Refining GreenSTEP: Impacts of Vehicle Technologies and ITS/Operational Improvements on Travel Speed and Fuel Consumption Curves

Final Report on Task 1: Advanced Vehicle Fuel-Speed Curves

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Prepared by

Alex Bigazzi and

Kelly Clifton, Ph.D.

Department of Civil & Environmental Engineering

Portland State University

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For more information on the contents of this report, contact:

Alex Bigazzi, abigazzi@pdx.edu

or

Kelly Clifton, kclifton@pdx.edu

Department of Civil & Environmental Engineering

Portland State University

P.O. Box 751, Portland, OR 97207-0751

503-725-4282

For more information about the Greenhouse Gas Statewide Transportation Emissions Planning Model (GreenSTEP), contact:

Brian Gregor, PE, Senior Transportation Analyst

Transportation Planning Analysis Unit

Oregon Department of Transportation

555 13th Street NE, Suite 2

Salem, OR 97301-4178

Brian.J.GREGOR@odot.state.or.us

EXECUTIVE SUMMARY

This report describes research undertaken to establish plausible fuel-speed curves for advanced vehicles. We use the PERE fuel consumption model with real-world driving schedules and a range of vehicle characteristics to estimate fuel economy (FE) in varying traffic conditions. The fuel-speed data points are used to fit FE versus average speed curves for 177 modeled vehicles of six types (light-duty internal combustion engine (ICE) vehicles, light-duty hybrid gas-electric vehicles (HEV), light-duty electric vehicles (EV), light-duty fuel cell vehicles (FCV), heavy-duty ICE vehicles, and heavy-duty HEV).

Analysis of the Fuel-Speed Curves (FSC) shows that advanced powertrain vehicles are expected to perform proportionally better in congestion than ICE vehicles. HEV are less sensitive to congestion than ICE vehicles, and tend to maintain their FE in congestion levels with speeds above 20 mph. FE *increases* for EV at slower speeds down to about 20-30 mph. The modeled effects of congestion on FCV are similar to the effects on HEV. Beyond powertrain type differences, relative FE in congestion is expected to improve for vehicles with less weight, smaller engines (for ICE), higher hybrid thresholds (for HEV), and lower accessory loads (such as air conditioning). *Relative* performance in congestion can also improve with attributes that disproportionately decrease FE at higher speeds, such as higher aerodynamic drag and rolling resistance factors.

The primary motivation for developing these FSC is to enable modeling of advanced powertrain vehicles in the GreenSTEP model. To this end we present a method for incorporating advanced vehicle FSC into the FE adjustment for congestion in GreenSTEP. The proposed method is a bounded approach, where the applied FE adjustment is an interpolation between extreme-case FSC. This allows FE adjustments for congestion to be sensitive to general vehicle trends over time without requiring specificity in the vehicle fleet characteristics.

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1 Project Introduction

We begin this report with an introduction to the project, comprising two tasks, our motivations for this research, a brief description of the GreenSTEP model and then proceed to documenting the work done. This research project comprises two tasks. Task 1 includes research into the likely impacts that advanced vehicle technologies will have on fuel consumption-average speed curves and methods for incorporating these findings into GreenSTEP. Similarly, Task 2 focuses on the effects that Intelligent Transportation Systems and other operational improvements will have on these fuel consumption-speed curves, with suggestions for how these findings can be included within GreenSTEP. The findings from Task 1 are the subject of this report.

1.1 Problem Statement

The Oregon Department of Transportation (ODOT) Transportation Planning and Analysis Unit (TPAU) has developed a model to forecast transportation-related greenhouse gas emissions (GHG) called the Greenhouse gas Statewide Transportation Emissions Planning model or GreenSTEP (Gregor 2010). GreenSTEP is a modeling tool, written in the "R" language, which can be used to assess the impact of a range of policies and other factors on transportation-born greenhouse gas emissions. It is designed to make use of the extensive disaggregate travel demand models available in Oregon and will be an important tool for meeting Oregon's legislative mandates to develop strategies to achieve GHG reduction targets. For the model to provide greater utility in policy evaluation, several refinements are needed, including improvements to the ability to account for future technological changes in vehicle performance, fuel type, and fleet composition and incorporation of the impacts of ITS and operational improvements.

1.2 Background

GreenSTEP is an evolving tool for evaluating transportation-sector related GHG emissions. The model is currently structured to be used for statewide policy analysis but will be modified in the future to be used for strategic planning analysis at the metropolitan area level as well. The model is sensitive to a large number of factors including land use, transportation, vehicle, price, fuels and other policy and exogenous inputs. Model components may be employed in conjunction with integrated statewide and urban transportation demand models to evaluate GHG emissions that result from various investments or growth policies.

The model makes use of current knowledge with respect to engine performance and fuel economy; however, as technological advances and fleet mix are likely to change dramatically over any forecast horizon of 30 to 50 years, incorporation of more refined estimates of vehicle fuel economy will enable more robust forecasts of GHG. Similarly, GreenSTEP performance would be enhanced by consideration of the potential emissions reductions that result from Intelligent Transportation Systems (ITS) and other operational improvements.

GreenSTEP will be used by transportation analysts within TPAU and ODOT regional planners to help the Department meet the requirements of Section 2 of Senate Bill 1059 (SB1059), passed by the Oregon Legislature and signed into law in 2010. It will provide an analytical tool for the development of statewide transportation strategy on greenhouse gas emissions to aid in achieving the greenhouse gas emissions reduction goals.

1.3 Objectives of the Project

This project is intended to enhance the capacity of GreenSTEP to address the climate change implications of various policy questions. The study objective has two major task components: 1) to provide guidance on the incorporation of advanced-vehicle fuel-economy versus average-speed relationships into GreenSTEP and 2) to provide guidance on the incorporation of ITS and traffic operational improvements into GreenSTEP. This report addresses the first task: advanced vehicle fuel-speed curves. Documentation on the second task is presented in a separate companion report. In the next section we provide a brief introduction and context more specifically for the Task 1 research.

2 Task 1 Introduction

Traffic congestion influences motor vehicle fuel consumption rates. Increasing levels of congestion lead to longer travel times, lower average speeds, and increased vehicle speed variability. These affect engine/motor operating loads and operating duration, which in turn influence fuel consumption per mile of travel. Vehicle fuel efficiency is most often expressed as Fuel Economy (FE), in travel distance per unit volume of fuel – typically miles per gallon (mpg).

Fuel-Speed Curves (FSC) summarize the relationship between vehicle fuel economy and congestion level (indicated by average travel speed) for average, aggregate conditions. Thus FSC can serve to estimate fuel consumption in macroscopic traffic and transportation models. In the GreenSTEP model, normalized FSC are used to adjust average fuel efficiencies for varying levels of metropolitan congestion.

While FSC for conventional, Internal Combustion Engine (ICE) vehicles have been previously studied (and adopted in GreenSTEP), FSC for advanced powertrain vehicles have received less attention. In order to enable incorporation of the impacts of congestion on advanced vehicles in GreenSTEP, this research develops FSC for Hybrid Electric Vehicles (HEV), Fuel Cell Vehicles (FCV), and fully Electric Vehicles (EV). Fuel economy at varying average travel speeds is estimated using an advanced-vehicle fuel consumption model with archetypal speed profiles. We also use the same modeling to refine the existing FSC for conventional ICE passenger vehicles and trucks.

The remainder of this report is as follows: first a discussion of the relevant literature and background information on advanced vehicle fuel-speed relationships is presented. Next is a description of the modeling methodology used in this study. Fuel modeling results are presented, including sensitivity to various vehicle parameters. Finally, the recommended fuel-speed curves for incorporation into GreenSTEP are described, along with a method for implementation.

3 Background and Literature

3.1 Vehicle Fuel Economy

Vehicle fuel economy (FE) has long been of interest to auto travelers, vehicle manufacturers, policy-makers, and others. FE for a specific vehicle and driver in controlled roadway conditions can be directly measured. But aggregate FE for an uncertain mix of fleet of vehicles in varying operating conditions is challenging to predict. FE projections are useful for consumer information, transportation system planning, and policy analysis (such as is undertaken with GreenSTEP).

In order to standardize vehicle FE estimates and predictions, the U. S. Environmental Protection Agency (EPA) has released a detailed set of guidelines (U.S. Environmental Protection Agency 2006). The general approach to FE testing and labeling is to run a test vehicle in a laboratory on a chassis dynamometer over a set of test driving schedules (test driving schedules are available online[1]). The fuel consumption test results are used to calculate expected real-world fuel economy.

Before 2008, vehicles were tested on two dynamometer driving schedules:

- "City" test: the Federal Test Procedure (FTP)
- "Highway" test: the Highway Fuel Economy Test (HFET)

Research and driver surveys have shown that real-world vehicle operation produces poorer FE than indicated by the FE results of these tests, so the EPA fuel economy method adjusted these test results down by 10% for the city test (FTP) and 22% for the highway test (HFET).

Now, beginning with model year 2008 vehicles, fuel economy is established using a set of five dynamometer driving schedules:

- FTP, as above
- HFET, as above
- US06, for high-speed highway driving and aggressive urban driving
- SC03, for the effects of running an air conditioner at high ambient temperatures
- Cold FTP, which is the FTP conducted at 20°F

These tests are performed at specific ambient temperatures and vehicle conditions (e.g. hot/cold starts), as shown in Table 3-1. The driving schedules in Table 3-1 are also the dynamometer

[1] http://www.epa.gov/nvfel/testing/dynamometer.htm

driving schedule tests used for pollution emissions testing. By the new EPA method, the FE test results from these driving schedules are combined in a vehicle-specific way to estimate the overall FE. This revised test procedure is intended to better capture the effects of faster, more aggressive real-world driving, air conditioning usage, and cold temperatures (U.S. Environmental Protection Agency 2006).

Table 3-1. 5-Cycle Fuel Economy Dynomometer Driving Schedule Tests (source: U.S. EPA (2006))

Test	Driving	Ambient Temperature	Engine Condition at Start	Accessories
FTP	Low speed	75°F	Cold and hot	None
HFET	Mid-speed	75°F	Hot	None
US06	Aggressive; low and high speed	75°F	Hot	None
SC03	Low speed	95°F	Hot	A/C on
Cold FTP	Low speed	20°F	Cold and hot	None

The new EPA fuel economy method also developed regression equations for calculating revised fuel economy based on the previous 2-cycle test results. Thus, fuel economy can be calculated simply from the FTP and HFET results as :

$$FE_{city} = \frac{1}{0.003259 + \frac{1.18053}{FE_{FTP}}} \tag{1}$$

and

$$FE_{highway} = \frac{1}{0.001376 + \frac{1.3466}{FE_{HFET}}} \tag{2}$$

where FE_{city} and $FE_{highway}$ are the city and highway adjusted fuel economy estimates, respectively, and FE_{FTP} and FE_{HFET} are the FTP and HFET fuel economy test results, respectively (U.S. Environmental Protection Agency 2006). Overall fuel economy is calculated using a weighted average of 55% city driving and 45% highway driving.

These FE tests and guidelines are designed to be representative for the aggregate U.S. fleet. But actual fuel economy for individual vehicles and drivers varies greatly. FE varies with driving style, ambient temperature, vehicle maintenance condition, terrain, roadway condition, and traffic congestion level, among other factors.

3.2 Congestion and Fuel Economy

Traffic congestion affects vehicle FE through lower average travel speed and increased vehicle speed variability (accelerations and decelerations). These influence engine/motor operating loads and operating duration, which in turn impact fuel consumption per mile of travel (Nam & Giannelli 2005). Estimating the effects of congestion on vehicle operating efficiency includes many factors (aerodynamic drag, combustion efficiency, acceleration frequency and intensity, etc.). Aggregate congestion effects can be more simply represented by Fuel-Speed Curves (FSC). FSC summarize the relationship between FE and average speed (which is indicative of congestion level for a specific facility). FSC show the expected average FE at a given average travel speed on a given road facility, including typical acceleration and deceleration activity. Facility-specific average travel speeds, in turn, represent the level of traffic congestion.

FSC are the fuel equivalent of Emissions-Speed Curves (ESC), which are used to estimate the aggregate impact of congestion on vehicle pollution emissions rates (Barth & Boriboonsomsin 2008; Barth et al. 1999; Bigazzi & Figliozzi 2011). The ESC approach has been shown to adequately represent congestion effects if the curves are based on representative, real-world driving patterns (Smit et al. 2008). The challenge is to select realistic driving patterns for ESC or FSC creation (Lin & Niemeier 2002). For the purpose of emissions modeling, the EPA has created a set of realistic driving schedules (driving patterns) for inclusion in the MOVES 2010 mobile-source emissions model (U.S. Environmental Protection Agency 2009; U.S. Environmental Protection Agency 2006).

