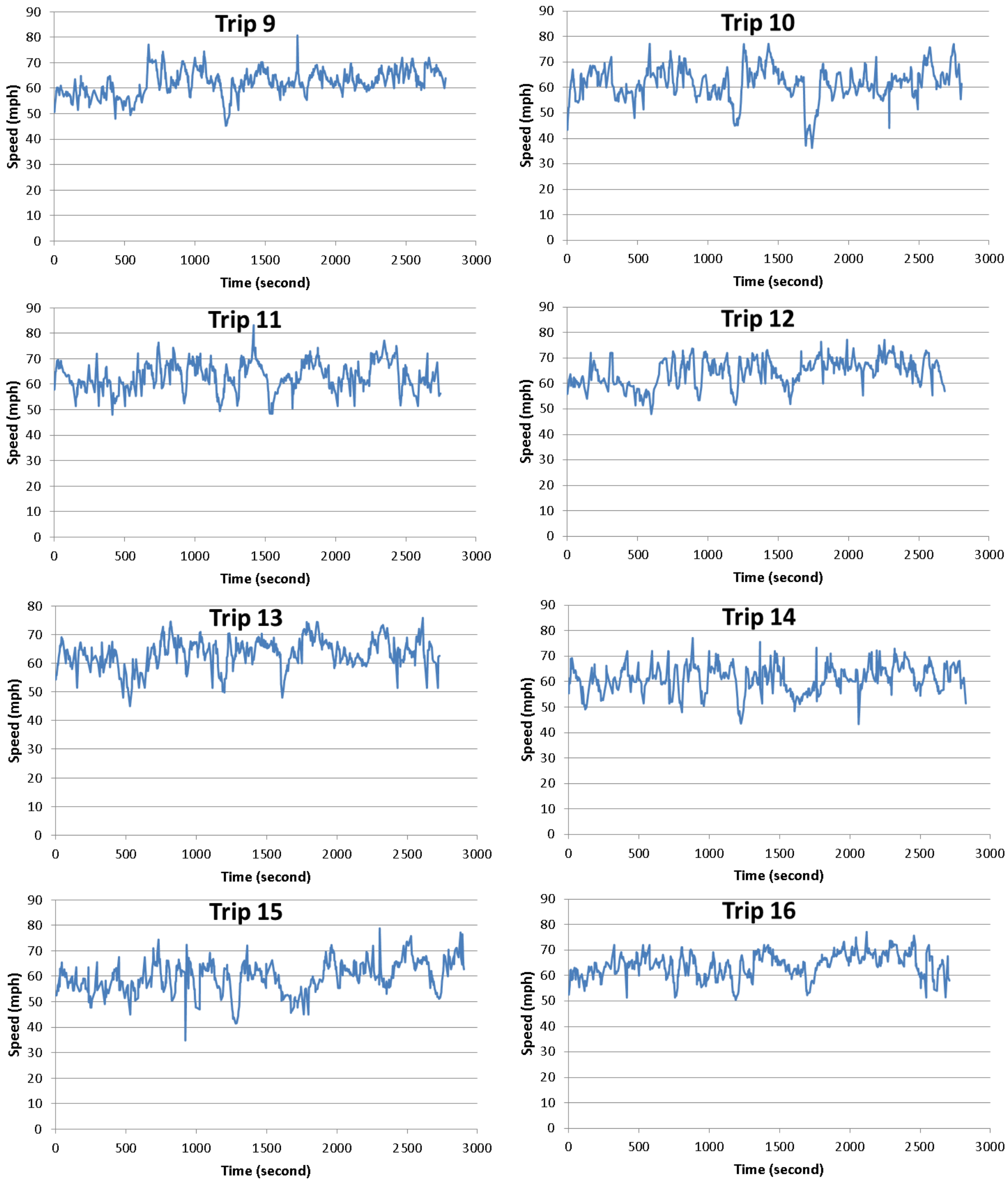


Figure C- 2. Driving Cycles for Trips 9 to 16

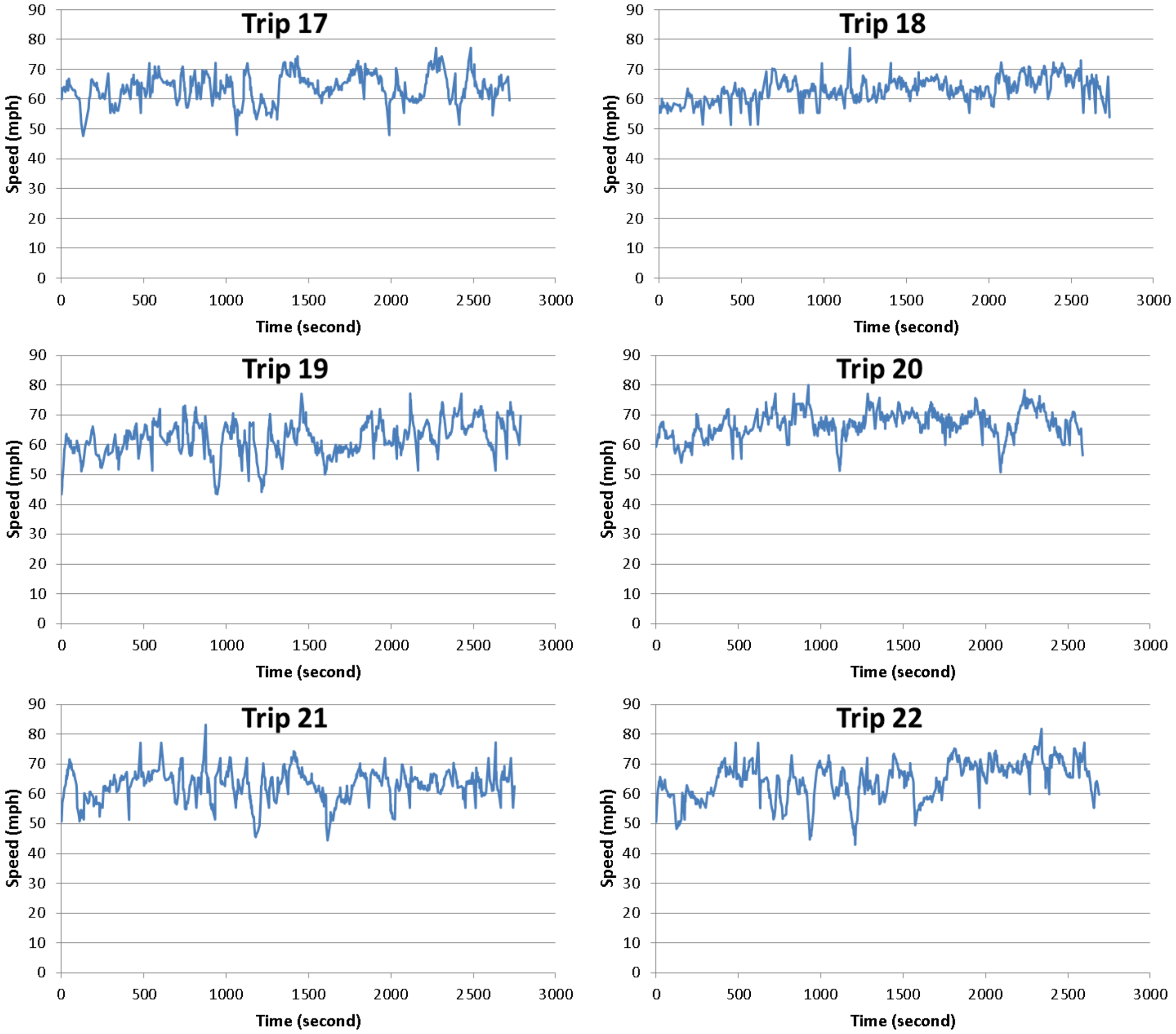


Figure C- 3. Driving Cycles for Trips 17 to 22