Existing research on FSC for ICE vehicles indicates that increasing levels of congestion – with lower average speeds – generally lead to increased fuel consumption rates (Barth et al. 1999). At very high speeds, however, fuel consumption rates increase as well, and there is an optimal average speed for fuel economy which depends on the vehicle fleet – often around 50 mph (Davis et al. 2010). The optimal speed represents balanced impacts of aerodynamic drag and low-speed inefficiency.

3.3 Fuel Economy of Advanced Vehicles

Given concerns about energy consumption and climate impacts of the U.S. vehicle fleet, there has been considerable attention paid to the potential fuel economy of advanced vehicles

(Markel et al. 2002; Nam & Giannelli 2005; Plotkin & M. K. Singh 2009; M. Singh et al. 2003). Advanced powertrain vehicles include Electric Vehicles (EV), Hybrid Electric Vehicles (HEV), and Fuel Cell Vehicles (FCV). Fuel economy estimates for advanced vehicles are challenging because fewer, if any, dynamometer test data are available. Thus, vehicle fuel consumption modeling is often undertaken to estimate or predict the performance of these vehicles. Various studies have demonstrated or predicted substantial fuel consumption or greenhouse gas emissions savings from the substitution of advanced powertrain vehicles for conventional Internal Combustion Engine (ICE) vehicles in the fleet (Earleywine et al. 2010; Plotkin & M. K. Singh 2009; C. Samaras & Meisterling 2008; Silva et al. 2009).

Most fuel consumption modeling for advanced vehicles has focused on average, aggregate fuel economy (such as the fuel economy estimates provided by the EPA). But speed-based or congestion-based FE estimates are needed to predict the effects of varying congestion levels on the performance of these vehicles. Delorme, Karbowski, & Sharer (2010) modeled the speed-dependent fuel consumption rates of select medium and heavy-duty vehicles, including several hybrid versions. They point out the importance of using realistic driving patterns and the challenge of a lack of a standard set of vehicle technical specifications for advanced vehicle modeling. Fontaras, Pistikopoulos, and Samaras (2008) modeled two hybrid passenger cars and found lower optimal speeds with respect to fuel consumption for the hybrid cars than for conventional cars (and lower overall fuel consumption rates). While modeling such as this suggests different FSC for advanced vehicles than for ICE vehicles, these studies do not provide the array of FSC needed for scenario testing of a variety of potential advanced vehicles in congestion.

Beyond the unique mechanical performance of advanced vehicles, some studies have suggested that advanced vehicles are driven differently. For example, real-time feedback on energy consumption can lead to more efficient driving styles (Barkenbus 2010). An empirical study by the EPA in Kansas City showed less aggressive driving for HEV than for ICE vehicles (U.S. Environmental Protection Agency 2006). The report acknowledges, however, that there are several other possible explanations besides driver behavior change in response to HEV/ICE vehicle differences. Other possibilities include less power available in the test hybrid vehicles and self-selection of fuel-conscious drivers for hybrid ownership. Alessandrini & Orecchini

(2003) studied EV operating in Rome and also found less aggressive driving – presumably owing to the limited power of the vehicles.

3.4 Fuel Consumption Models

Fuel consumption modeling allows fuel economy estimates for a wide range of hypothetical vehicles operating in varying conditions. Vehicle fuel consumption models exist for varying scales of analysis. Some very high-level models only attempt rough characterization of the vehicle fleet, with no specificity in the vehicle operating conditions or roadway characteristics. These models are intended for broad scenario analyses and inventory calculations. Very detailed vehicle fuel models also exist which attempt to represent each stage of an individual vehicles' power production and transmission process. These models are intended for vehicle design and development or microscopic analyses and require a great deal of input data or assumptions.

A summary of relevant vehicle fuel consumption models is presented in Table 3-2. For each model a qualitative assessment of the relevant scope of analysis is presented, along with whether the model has the ability to estimate fuel consumption at varying operating speeds and whether the model can represent advanced powertrain vehicles. Each model is discussed in detail in Appendix A, with an assessment of its suitability for application in this study.

Table 3-2. Summary of Relevant Vehicle Fuel Consumption Models

Model	Scope	Speed-Based?	Advanced Powertrains?
PSAT/Autonomie	Individual Vehicles	Yes	Yes
ADVISOR	Individual Vehicles	Yes	Yes
PERE	Individual Vehicles	Yes	Yes
CMEM	Individual Vehicles	Yes	No
MOVES	Fleets of Vehicles	Yes	No
VISION	Fleets of Vehicles	No	Yes, though not in detail
GREET	Vehicle/Fuel Lifecycles	No	Yes, though not in detail

The Powertrain Systems Analysis Toolkit (PSAT), Autonomie, and the ADvanced Vehicle SImulatOR (ADVISOR) are models developed primarily for HEV analysis, and contain much detail about the individual vehicles' operating and control system characteristics. The Physical Emissions Rate Estimator (PERE) and the Comprehensive Modal Emissions Model (CMEM) are also at the individual vehicle scale, but incorporate less detail about the vehicle control systems. PERE has algorithms to model HEV in parallel configuration, FCV, and an un-validated approach to modeling EV (simply as HEV with no ICE). CMEM does not have an HEV configuration.

The MOtor Vehicle Emissions Simulator (MOVES) models vehicle classes instead of individual vehicles, and has no integrated module for advanced powertrain vehicles (though it can interface with PERE model outputs for advanced vehicles). The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) and VISION models are much broader tools which do not allow vehicle fuel consumption to be modeled as a function of operating speed.

3.5 Modeling Congestion in GreenSTEP

In order to understand the motivation for the study methodology, it is important to be familiar with the structure of GreenSTEP and the role of FSC within the model. Average fleet fuel economy by vehicle type (passenger car, passenger truck, heavy truck, bus) and year are inputs to each model run. GreenSTEP accounts for congestion effects by adjusting the fleet-average fuel economy, as illustrated in Figure 1. For each metropolitan area, the Daily Vehicle Miles Traveled (DVMT) and lane-mile capacity of the roadway network are used to estimate the distribution of DVMT by facility type and congestion level. Each congestion level has an associated average speed (depending on the facility type and the level of incident management). This leads to a distribution of DVMT by average speed. Finally, normalized FSC are used to scale the average fleet fuel economy based on the estimated average speed distribution of metropolitan DVMT. These adjustments are *not* made for vehicle travel using stored electricity (for fully electric vehicles or plug-in hybrid electric vehicles).

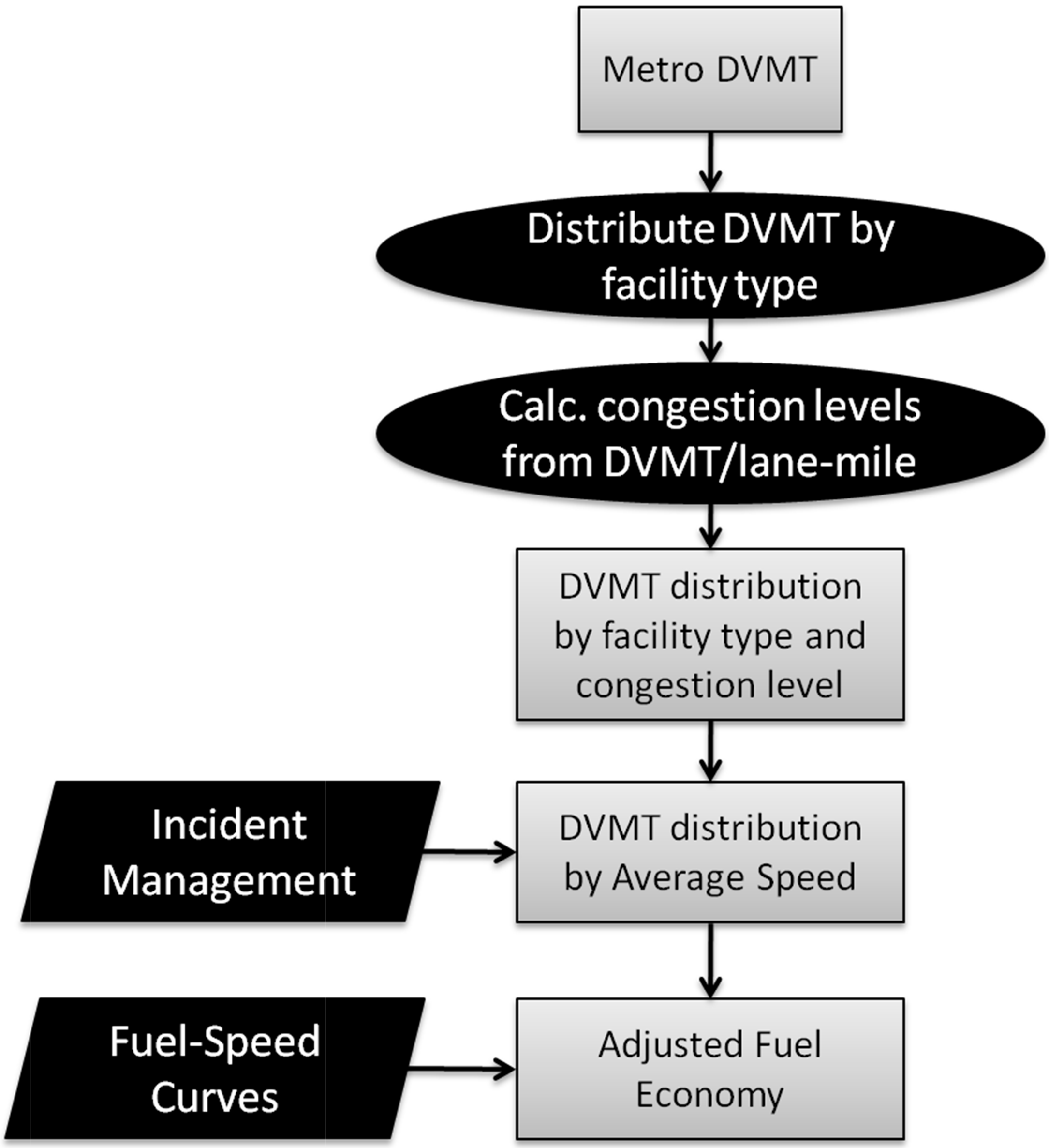

Figure 1. GreenSTEP Process for Adjusting Average Fuel Economy for Congestion

Three types of metropolitan roadways are included: freeways, principal arterials, and other local roads. The freeway and arterial roads have 5 levels of congestion: None, Moderate, Heavy, Severe, and Extreme. No congestion adjustment is made for other local roads. Average speeds for each facility-congestion level combination are shown in Table 3-3, with and without incidents. Different levels of incident management are accounted for by interpolating between the speeds with and without incidents. These speed estimates are based on regressions from data in the Urban Mobility Report (Schrank & Lomax 2009) – see GreenSTEP documentation for details (Gregor 2010).

Table 3-3. Average Speeds (in mph) Associated with Congestion Levels in GreenSTEP

Congestion Level	Freeways – with incidents	Freeways – without incidents	Arterials –with incidents	Arterials – without incidents
None	60.0	60.0	30.0	30.0
Moderate	50.8	56.2	25.0	29.4
Heavy	44.8	53.2	23.7	28.5
Severe	35.5	47.5	22.5	27.7
Extreme	24.8	40.0	20.8	26.4

In the current version of GreenSTEP, FSC are normalized to an assumed Free Flow Speed (FFS) and then fleet-average fuel economy is adjusted for congested speeds using the normalized FFS. Assumed FFS are 60 mph for freeways and 30 mph for arterials (except for buses, which use an arterial FFS of 20 mph). This approach assumes that base average fuel economy is calculated for free-flow conditions. But fuel economy labeling is intended to reflect real-world driving as much as possible, including existing congestion levels for average U.S. driving (see Section 3.1 and U.S. Environmental Protection Agency (2006)). The HFET "highway test" drive schedule has an average speed of 48 mph, for example – which is below most assumed highway free-flow speeds. Therefore, adjusting the base fuel economy with respect to free flow speeds double-counts some congestion effects. Ideally, congestion adjustments should be made with respect to the base congestion levels implicit in the average fuel economy estimates – though these base congestion levels are not explicit. The next section describes the modeling methodology of this study, which attempts to develop realistic FE adjustment curves at the GreenSTEP scope of modeling.

4 Methodology

The objectives of this task are to develop fuel-speed curves that can be used to adjust FE for congestion and to provide a method for their incorporation into GreenSTEP. In order to incorporate the impacts of congestion on advanced vehicles, this research develops FSC for Hybrid Electric Vehicles (HEV), Fuel Cell Vehicles (FCV), and fully Electric Vehicles (EV). Fuel consumption rates (per vehicle-mile of travel) as a function of average travel speed are estimated from vehicle fuel consumption modeling using archetypal speed profiles. We also use the same modeling to refine the FSC for conventional Internal Combustion Engine (ICE) passenger vehicles and trucks.

4.1 Modeling Approach

An overview of the modeling procedure is illustrated in Figure 2. First, a large set of real-world driving schedules (a) and a test set of 145 hypothetical vehicles with a variety of characteristics (b) are used as inputs to the PERE fuel consumption model (c) to estimate fuel consumption rates by Vehicle Specific Power (VSP) bin (e) for each vehicle. Next, the same set of driving schedules (a) and vehicle characteristics (b) are used to calculate (d) VSP bin distributions of operating time for each driving schedule, for each vehicle (f). The driving schedules represent a variety of congestion levels on freeway and arterial facilities. Combining (e) and (f) generates estimates of average FE for each driving schedule, for each vehicle (g). We fit these FE estimates to a curve as a function of the average speed for each driving schedule, producing a FSC for each vehicle on each facility type (h). Finally, the freeway and arterial FSC for each vehicle are normalized to the average speeds implied by EPA test driving schedules (i).

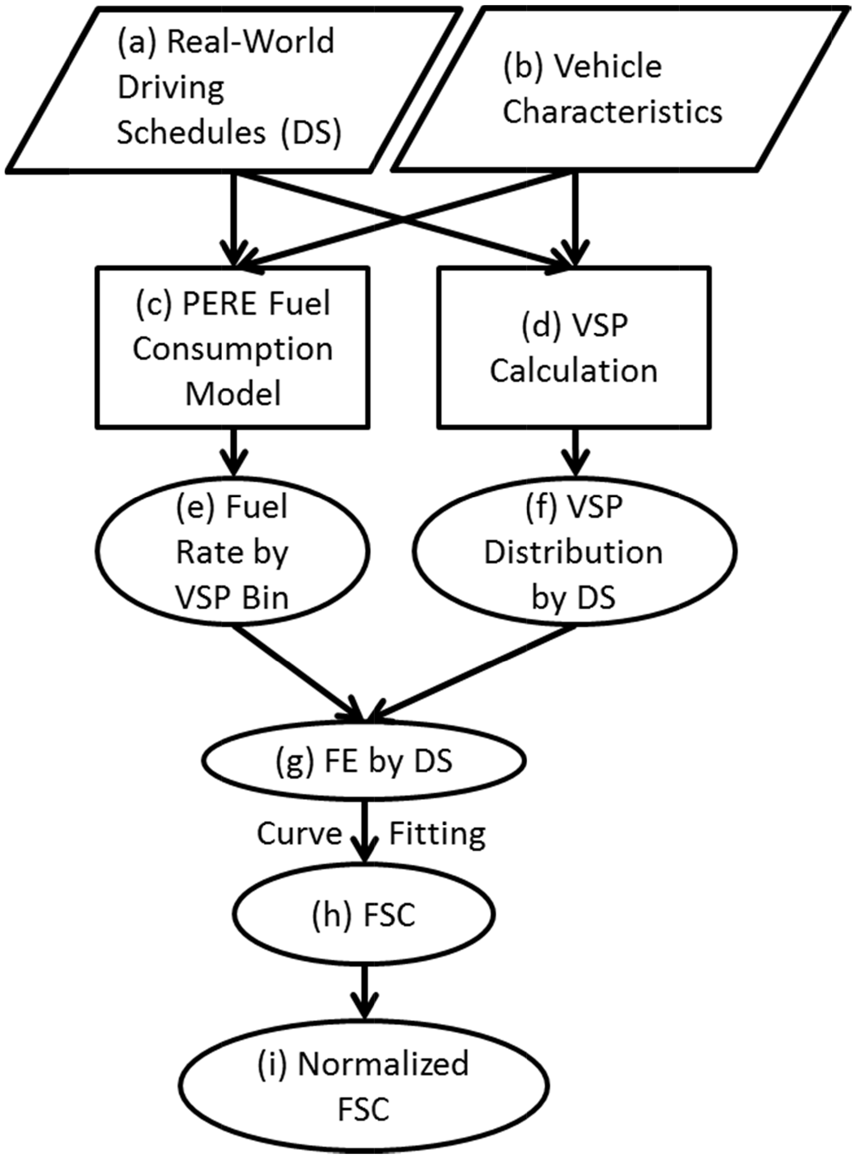

Figure 2. Overview of Modeling Methodology to Generate Normalized FSC

We also proposed method for implementation of these normalized FSC in GreenSTEP, illustrated in Figure 3. For each modeled vehicle/powertrain type, the vehicles that are most and least sensitive to congestion are selected from the plausible range of vehicle characteristics (the High- and Low-Sensitivity FSC in Figure 3). Then in GreenSTEP, normalized FSC for each vehicle type are calculated by interpolating between these “extreme-case” vehicles’ FSC. The interpolation point is added to GreenSTEP as a model input, to be based on congestion sensitivity as assessed from an expected mix of vehicle characteristics. In GreenSTEP, input FE is adjusted using the interpolated FSC. We next describe components of the modeling methodology in more detail.

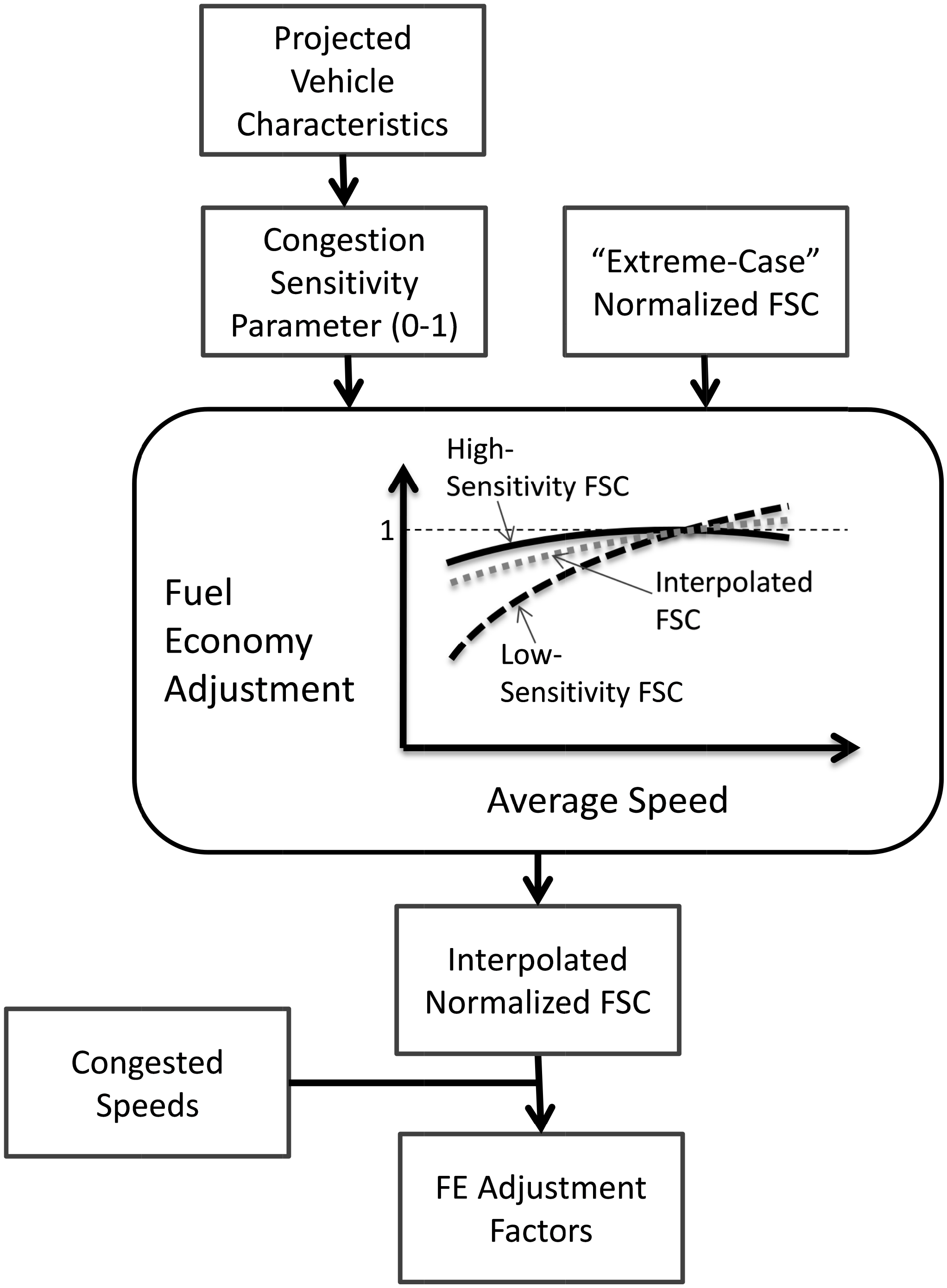

Figure 3. Overview of Implementation Strategy for Normalized FSC in GreenSTEP

4.2 Fuel Consumption Model Selection

Based on the investigation of potential models described in Appendix A, PERE was selected as the most appropriate fuel consumption model for this project. As described in Appendix A, PERE is a physical/modal vehicle fuel consumption model developed by the EPA to supplement the MOVES mobile-source emissions model for untested vehicles (Nam & Giannelli 2005). The vehicle powertrain models (Autonomie, ADVISOR, PSAT) are oriented toward individual vehicles, and too detailed/data-intensive for modeling fleets of uncertain vehicles. On the other end, the high-level models (GREET and VISION) are too broad for this project because they cannot model transient driving patterns (so they do not model speed-specific or congestion-specific fuel consumption). The more established emissions models, both microscopic and macroscopic (CMEM and MOVES), do not model the unique performance of advanced powertrains – such as regenerative braking.

PERE adopts a physical approach that is ideal for advanced vehicle technologies without vehicle test data. It also utilizes parameters that are aligned with the scope of vehicle-class modeling (such as hybrid power threshold) as opposed to parameters used for individual vehicle design (such as control system logic). The primary drawback of PERE is the lack of validation for electric vehicles. Although the model is built on the well-established methodology of CMEM, by the very nature of predictive modeling we cannot validate the forecasts for some as-yet hypothetical vehicles. Furthermore, there is no cold-start module in PERE, though this is unlikely to have a significant impact on the modeled congestion effects.

The primary vehicle input parameters for PERE (in general order of importance as indicated in the PERE documentation) are:

1. Vehicle type (light-duty or heavy-duty, and passenger car or passenger truck for light-duty)
2. Engine indicated (thermal) efficiency
3. Vehicle model year
4. Road load power (method and coefficients)
5. Vehicle weight
6. Engine size (displacement)
7. Motor peak power (HEV/EV only)
8. Fuel cell power rating (FCV only)

9. Hybrid threshold (HEV only)
10. Powertrain type (ICE, HEV, EV, FCV)
11. Fuel type (gas or diesel for ICE vehicles – representing spark-ignition or compression-ignition engines – or gas for gas-equivalent fuels)
12. Transmission type (automatic or manual)

The details and model sensitivity for these parameters are discussed in the PERE documentation (Nam & Giannelli 2005). However, the documentation discusses overall, average fuel economy sensitivity to these inputs. For this study we are not interested in average fuel economy but in changing fuel economy with average speed. Thus, PERE provides limited guidance on the most important model inputs.

In addition to the vehicle parameters, modeling requires a driving schedule. The driving schedule is simply a time series of 1-second vehicle speeds. Vehicle acceleration is differentiated from the speeds, and Vehicle Specific Power (VSP) is calculated using a Road Load Power method, described in the documentation. VSP is a widely-used proxy for engine loading, often used in vehicle emissions and fuel consumption modeling (H. C. Frey et al. 2002; Song & Yu 2009).

There are two major caveats that must be included with the PERE modeling approach. The first is that PERE only models parallel-configuration HEV. HEV with series-configuration powertrains cannot be modeled. This is not major concern, since there are other powertrain configurations which are not being modeled as well. This modeling can only cover the most expected advanced powertrain characteristics, since we lack the prescience to know what new configurations and control systems will be developed over long time horizons.

The second major caveat is that the application of PERE for EV has not yet been validated. This is primarily due to a lack of validation data at the time of development. There is still little data available on the real-world fuel consumption performance of EV, so in fact few validated tools are available for this application. Still, it lends confidence to the modeling of EV in PERE that EV are modeled as modified HEV (with the ICE removed), and the HEV model in PERE has been well validated (Nam & Giannelli 2005).

4.3 Strategy for Implementing PERE

The PERE documentation describes a method for using PERE to derive advanced vehicle fuel consumption rates to be applied in MOVES modeling. This method is discussed in Section XI of the PERE report (starting on page 73), with the section on advanced Technologies on page 81 (Nam & Giannelli 2005). By this method, the vehicles of interest are modeled over a combination of transient driving schedules, and the average fuel consumption rates binned by VSP. There are 17 VSP bins used by MOVES, shown in Table 4-1.