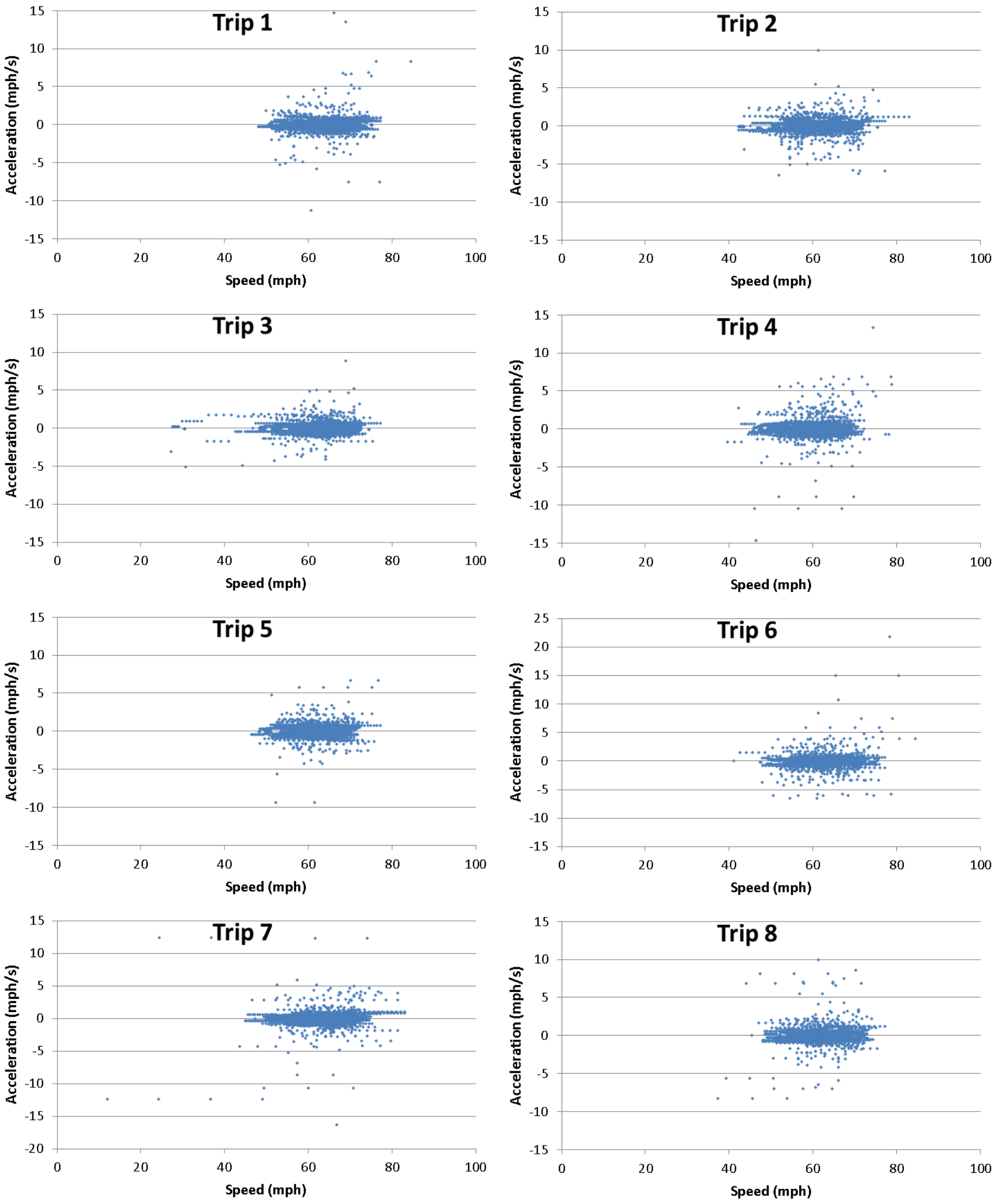

Trip 1
Trip 2
Trip 3
Trip 4
Trip 5
Trip 6
Trip 7
Trip 8

Figure C- 4. Acceleration-Speed