Table 4-1. MOVES VSP Bin Definitions (U.S. Environmental Protection Agency 2006)

MOVES VSP Bin	Vehicle Speed (mph)	Vehicle Specific Power (kW/Mg)
0	Deceleration	--
1	Idle	--
11	1-25	<0
12		0-3
13		3-6
14		6-9
15		9-12
16		>12
21	25-50	<0
22		0-3
23		3-6
24		6-9
25		9-12
26		>12
33	>50	<6
35		6-12
36		>12

With fuel rates tabulated by VSP bin for each vehicle, total fuel consumption can be quickly computed from the VSP-distribution of second-by-second vehicle activity. Vehicle activity distribution by VSP can be computed from speed profiles – such as embodied in driving schedules (Nam 2003). Using coastdown coefficients A, B, and C (also known as Road Load Coefficients - RLC) from the dynamometer load equation, VSP is calculated as

$$VSP = \mathrm{A}\frac{v}{m} + \mathrm{B}\frac{v^2}{m} + \mathrm{C}\frac{v^3}{m} + 1.1v(a + g * \mathrm{grade}) \quad (3)$$

from (Nam & Giannelli 2005), where VSP is in kW/Mg, v is speed in m/s, a is acceleration in m/s^2, g is the acceleration due to gravity in m/s^2, and m is vehicle mass in Mg. The three RLC correspond to rolling, rotating, and aerodynamic resistive factors, respectively (Nam & Giannelli 2005).

The RLC, if not provided as a vehicle parameter, can be estimated from the vehicle mass or the Track Road Load HorsePower (TRLHP) – with different methods for LD and HD vehicles (Koupal et al. 2005; Nam & Giannelli 2005). This approach of using many driving schedules to estimate fuel rates by VSP bin then distributing activity by VSP bin provides more fuel consumption data in each VSP bin and more vehicle activity flexibility than simply using a single driving schedule to model fuel rate at an average speed.

The adopted strategy for advanced vehicle modeling in this project mirrors the PERE-MOVES approach, as illustrated in Figure 2. The additional benefit of this approach is that vehicle activity distributions by VSP bin can be adjusted based on projected changes in roadway operations, vehicle performance, or driver behavior. In this way fuel-speed curves can be sensitive to changing traffic operations and driving behaviors without repeating the engine/fuel modeling process.

4.4 Driving Schedules

The EPA has generated facility-specific driving schedules for different levels of congestion (with different average speeds) based on real-world measurements. These driving schedules are included in the MOVES model, where they are used to compute emissions and fuel rates for a given average speed and facility type. The MOVES driving schedules are not test schedules for dynamometers, but rather designed to reflect actual on-road vehicle activity, and so represent actual congestion effects (Smit et al. 2008). The MOVES database includes 18 relevant Light-Duty (LD) driving schedules with average speeds from 3 to 76 mph, 11 Medium-Duty (MD) driving schedules (average speeds of 5 to 73 mph), and 11 Heavy-Duty (HD) driving schedules (average speeds of 6 to 72 mph) – each vehicle type with a mix of freeway and arterial driving schedules (some of which apply for both). These driving schedules are summarized in Table 4-2. Concatenating the relevant MOVES driving schedules for modeling in PERE leads to long driving schedules for fuel estimates: 3.7 hours for LD vehicles, 5.9 hours for MD vehicles, and 5.0 hours for HD vehicles.

Table 4-2. Summary of MOVES Driving Schedules

Drive Schedule ID	Drive Schedule Name	Vehicle Type	Facility Type	Average Speed (mph)	Duration (minutes)
101	LD Low Speed 1	LD	Fwy, Art	2.5	10.0
1033	Final FC14LOSF Cycle (C15R05-00424)	LD	Fwy	8.7	14.2
1043	Final FC19LOSAC Cycle (C15R08-00267)	LD	Fwy	15.7	14.5
1041	Final FC17LOSD Cycle (C15R05-00480)	LD	Art	18.6	11.8
1021	Final FC11LOSF Cycle (C15R01-00876)	LD	Fwy	20.6	15.1
1030	Final FC14LOSC Cycle (C10R04-00104)	LD	Art	25.4	8.6
153	LD LOS E Freeway	LD	Fwy	30.5	7.6
1029	Final FC14LOSB Cycle (C15R07-00177)	LD	Art	31.0	12.6
1026	Final FC12LOSE Cycle (C15R10-00782)	LD	Art	43.3	15.2
1020	Final FC11LOSE Cycle (C15R11-00851)	LD	Fwy	46.1	16.2
1025	Final FC12LOSD Cycle (C15R09-00037)	LD	Arterial	52.8	13.4
1019	Final FC11LOSD Cycle (C15R10-00068)	LD	Fwy	58.8	12.2
1024	Final FC12LOSC Cycle (C15R04-00582)	LD	Arterial	63.7	14.8
1018	Final FC11LOSC Cycle (C15R09-00849)	LD	Fwy	64.4	15.1
1017	Final FC11LOSB Cycle (C10R02-00546)	LD	Fwy	66.4	8.7
1009	Final FC01LOSAF Cycle (C10R04-00854)	LD	Fwy, Art	73.8	9.5
158	LD High Speed Freeway 3	LD	Fwy, Art	76.0	9.7
201	MD 5mph Non-Freeway	MD	Fwy, Art	4.6	4.9
202	MD 10mph Non-Freeway	MD	Fwy, Art	10.7	5.2
203	MD 15mph Non-Freeway	MD	Fwy, Art	15.6	7.6
204	MD 20mph Non-Freeway	MD	Fwy, Art	20.8	17.4
205	MD 25mph Non-Freeway	MD	Fwy, Art	24.5	9.4
206	MD 30mph Non-Freeway	MD	Fwy, Art	31.5	16.5
251	MD 30mph Freeway	MD	Fwy, Art	34.4	27.3
252	MD 40mph Freeway	MD	Fwy, Art	44.5	58.4
253	MD 50mph Freeway	MD	Fwy, Art	55.4	45.3
254	MD 60mph Freeway	MD	Fwy, Art	60.4	81.1
255	MD High Speed Freeway	MD	Fwy, Art	72.8	79.7
301	HD 5mph Non-Freeway	HD	Fwy, Art	5.8	4.3
302	HD 10mph Non-Freeway	HD	Fwy, Art	11.2	10.1
303	HD 15mph Non-Freeway	HD	Fwy, Art	15.6	9.5
304	HD 20mph Non-Freeway	HD	Fwy, Art	19.4	9.3
305	HD 25mph Non-Freeway	HD	Fwy, Art	25.6	16.4
306	HD 30mph Non-Freeway	HD	Fwy, Art	32.5	13.5
351	HD 30mph Freeway	HD	Fwy, Art	34.3	37.9
352	HD 40mph Freeway	HD	Fwy, Art	47.1	53.3
353	HD 50mph Freeway	HD	Fwy, Art	54.2	88.9
354	HD 60mph Freeway	HD	Fwy, Art	59.4	29.9
355	HD High Speed Freeway	HD	Fwy, Art	71.7	29.9

As discussed above, it is possible that new engine/powertrain technologies could influence driving patterns for certain speed-facility combinations. Given the uncertainty that this is a real effect – and if it is real, what exactly the effect would be – we use the same driving schedules for all vehicles modeled. If advanced vehicles are driven more conservatively than conventional vehicles, this could improve the fuel economy from these vehicles. But what effect this would have on the shape of the FSC is not known. Until more data is available on driving behavior changes for advanced-powertrain vehicles, any adjustment to the normalized FSC would be speculation. We assume that driving behavior changes, in aggregate, can be represented by eco-driving, which is discussed in Task 2.

In addition to using MOVES driving schedules, we computed fuel economy estimates using real-world vehicle speed data from a freeway in Portland, Oregon. Vehicle speed data were gathered on OR-217 in the summer and fall of 2010 using Global Position System (GPS) data in a probe vehicle. This freeway had average daily traffic of about 100,000 vehicles in 2009 (Oregon Department of Transportation 2010), with regular congestion in both directions. In total, 59 probe vehicle runs were collected before, during, and after the PM peak period using passenger cars traveling in both directions (northbound and southbound). The vehicle trajectory data were gathered using in-vehicle GPS devices collecting 1 second location and speed information. The 1 second speeds were differentiated with respect to time to calculate second-by-second vehicle acceleration. Probe vehicles followed a "floating car" data collection approach, wherein they traveled as close as possible to the average speed of the traffic stream. Travel lanes were not specified— probe vehicle drivers being allowed to use their own judgment for lane changing maneuvers. The probe vehicle data are summarized in Table 4-3.

Table 4-3. Probe Vehicle Data Summary

Roadway Name	OR-217
Number of Runs	59
Probe Run Length (miles)	6.4
Average Run Time (min)	10.8
Std. Dev. Of Run Times (min)	2.9
Range of Run Times (min)	7.2 - 21.2
Equivalent Average Speed (mph)	35.6
Std. Dev. of Equivalent Speed (mph)	9.3
Equivalent Average Speed Range (mph)	18.2 - 53.7

Fuel economy is also estimated for the set of EPA test driving schedules (see Table 3-1) used for fuel economy labeling as described in Section 3.1. Additionally, as an upper bound on the fuel economy possible with optimal driving conditions, fuel economy estimates are made for constant-speed driving. This is in comparison to the real-world transient driving schedules represented by MOVES and the Portland/OR-217 GPS data. The constant-speed driving schedules are simply that: a steady-state time series of a single speed with zero acceleration. This represents the maximal fuel economy that could be achieved through eco-driving and intelligent transportation systems/management. A similar approach was used by Barth and Boriboonsomsin (2008) to estimate the impacts of congestion on CO_2 emissions.

The constant-speed FE estimates are modeled slightly differently from the approach illustrated in Figure 2 – by omitting the VSP binning step. Since hypothetical constant-speed driving is not based on real-world transient speeds, the VSP-binned average fuel rates are not appropriate to use. Instead, constant-speed driving schedules (at intervals of 10 mph) are input to PERE directly and fuel economy estimated for each speed and each vehicle modeled (only select test vehicles were modeled at constant speed).

4.5 Vehicle Characteristics

FSC are generated for the following vehicle types:

1. Light-duty vehicles – passenger cars and light trucks
    a. Conventional ICE (spark ignition and compression ignition)
    b. Hybrid Electric Vehicles (HEV)
    c. Electric Vehicles (EV)
    d. Fuel Cell Vehicles (FCV) – with and without electric motor hybridization
2. Heavy-duty vehicles – local delivery and long-haul combination trucks
    a. Conventional ICE
    b. Hybrid Electric Vehicles

We model FCV despite the fact that they are not currently included in GreenSTEP (nor are there plans for immediate implementation of FCV). We chose to include FCV in this research in order to obtain a broader view of the potential performance of advanced drivetrain vehicles in congestion.

Vehicle parameter assumptions as required by PERE are based on a variety of sources. Many representative characteristics are included as defaults within the PERE model (transmissions shift points, mechanical efficiency, etc.). Other vehicle characteristics are based on the literature – vehicle projection studies and similar research on future vehicle performance (Delorme et al. 2010; Nam & Giannelli 2005; Plotkin & M. K. Singh 2009; M. Singh et al. 2003; U.S. Environmental Protection Agency 2006; U.S. Environmental Protection Agency 2010; Farrington & Rugh 2000; Davis et al. 2010). Some vehicle characteristics are based on EPA inventory data and modeling guidance for the U.S. vehicle fleet (U.S. Environmental Protection Agency 2010).

Additionally, some vehicles' characteristics are based on manufacturers' specifications (including vehicles of all three advanced powertrain types). We include in the vehicle test matrix vehicles of known attributes (for the 2010 model year), including:

- HEV: Toyota Prius, Toyota Camry Hybrid, Toyota Highlander Hybrid, Honda Civic Hybrid, Honda CR-Z Sport Hybrid, Honda Insight, Ford Escape Hybrid, and Ford Fusion Hybrid
- EV: Nissan Leaf, Tesla Roadster, Coda, and Mitsubishi MiEV
- FCV: Toyota FCHV, Ford Focus, GM HydroGen3, and Honda FCX

Because of the intended use of FSC for long-range scenario analysis with uncertain fleets, the vehicle generation strategy is not to constrain the modeling to existing or even prototype vehicles. The selected vehicle attributes thus include not only the probable but also the possible range of characteristics. In other words, we set the bounds wide enough to capture an uncertain future fleet. Note that in some cases, that means widening the original range of attributes tested in the PERE model (such as for hybrid thresholds).

The key parameters for FSC shape sensitivity testing are:

1. Vehicle weight
2. Combustion engine size (displacement)
3. Engine indicated efficiency (the thermodynamic efficiency limit of the engine)
4. Electric motor peak power
5. Fuel cell power rating
6. Hybrid threshold (the power demand at which the engine or fuel cell is required in addition to the motor in an HEV or FCV)

7. Transmission type (automatic or manual)
8. Fuel type (gasoline or diesel – also indicates spark-ignition or compression-ignition)
9. Power accessory load (such as air conditioning)
10. Road load/coastdown coefficients (also used in VSP calculation)
11. Model year (which impacts engine and torque parameters through assumed trends)

Other parameters included in the PERE model are not varied due to low model sensitivity (Nam & Giannelli 2005) or no published information on expected changes to the value. Some combustion engine characteristics are adjusted within PERE based on the vehicle model year (engine friction, enrichment threshold, peak torque, and peak power). The coastdown/road-load coefficients A, B, and C for VSP calculation (see Equation 3) are based on EPA documentation (U.S. Environmental Protection Agency 2010) or estimated from the vehicle weight as described in the PERE documentation (Nam & Giannelli 2005). For fuel types other than gasoline or diesel (such as electricity), PERE converts consumed energy to gasoline equivalent units using an assumed energy density for gasoline of 32.7 MJ/L.

The ranges of tested values of vehicle parameters for Light Duty (LD) vehicles (passenger cars and light trucks) are shown in Table 4-4. Similarly, the test ranges for Heavy Duty (HD) vehicles are shown in Table 4-5. All modeled vehicles are included in Appendix B. The range of vehicle characteristics is tested over a set of 145 LD vehicles and 32 HD vehicles (not every possible combination of characteristics is modeled). Note that these parameters are modeled over their range of values, not simply at the extremes. While the ranges are wide compared to probable vehicle attributes, they also include the set of expected vehicles.

The light duty vehicles represent a range from very small neighborhood electric vehicles to large pickup trucks and Sports Utility Vehicles (SUVs). The heavy duty vehicles represent a range of trucks, from relatively small local delivery, single-unit trucks to large long-haul tractor trailers. Note that for HD vehicles no hotelling or extended idling activity is considered in this modeling. Also, the HD vehicle class includes medium and heavy HD vehicles, as described by MOVES, with a division at 33,000 lbs Gross Vehicle Weight Rating (GVWR).

Table 4-4. Tested Vehicle Parameter Ranges for Light Duty Vehicles

Vehicle Parameter	Values
Model year	2005-2040
Fuel type	gas, diesel
Transmission type	manual, automatic
Powertrain type	conventional, hybrid, electric, fuel cell
Engine size	1-4.5 liters
Vehicle curb weight	2,000 to 5,000 lbs
Road Load Method	weight-based, RLC
Hybrid threshold	1 to 6 kW
Motor peak power	10 to 215 kW
Fuel cell power rating	60 to 155 kW
Accessory load	0.75 to 4 kW
Engine indicated efficiency	0.4 to 0.6 gas, 0.45 to 0.6 diesel

Table 4-5. Tested Vehicle Parameter Ranges for Heavy Duty Vehicles

Vehicle Parameter	Values
Model year	2000-2050
Fuel type	diesel only
Transmission type	manual only
Powertrain type	conventional and hybrid
Engine size	5 to 16 liters
Vehicle curb weight	20,000 to 100,000 lbs
Road Load Method	weight-based
Hybrid threshold	2 to 4 kW
Motor peak power	50 to 200 kW
Accessory load	0.75 to 6 kW
Engine indicated efficiency	0.48

4.6 Fuel-Speed Curve Calculation

Data for the FSC are generated by combining the fuel consumption from each VSP bin for each modeled driving schedule. Let f_b be the modeled fuel consumption rate (in kg/second) in VSP bin b, where $b \in B$ and B is the set of 17 VSP bins. This is (e) in Figure 2. For EV and FCV, PERE estimates energy consumption and then generates f_b in gasoline-equivalent units using an assumed energy content of 44 kJ/g for gasoline. Also, let t_b be the amount of driving time (in seconds) spent in VSP bin b for a given driving schedule – (f) in Figure 2. Then the modeled fuel consumption (in kg) for that driving schedule is calculated

$$f = \sum_{b \in B} (t_b \cdot f_b) \ . \qquad (4)$$

For a given fuel density of d_f in kg/gallon and a driving schedule distance of D in miles, the fuel economy FE (in gasoline-equivalent miles per gallon – mpg) for that driving schedule is then calculated

$$FE = \frac{D \cdot d_f}{f} \ . \tag{5}$$

This is (g) in Figure 2. We use $d_f = 0.744$ kg/L for gasoline and $d_f = 0.811$ kg/L for diesel from the PERE model, which converts to $d_f = 2.82$ kg/gallon and $d_f = 3.07$ kg/gallon, respectively. The average speed for the drive schedule, v, is simply $v = \frac{3600 \cdot D}{\sum_{b \in B} t_b}$.

Since this fuel modeling approach creates discrete fuel–speed data points, a curve fit is applied to establish a full FSC – (h) in Figure 2. We fit the FSC to an exponentiated 4th-order polynomial functional form, following previous emissions modeling research (Barth & Boriboonsomsin 2008; Bigazzi & Figliozzi 2011; Sugawara & Niemeier 2002). The functional form is

$$FE = \exp\left(\sum_{i=0}^{4} \alpha_i v^i\right) , \tag{6}$$

where v is the average travel speed in mph and α_i are fitted parameters. The FSC are fit to this functional form using an iteratively reweighted least squares (IWLS) method. Separate fits are made for freeway and arterial driving schedules. Freeway driving schedules include MOVES and OR-217 sources. Arterial driving schedules are sourced from MOVES only. The shapes of the FSC are then compared for varying vehicle types and vehicle parameters.

FSC normalization to a given reference speed can be calculated using the fitted parameters α_i. If the FSC is to be normalized to a calculated reference fuel economy, FE_{ref}, at reference speed v_{ref}, then FE_{ref} can be calculated from Equation 6. The normalized fuel economy, FE_{norm}, at speed v is then calculated

$$FE_{norm} = \frac{FE}{FE_{ref}} = \frac{\exp\left(\sum_{i=0}^{4} \alpha_i v^i\right)}{\exp\left(\sum_{i=0}^{4} \alpha_i {v_{ref}}^i\right)} = \exp\left(\sum_{i=1}^{4} \alpha_i \left(v^i - {v_{ref}}^i\right)\right) . \tag{7}$$

4.7 Fuel Rate Normalization

Since average fuel economy is an input to the GreenSTEP model, the FSC are only used to adjust fuel economy for varying congestion levels (see Section 3.5). Therefore, we need not calculate absolute fuel economy, but simply how the fuel economy varies with average speed. In this case the FSC should be normalized to the fuel economy at the congestion level represented in the average fuel economy estimates.

The reference FE is not manifest, however. As stated above, the current GreenSTEP model uses assumed FFS as the reference condition. Average fleet FE estimates based on EPA methodology do not assume all free-flow conditions, but the intrinsic congestion levels in the EPA FE estimates are unclear. The new 5-cycle method for FE estimates uses a complicated combination of several driving schedules, and these driving schedules are used partially because they were already in widespread use (U.S. Environmental Protection Agency 2006). In other words, the test driving schedules are used to gather base fuel consumption data, but are not necessarily indicative of the expected driving conditions for the FE estimates.

The 2-cycle method, similarly, uses driving schedules to gather base data then adjusts the FE estimates for poorer performance in more realistic driving conditions. Part of that adjustment is for heavier congestion levels and higher-speed highway driving, in addition to varying environmental conditions (road roughness, surface winds, grades, etc.), driver behavior, and vehicle condition (U.S. Environmental Protection Agency 2006). Thus, the EPA fuel economy test driving schedules only roughly approximate the congestion levels inherent to the EPA fuel economy estimates.

The selected approach for normalizing the freeway FSC is to scale to the modeled FE at the average speed of the "highway" EPA test driving schedule (HFET – see Table 3-1). The arterial FSC normalization uses a different reference speed approach, as described below. The freeway approach assumes that the HFET speeds are indicative of the congestion levels inherent in the EPA "highway" FE estimates, and that the EPA adjusted FE estimates used as input to GreenSTEP are most representative of real-world fuel efficiency. Using the test driving schedule speeds (as opposed to using FFS reference conditions) is our best estimate to avoid double-counting the congestion levels inherent in the FE estimates which are input to GreenSTEP. Referencing to the PERE-modeled FE allows us to normalize for traffic effects alone. Referencing to the EPA adjusted FE estimates would essentially remove the other, non-traffic-related adjustments (for environmental factors, etc.) from the input FE estimates. We make comparisons in the results sections below between these three normalization approaches – with respect to FFS, EPA test speeds, and EPA adjusted FE.

The average speed for the HFET "highway" driving schedule is 48.2 mph. From Table 3-3, this corresponds to a freeway congestion level in GreenSTEP (including incidents) roughly midway between "Moderate" and "Heavy" congestion. Since we do not have a real-world driving schedule for this exact speed, the reference FE is interpolated from the PERE-modeled FE at the upper/lower neighbor speeds.

The "city" EPA test driving schedule includes vehicle operation on mixed facilities of both principal arterials and more minor local roads. Thus, the average speed from the "city" driving schedule will be too low for arterial FSC normalization. Instead, we draw a parallel with the "highway" driving schedule approach and assume that the average arterial congestion level inherent in FE estimates is roughly midway between "Moderate" and "Heavy" congestion. Interpolating from the values in Table 3-3, we calculate the reference speed for arterial FSC normalization as 24.4 mph.

4.8 Congestion Impacts on Fuel Economy

For testing the impacts of vehicle characteristics on the normalized FSC, we use an original indicator called the "Congestion Impact". This is simply the ratio of a vehicle's modeled FE in congested versus uncongested conditions on each type of roadway. For LD vehicles on the freeway we use driving schedules at Level of Service (LOS) B to represent uncongested conditions and at LOS F to represent congested conditions. Drawing from Table 4-2, the selected driving schedules are shown in the first two rows of Table 4-6. These driving schedules have average speeds just outside the maximum and minimum average speeds estimated for GreenSTEP congestion levels (see Table 3-3).

For LD vehicles on arterials we again use LOS B to represent uncongested conditions, which is near the uncongested average speed estimate in GreenSTEP for Arterials of 30 mph (see Table 3-3). But for the congested conditions on arterials we use LOS D instead of LOS F, since the LOS D driving schedule is closer to the minimum speed modeled for congestion in GreenSTEP (20.8 mph). These driving schedules, too, are shown in Table 4-6.

For MD and HD vehicles the driving schedules selected to represent uncongested conditions are those nearest the GreenSTEP free-flow speeds of 60 mph (for freeways) and 30 mph (for arterials). For congested conditions we use the driving schedules closest to 20 mph for freeways and to 15 mph for arterials – which are each just below the minimum GreenSTEP assumed speed for each facility and the congested driving schedule average speeds for LD vehicles. All selected driving schedules for Congestion Impact calculation are shown in Table 4-6.

Table 4-6. Selected Driving Schedules to Represent Congestion and Uncongested Conditions

Vehicle Type	Roadway	Conditions	MOVES Drive Schedule ID	Average Speed
LD	Freeway	Free-flow	1017	66.4
LD	Freeway	Congested	1021	20.6
LD	Arterial	Free-flow	1029	31.0
LD	Arterial	Congested	1041	18.6
MD	Freeway	Free-flow	254	60.4
MD	Freeway	Congested	204	20.8
MD	Arterial	Free-flow	206	31.5
MD	Arterial	Congested	203	15.6
HD	Freeway	Free-flow	354	59.4
HD	Freeway	Congested	304	19.4
HD	Arterial	Free-flow	306	32.5
HD	Arterial	Congested	303	15.6

For each vehicle the Congestion Impact (CI) is calculated as

$$CI = \left(\frac{FE_{CongDS}}{FE_{UncongDS}} - 1\right) \times 100\% \,. \tag{8}$$

where FE_{CongDS} is the fuel economy calculated by the congested driving schedule in Table 4-6 and $FE_{UncongDS}$ is the fuel economy calculated by the uncongested (free-flow) driving schedule in Table 4-6. Thus, a value of $CI = 0$ indicates no congestion impact on FE, $CI < 0$ indicates *decreased* FE economy in congestion (less efficiency, increased fuel consumption), and $CI > 0$ indicates *increased* FE in congestion (more efficiency, decreased fuel consumption).