Profiles for Trips 1 to 8

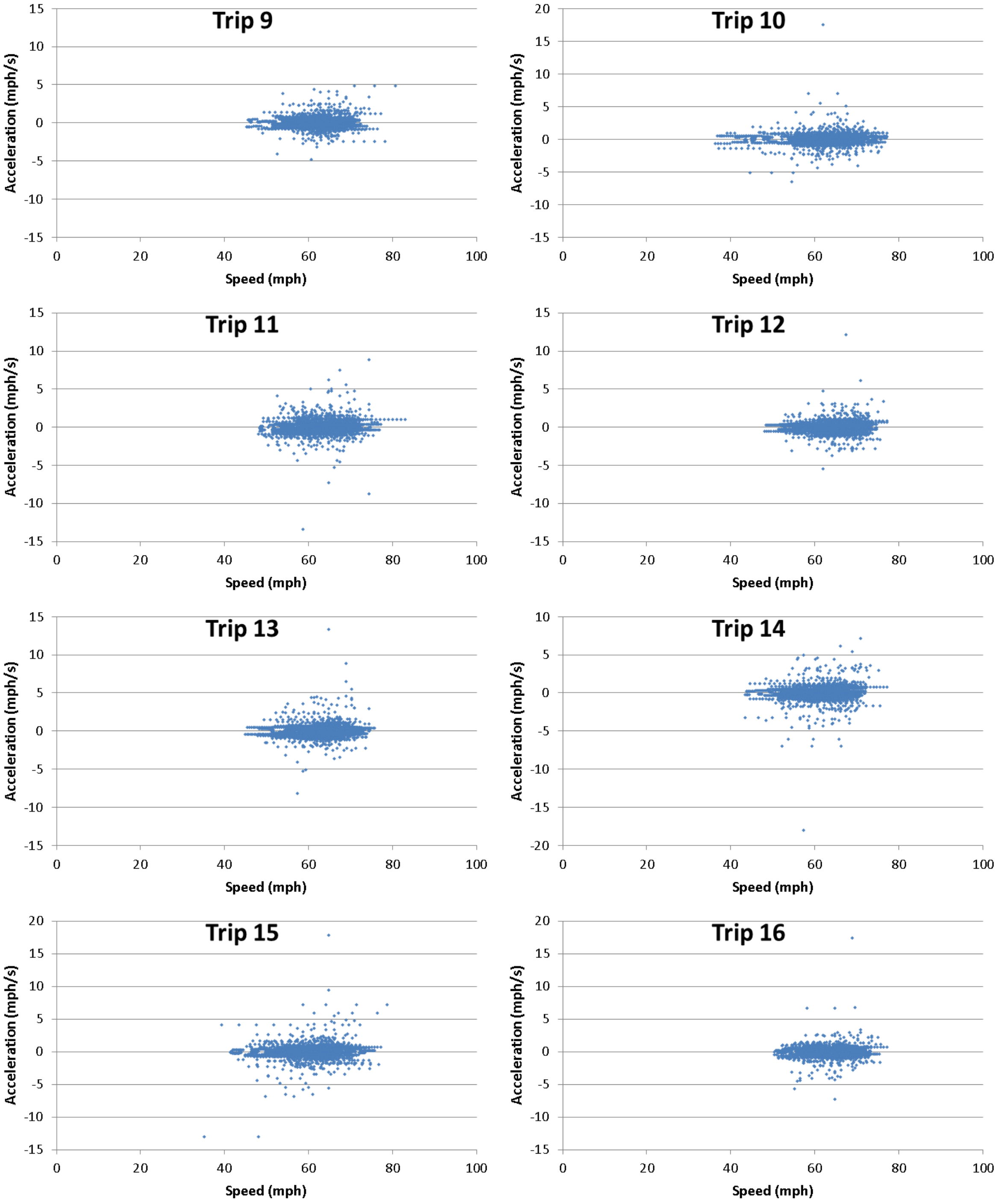


Figure C- 5. Acceleration-Speed Profiles for Trips 9 to 16

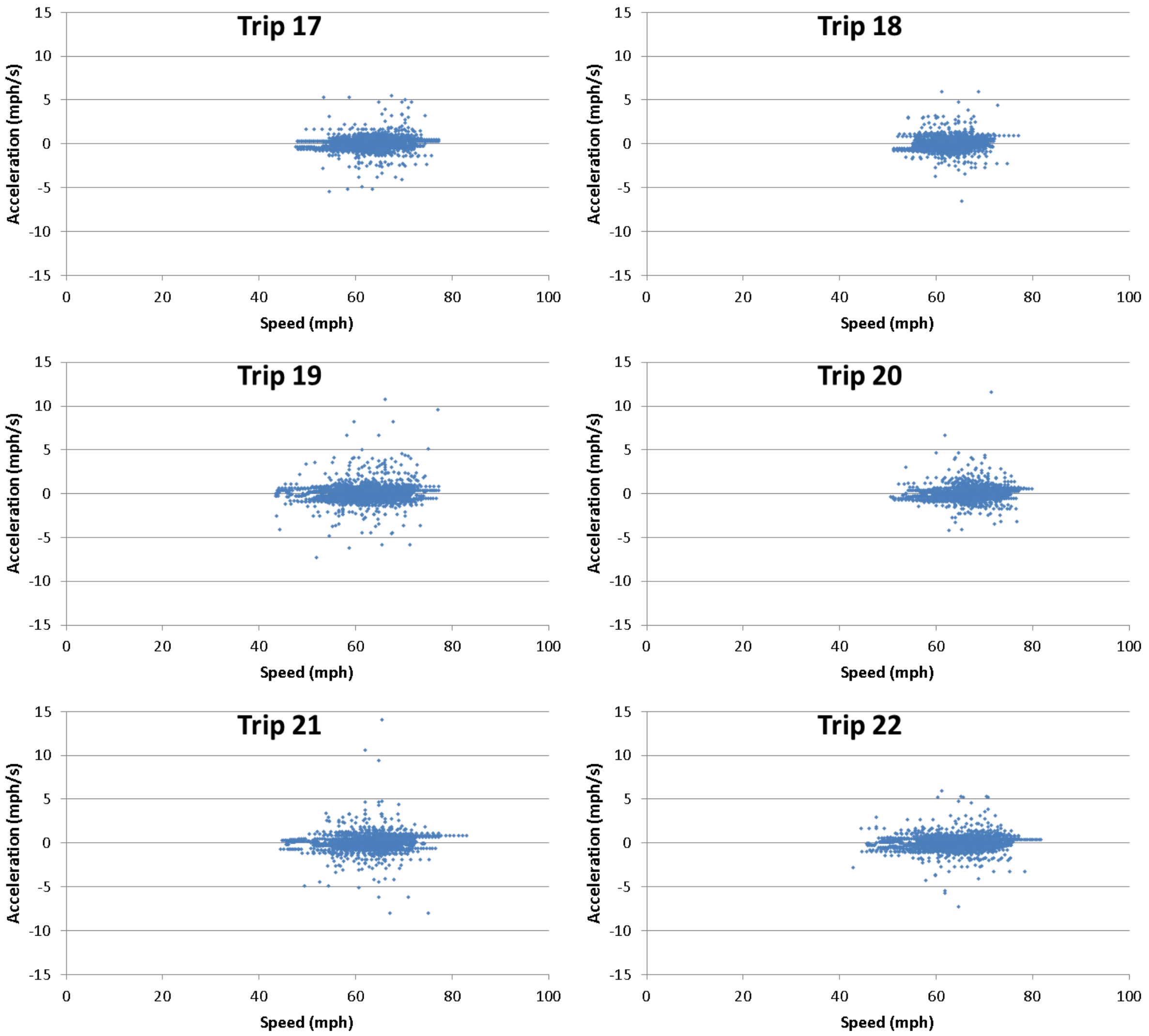


Figure C- 6. Acceleration-Speed Profiles for Trips 17 to 22

Appendix D. Comparisons of Characteristics of Driving Cycles for Trips 2 through 5