4.9 Modeling Procedure Summary

The FE modeling procedure can be summarized in the following steps:

1) Estimate average fuel consumption by VSP bin using PERE
    a) Create a vehicle test matrix from the range of vehicle characteristics described above (see example in Figure 4 – the complete matrix is shown in Appendix B)
    b) Create a composite driving schedule from all relevant MOVES driving schedules
    c) Execute the PERE model for each vehicle in the vehicle test matrix and record the fuel consumption rates by VSP bin in the test matrix
2) Bin vehicle activity by VSP
    a) Calculate second-by-second VSP for each vehicle over each relevant test driving schedule as per Equation 3 (assuming 0% grade)

b) Bin each second of vehicle activity in the driving schedules based on Table 4-1 (using VSP, speed, and acceleration)

3) Calculate fuel economy

a) Combine the fuel consumption rates with the VSP bin distribution of activity to estimate fuel consumption for each vehicle over each driving schedule by Equation 4

b) Calculate fuel economy for each vehicle-drive schedule combination using Equation 5

4) Create FSC

a) Fit a curve to the FE-speed data points with the functional form in Equation 6

b) Normalize the FSC to the modeled FE at average speeds of 48.2 mph (freeways) and 24.4 mph (arterials)

	Parameters								.....
Parameters	VehType	LD	LD	LD	LD	LD	LD	LD	
	Car_Truck	car	car	car	car	car	car	car	
	FuelType	g	g	g	g	d	g	g	
	TransmissionType	a	a	m	m	a	a	a	
	PowertrainType	c	c	c	c	c	c	c	
	ModelYear	2005	2010	2005	2010	2010	2040	2010	
	VehicleWeight	3750	3750	3750	3750	3750	3750	2500	
	EngineDisplacement	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
	RoadLoadMethod	3	3	3	3	3	3	3	
	RoadLoadA	156.5	156.5	156.5	156.5	156.5	156.5	156.5	
	RoadLoadB	2.002	2.002	2.002	2.002	2.002	2.002	2.002	
	RoadLoadC	0.493	0.493	0.493	0.493	0.493	0.493	0.493	
	Efficiency_gas	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
	Efficiency_diesel	0.45	0.45	0.45	0.45	0.45	0.45	0.45	
	MotorPeakPower_kW	NA	NA	NA	NA	NA	NA	NA	
	HybridThreshold	NA	NA	NA	NA	NA	NA	NA	
	FuelCellPowerRating	NA	NA	NA	NA	NA	NA	NA	
	PeakPower_kW	155	159	155	159	178.8	188	159	
	TotalPeakPower_kW	155	159	155	159	178.8	188	159	
	SpecificPower_W/kg	91.12	93.49	91.12	93.49	105.1	110.5	140.2	
Fuel Rate by VSP bin	Bin_0	0.368	0.345	0.368	0.345	0.165	0.239	0.345	
	Bin_1	0.235	0.219	0.235	0.219	0.092	0.148	0.219	
	Bin_11	0.353	0.331	0.353	0.331	0.162	0.23	0.327	
	Bin_12	0.483	0.465	0.451	0.432	0.308	0.378	0.421	
	Bin_13	1.002	0.977	0.886	0.861	0.744	0.863	0.793	
	Bin_14	1.435	1.408	1.245	1.218	1.137	1.285	1.085	
	Bin_15	1.815	1.788	1.562	1.534	1.491	1.662	1.345	
	Bin_16	2.498	2.468	2.093	2.065	2.091	2.331	1.769	
	Bin_21	0.385	0.361	0.385	0.361	0.168	0.25	0.358	
	Bin_22	0.603	0.579	0.59	0.566	0.374	0.467	0.523	
	Bin_23	0.921	0.897	0.885	0.861	0.672	0.785	0.731	
	Bin_24	1.254	1.23	1.193	1.169	0.983	1.119	0.958	
	Bin_25	1.572	1.548	1.488	1.463	1.284	1.437	1.171	
	Bin_26	2.408	2.381	2.226	2.2	2.035	2.257	1.705	
	Bin_33	0.786	0.756	0.766	0.737	0.508	0.621	0.655	
	Bin_35	1.559	1.529	1.485	1.454	1.23	1.39	1.191	
	Bin_36	2.605	2.572	2.456	2.423	2.185	2.424	2.096	

Figure 4. Example Section of the LD Vehicle Test Matrix

5 Modeling Results: Fuel-Speed Curves

In this section we present the development of the FSC as calculated by the described methodology. We first show the results from the intermediate steps of fuel rate modeling in PERE and vehicle activity distribution by VSP bin. We then look at fuel consumption rates at different average speeds, and how congestion impacts fuel economy for different vehicle characteristics (using the Congestion Impact metric). Finally, we model FSC for each vehicle and setup the recommended method for implementation in GreenSTEP, which is presented in the subsequent section.

5.1 Fuel Consumption Rates by VSP Bin

Average fuel consumption rates by VSP bin for every modeled vehicle are presented in Appendix C. Boxplots of fuel consumption rates (in gasoline-equivalent grams per second) by VSP bin are also shown in Figure 5 for LD vehicles of each powertrain type, and in Figure 6 for HD vehicles. As expected, fuel consumption rates are higher for higher-powered VSP bins. Referring to Table 4-1, increasing VSP level between bins (e.g. between bins 15 and 16) is clearly a bigger factor than increasing the speed level at the same VSP level (e.g. between bins 15 and 25). At the same VSP bin, ICE vehicles tend to have the highest fuel consumption rates and EV the lowest – again, as expected. There is high variability in average fuel consumption rates within each bin, based on varying vehicle characteristics besides powertrain type. Comparing Figure 6 and Figure 5, HD vehicles have the same trends across VSP bins, with fuel consumption rates roughly 10 times those of modeled LD vehicles.

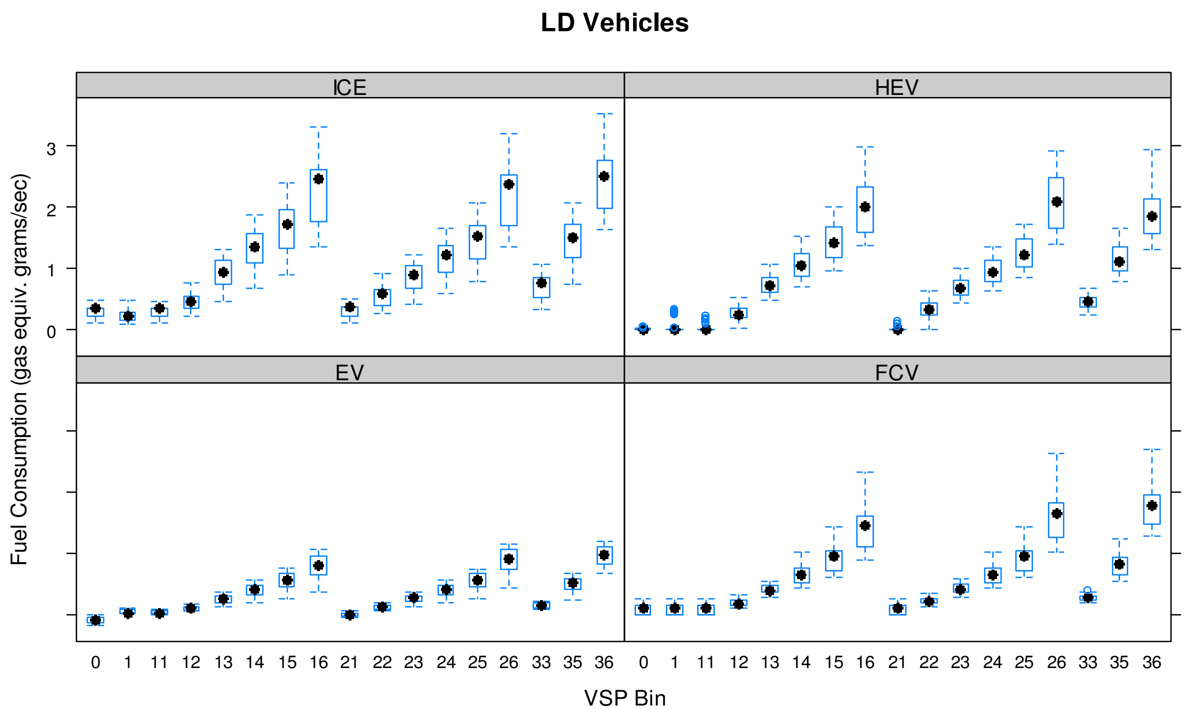

Figure 5. Modeled LD Vehicle Fuel Consumption Rates by VSP Bin

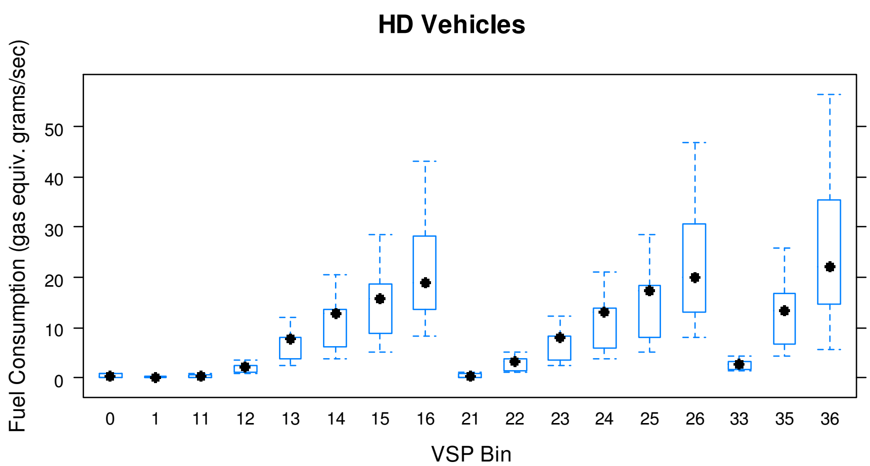

Figure 6. Modeled HD Vehicle Fuel Consumption Rates by VSP Bin

5.2 Vehicle Specific Power from Driving Schedules

In addition to having different fuel consumption rates, each vehicle also has different power demands over the driving schedules. This is due to different vehicle inertial masses which must be accelerated and different rolling resistances, aerodynamic drag, etc. which must be overcome to follow the speed traces of the driving schedules. Vehicle Specific Power is calculated for each vehicle over each relevant driving schedule as described in Section 4.3.

The driving schedule dictates the second-by-second speed and acceleration of the modeled vehicles. The remaining inputs to the VSP calculation are coastdown/road-load coefficients and vehicle mass (see Equation 3). Since these other inputs vary by vehicle, so do the VSP distributions for each driving schedule. Other vehicle characteristics which may influence the fuel consumption rates in different VSP bins do not impact the VSP bin distribution of time (e.g. fuel type, powertrain type, accessory load, engine/motor power). In other words, VSP is based the external vehicle forces only. Internal factors such as accessory loads due to air conditioning usage affect the fuel consumption rate estimates in PERE.

Figure 7 shows boxplots of the VSP bin distributions of time for different vehicles over the HFET and FTP driving schedules (described in Section 4.4). The HFET driving schedule produces widely varying VSP distributions for the high VSP bins (high speed driving). This is due to varying coastdown coefficients and vehicle masses used in Equation 3. Higher coastdown coefficients (associated with larger, less aerodynamic vehicles) will lead to more time in the high VSP bins. At the same time, larger vehicle masses tend to decrease the VSP at a given speed and acceleration. These same effects are seen for varying HD vehicle characteristics (plot not shown).

The FTP driving schedule has much less variability in VSP distribution than the HFET. Looking at Equation 3, the RLC and vehicle mass have bigger impacts at higher speeds (the impact of RLC "*C*" increases with the cube of speed). The impact of acceleration, however, is independent of mass or RLC. Thus, the VSP distribution of the highway test driving schedule (with higher speeds and fewer accelerations) is more impacted by vehicle characteristics (mass and RLC) than the VSP distribution of the city test driving schedule (with more accelerations and lower speeds). More generally, *we can expect the VSP distribution of vehicle activity in uncongested driving to be more impacted by vehicle characteristics (mass and RLC) than in congested driving*. The same can be said for arterial versus freeway driving, with freeway driving more impacted by vehicle characteristics.

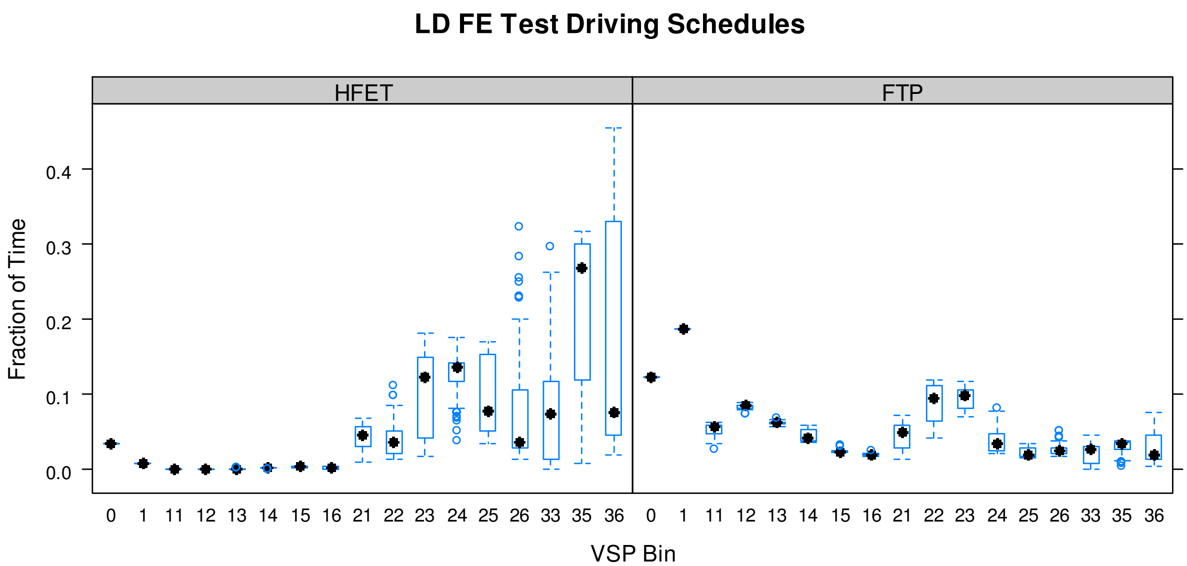

Figure 7. Comparison of VSP Distributions of Vehicle Activity from FTP and HFET Test Driving Schedules for LD Vehicles

5.2.1 Speed Distribution Comparisons of MOVES and Portland Driving Data

Besides vehicle characteristics, the varying speed and acceleration mix of driving schedules results in different VSP distributions of time, even if the driving schedules have similar average speeds. For this reason it is interesting to compare the MOVES driving schedules with the driving schedules gathered on OR-217 in Portland (see Section 4.4). Figure 8 presents a speed distribution comparison using Gaussian kernel density plots for all probe vehicle runs combined and the nearest-neighbor (by speed) MOVES driving schedules. The MOVES light-duty driving schedule used for comparison is a composite of the upper and lower neighbor driving schedules with the closest average speeds to the combined probe vehicle speed data (MOVES drive schedule ID's 153 and 1020). The average-speed difference between the combined probe vehicle and the composite driving schedule data is 5 mph.

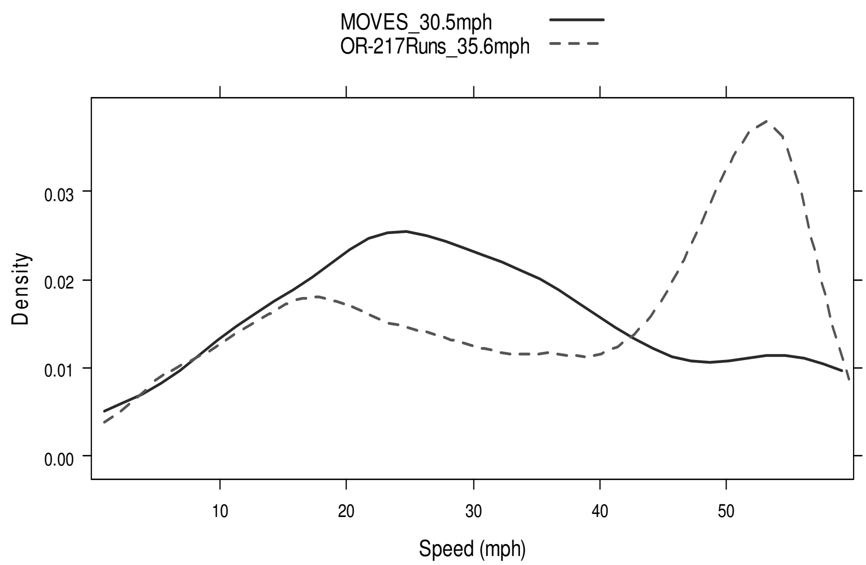

Figure 8. Comparison of Speed Distributions between MOVES Driving Schedules and the Combined Probe Vehicle Speed Data

In Figure 8 the probe vehicle speeds have a more distinct bimodal distribution while the MOVES distribution lacks clear separate peaks. The driving schedule average speeds are similar, but the distributions of second-by-second speeds are markedly different. This makes sense because drive schedules are supposed to represent average conditions over a range of space and time – while the probe vehicle data were collected on a single roadway with less variability in conditions, albeit in varying levels of congestion.

Figure 9 makes a similar comparison with the added dimension of acceleration. To create this figure, MOVES driving schedules (the same as used in Figure 8) and probe vehicle speeds were partitioned in 5 mph (speed) and 1 mph/sec (acceleration) intervals as shown on the *x* and *y* axes. The percent of total observations in each bin was calculated; the difference in percentage between the MOVES driving schedules and the probe vehicle speed data was then plotted in the speed-acceleration plane. Squares with more blue shading represent a greater share of time for the MOVES drive schedules, while more pink shading represents a greater share of time from the probe vehicle speed data. With the addition of acceleration data, we see that the MOVES distribution is less concentrated at low acceleration intervals and more concentrated at high accelerations. This implies more second-by-second speed variability in the MOVES driving schedules, and possibly a more “aggressive” driving style.

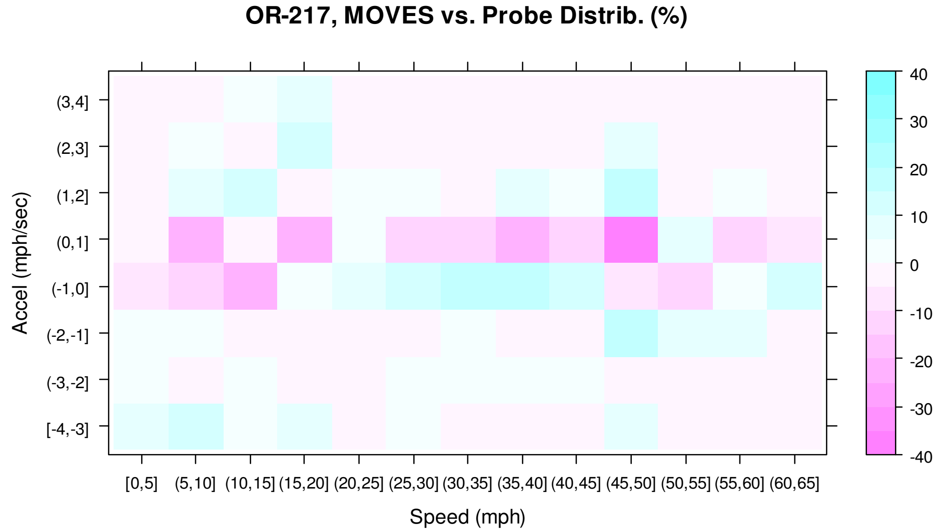

Figure 9. Comparison of Speed and Acceleration Distributions between MOVES Driving Schedules and Combined Probe Vehicle Speed Data

5.2.2 Vehicle Specific Power Comparison of MOVES and Portland Driving Data

Speed and acceleration differences lead to VSP distribution differences, as described above. Figure 10 shows the differences in VSP bin distributions (as percentage of time) when comparing each probe vehicle run with its nearest-neighbor (by average speed) MOVES drive schedules. The boxplots show the median, upper/lower hinges, and upper/lower whisker values for all runs, with the circles as statistical outliers. Positive values indicate proportionally more time in that VSP bin for the MOVES driving schedules than for the probe vehicle data. Using chi-squared tests, each run's VSP bin distribution is statistically significantly different from the neighboring MOVES drive schedule's distribution at p=0.01. The MOVES drive schedules tend to have more operating time in Bin 0 (deceleration) and in high-speed, high-power driving Bin 36. This indicates generally more aggressive driving for the MOVES drive schedules than the OR-217 data, as suggested in Figure 9.

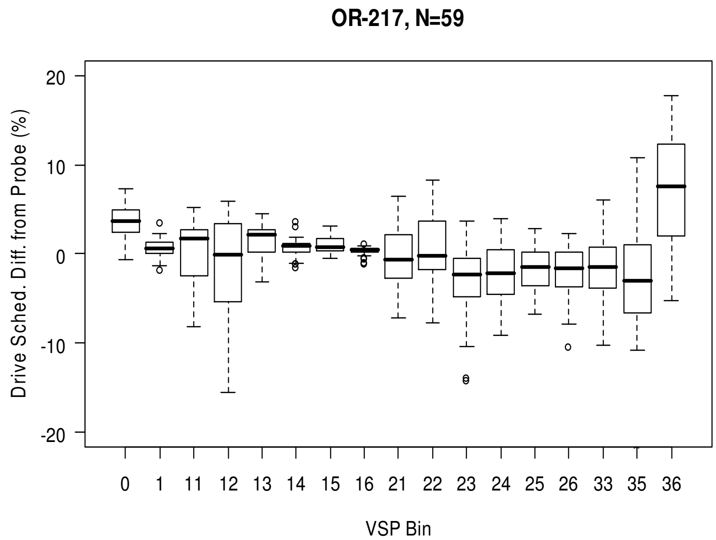

Figure 10. Differences in VSP Bin Distributions between Nearest-Neighbor MOVES Driving Schedules and the Probe Vehicle Data

These results showing unique operating mode patterns are not surprising since it has been established that distinct driving characteristics can be expected of any locality (Lin & Niemeier 2003; Ericsson 2000). The more distributed nature of the MOVES driving schedules reflects the fact that they are archetypal driving patterns designed to represent a wide variety of urban roads and drivers for aggregate fuel and emissions estimates throughout the U.S. For accurate local fuel consumption estimates, the database of driving schedules would ideally be collected locally in order to be more representative. But recording a unique set of driving schedules at the full range of average speeds and vehicle types for multiple roadways would be a time and cost intensive process, and is rarely undertaken.

5.3 Fuel Economy and Average Speed

The average fuel consumption rates by VSP bin and VSP bin distribution of time for each vehicle-drive schedule combination were combined to create Fuel Economy-Average Speed data points, as described by Equations 4 and 5 in Section 4.6. Figure 11 shows the Fuel Economy-Average Speed data points for all LD vehicles on both arterials and freeways using the Portland GPS (OR-217), EPA Test, and MOVES driving schedules described in Section 4.4. The figure is segmented by powertrain type, with different symbols to represent the different drive schedule sources. The vertical spread in data points reflects the FE differences of the modeled vehicles, which are described in Section 4.5 and detailed in Appendix B. EV fuel economy is in gasoline-equivalent units, as described in Section 4.6.

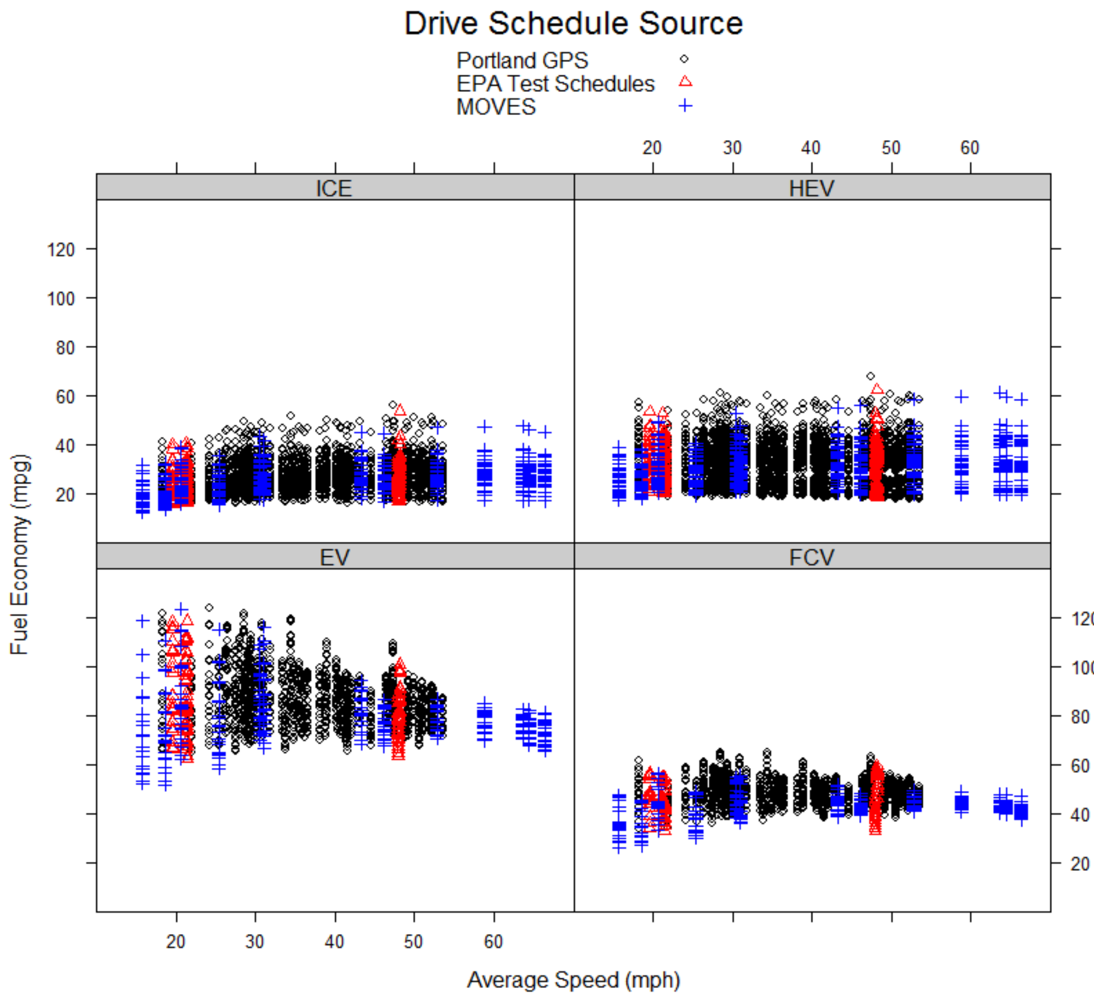

Figure 11. Fuel Economy vs. Average Speed by Powertrain Type, LD Vehicles on Freeways and Arterials

As expected from the fuel rates, EV have the highest fuel economy and ICE the lowest. EV also have the widest range of fuel economies for the modeled vehicles (particularly at lower speeds), followed by HEV. For each powertrain type the fuel economy values are fairly steady across the range of average speeds, with the exception of EV which increase FE at lower speeds. FE tends to decrease for average speeds below 20 mph for all powertrain types.