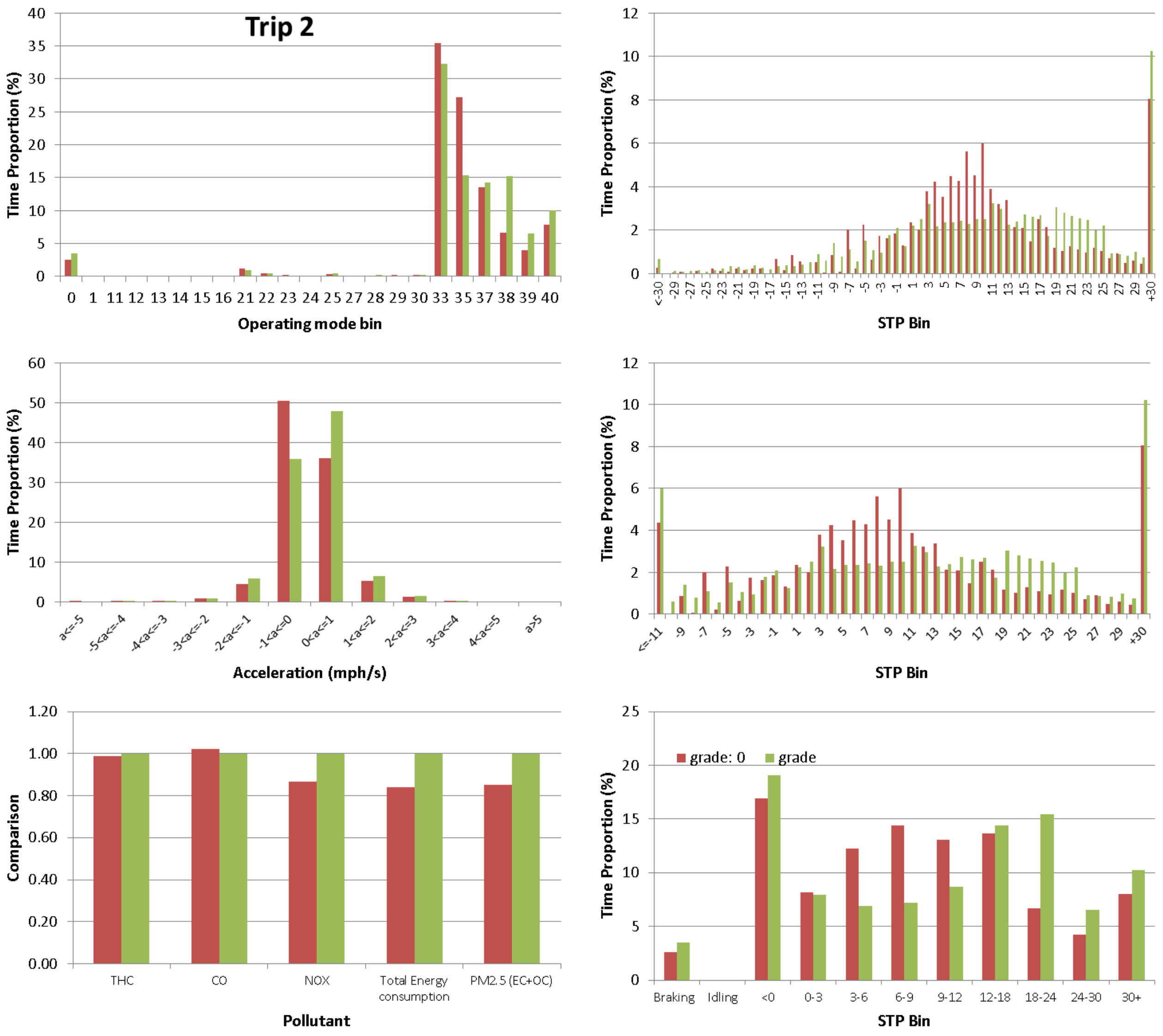


Figure D- 1. Characteristics Comparisons Among Three Cases for Trip 2

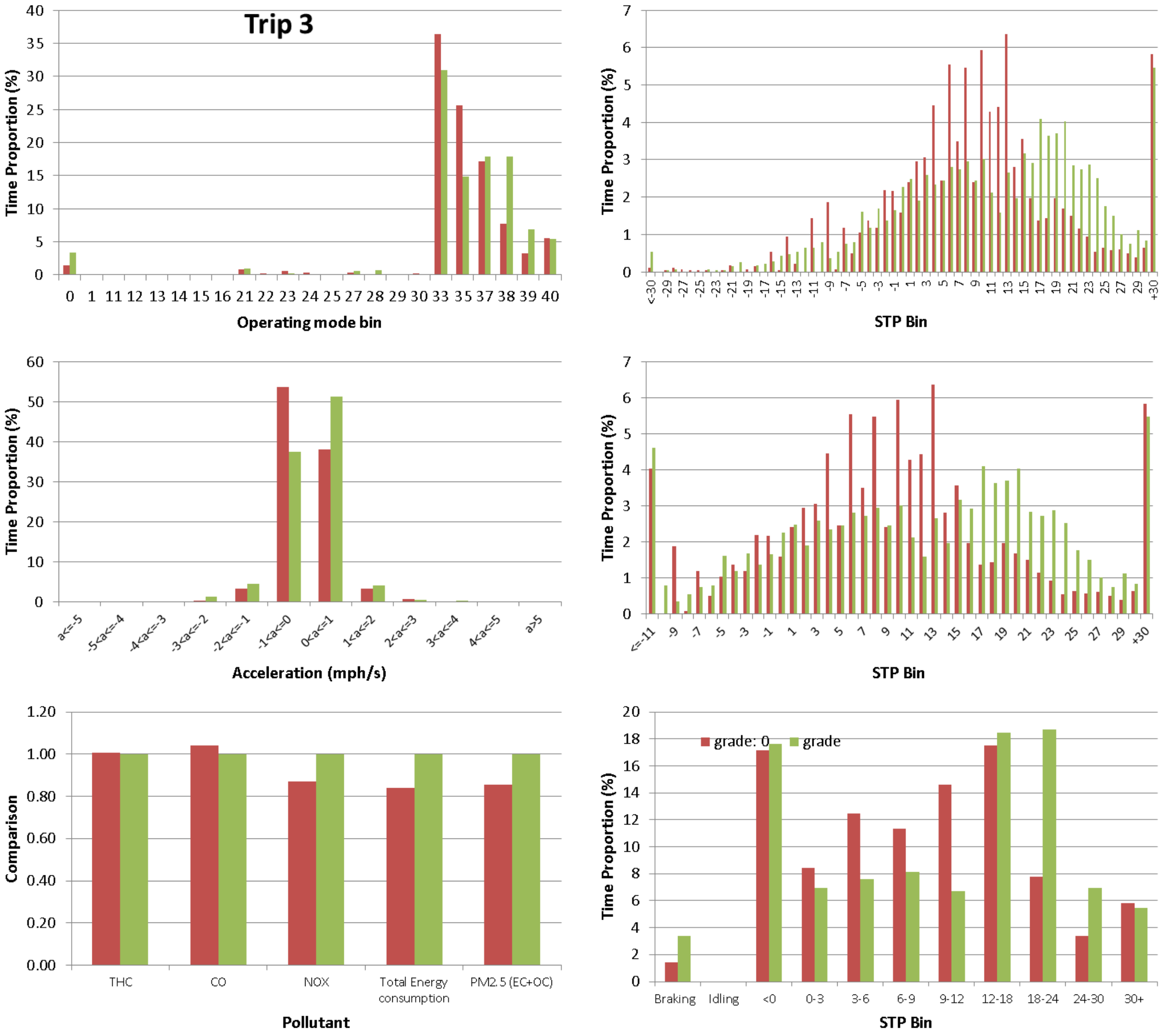


Figure D- 2. Characteristics Comparisons Among Three Cases for Trip 3

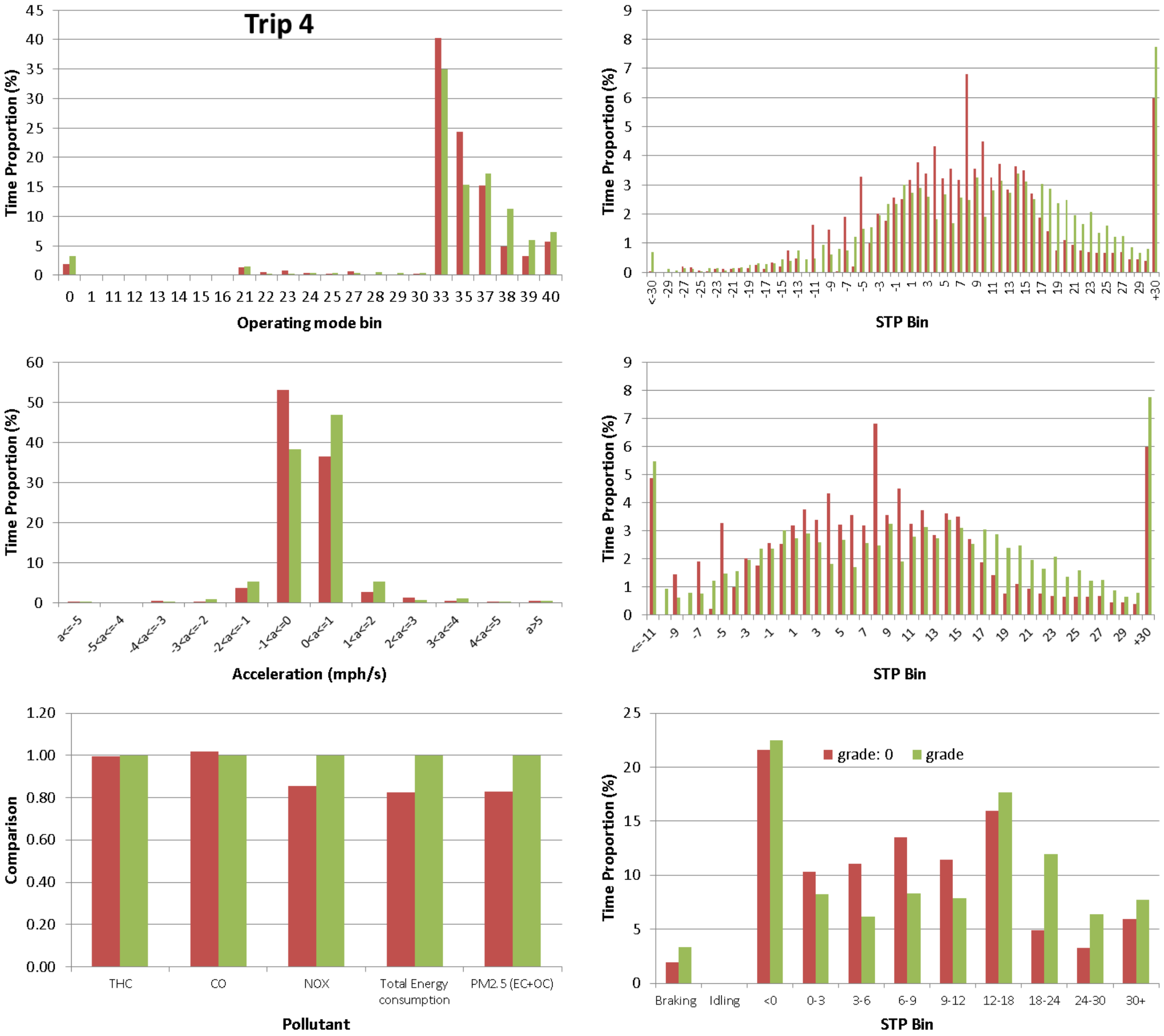


Figure D- 3. Characteristics Comparisons Among Three Cases for Trip 4

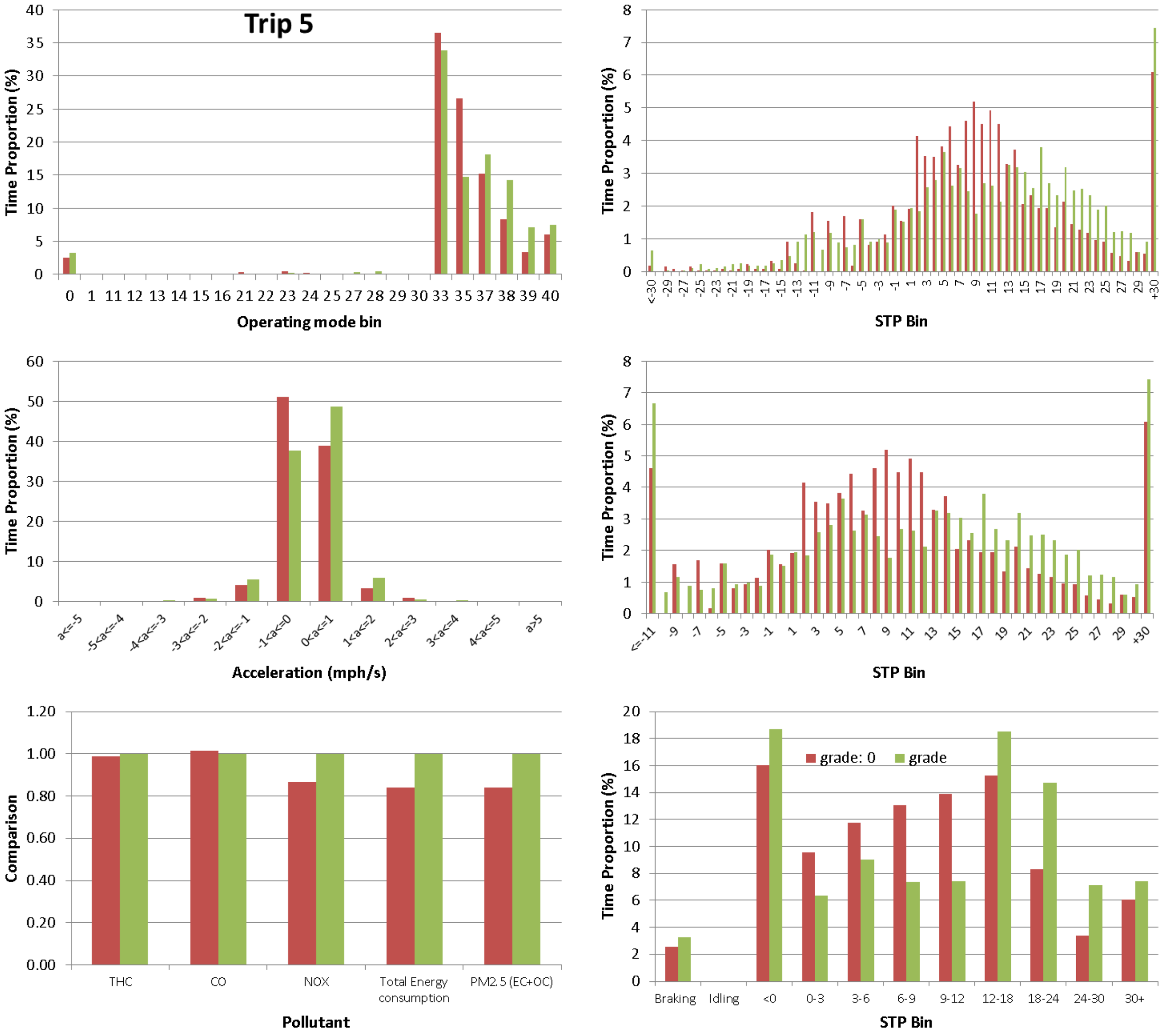


Figure D- 4. Characteristics Comparisons Among Three Cases for Trip 5

VITA

Jeongran Yun received her Bachelor of Science degree in Environmental Engineering from Ajou University in South Korea in 2001. While attending Ajou University, she studied at the University of Tennessee at Knoxville as an exchange student during the academic year 2000-2001. After graduating from Ajou University, she moved back to Knoxville. She obtained her Master of Science degree in Environmental Engineering with a minor in Statistics from the University of Tennessee at Knoxville in 2004. She enrolled at the University of Tennessee at Knoxville in the Ph.D. program in Civil Engineering with a concentration in Environmental Engineering. During the years at the University of Tennessee, she has worked on a number of mobile emissions modeling related projects. She has worked on estimating and developing on-road mobile source emission inventory for years 2002 and 2005 for the State of Tennessee using the MOBILE6 model. She was involved in several projects for the Tennessee Department of Transportation using the new EPA's mobile emissions model, MOVES2010a. She was also involved in other projects on heavy duty truck emissions modeling using MOVES2010a. She became a member of the Honor Society of Phi Kappa Phi and the National Leadership Honor Society of Omicron Delta Kappa in 2004. She was listed on the 2004-2005 Chancellor's List. In 2012, she received her Ph.D. in Civil Engineering with a concentration in Environmental Engineering.