Figure 12 shows the Fuel Economy-Average Speed data points for all LD vehicles on freeways, with FE normalized to the EPA adjusted fuel economy for each vehicle (based on

Equations 1 and 2). Clearly, the modeled fuel economy based on these driving schedules is higher than from the EPA regression equations shown in Equations 1 and 2. This is logical, since the EPA regressions are designed to account for various factors not included in EPA test driving schedules or PERE modeling (such as cold starts and varying outside temperatures). These effects are outside the scope of this research, since we are attempting to quantify congestion effects alone. Therefore, normalization to the modeled fuel economy at a reference speed is more logical than normalization to a reference fuel economy (since different models will include slightly different factors).

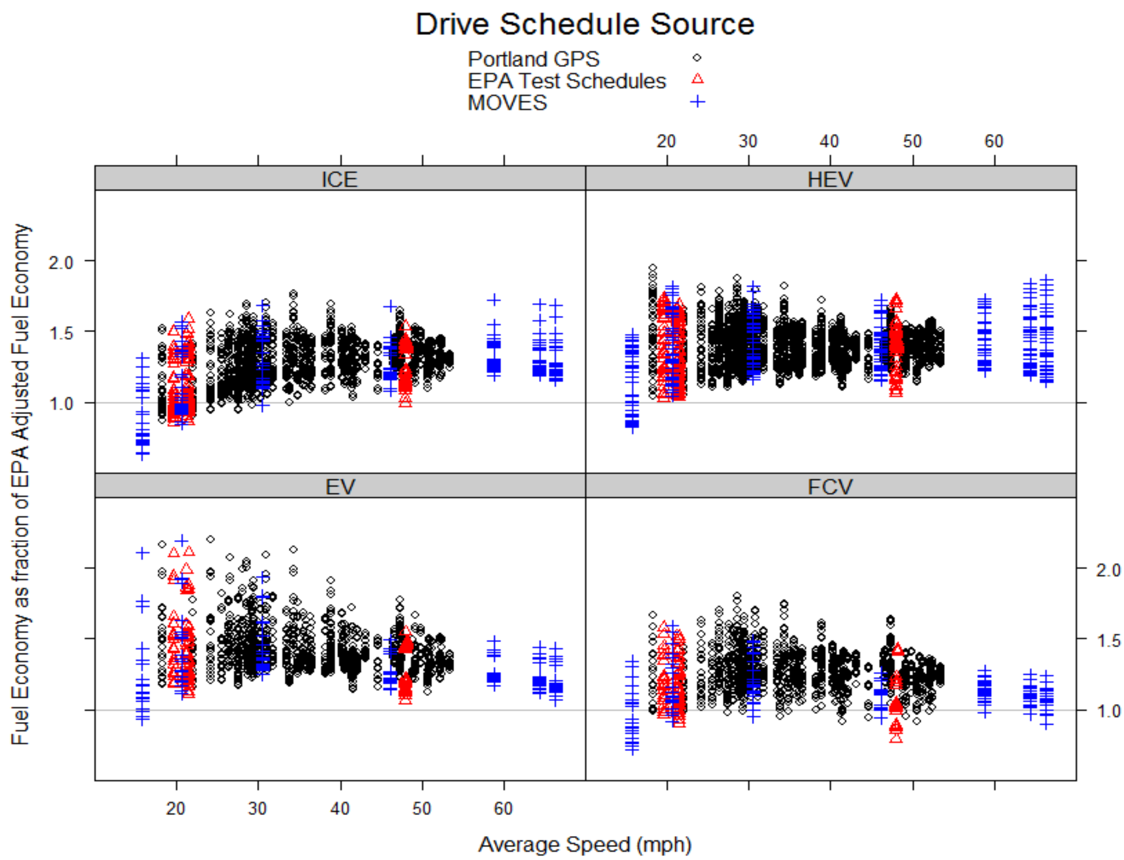

Figure 12. Fuel Economy (Normalied to EPA Adjusted Fuel Economy) vs. Average Speed by Powertrain Type, LD Vehicles for Freeways Only

Figure 13 presents the same data as Figure 12, but with FE normalized to the modeled fuel economy for each vehicle from the assumed MOVES free-flow freeway driving schedule, #1017 (see Table 4-6). This normalization has less bias, and allows us to compare trends with respect to high-speed FE. Normalized FE of 1.0 means that the FE is the same as in free-flow freeway conditions, while greater values of normalized FE indicate improved efficiency and lower values indicate decreased efficiency. ICE vehicle FE is generally flat from free-flow speed down to around 30 mph, at which point FE begins to decrease. HEV are similar, though the FE is flat for all except the low-speed MOVES driving schedule (1043). EV fuel economy *increases* with decreasing speed from the free-flow speed, down to around 20-30 mph. FCV fuel economy also increases somewhat as speed decreases, though to a lesser degree than EV.

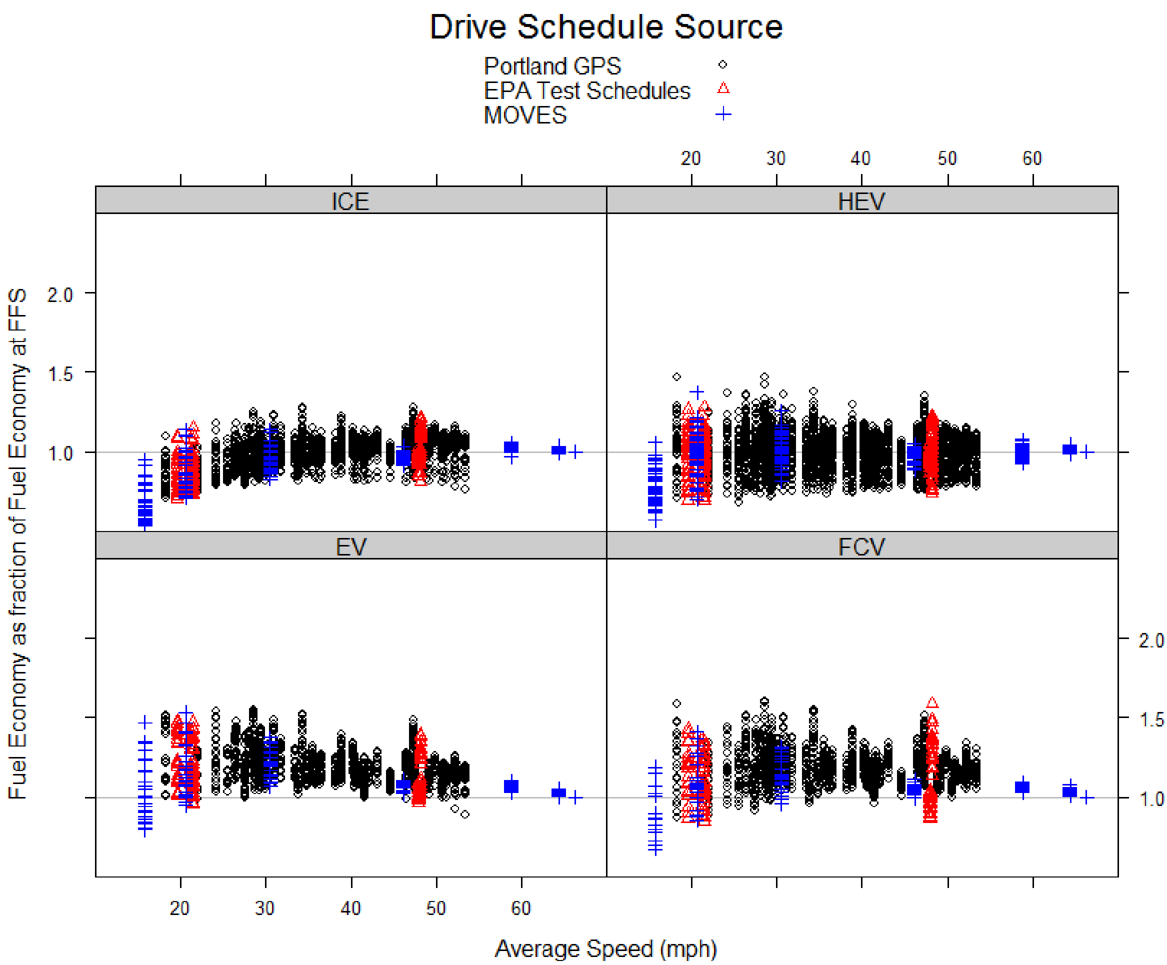

Figure 13. Fuel Economy (Normalized to Free-Flow Speed Fuel Economy) vs. Average Speed by Powertrain Type, LD Vehicles for Freeways Only

As described above, the EPA fuel economy labels are intended to represent an expected level of traffic congestion while driving, so normalization should ideally take this into account. Figure 14 does this by normalizing the FE (for the same set of Fuel-Speed data points) to the modeled fuel economy at the EPA highway test speed of 48.2 mph – by interpolating between the nearest MOVES driving schedules (see Section 4.7). Figure 14 shows the same trends as Figure 13, but with relative FE more centered around 1.0.

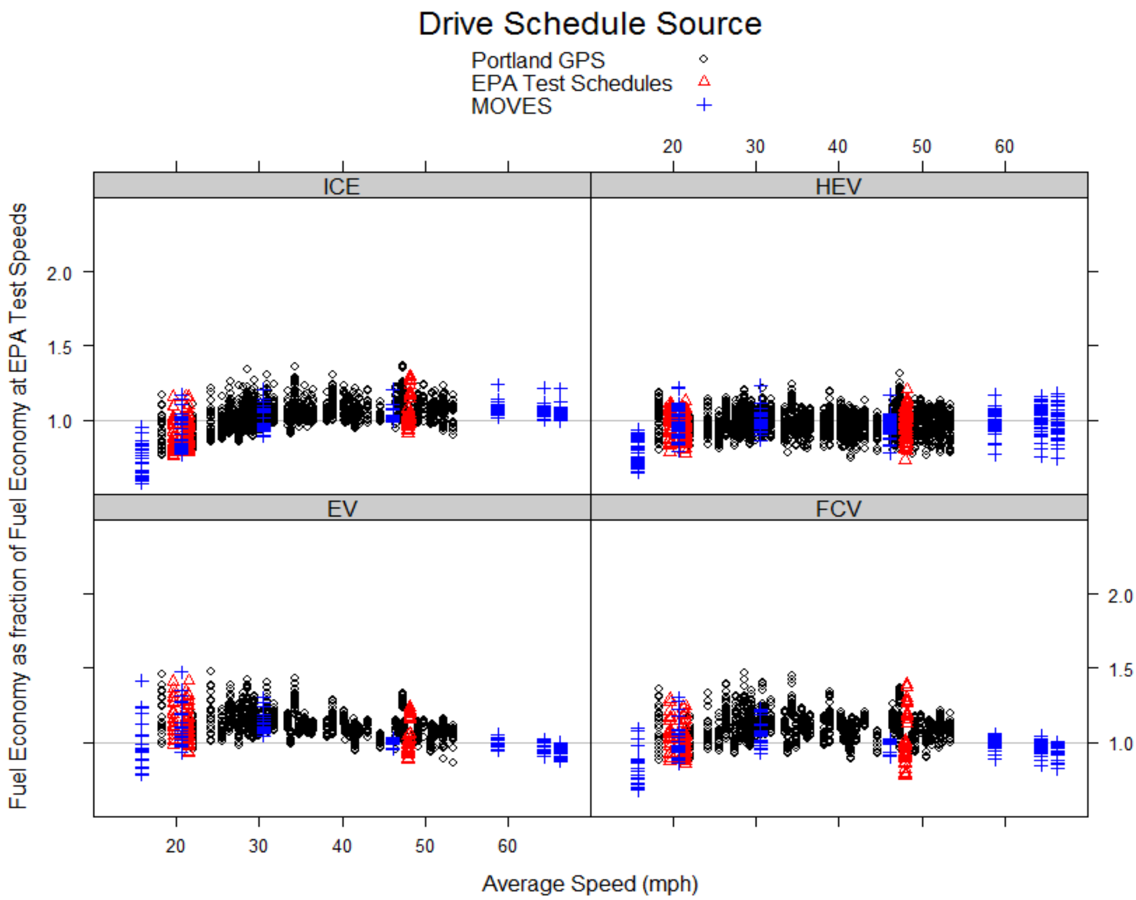

Figure 14. Fuel Economy (Normalied to Fuel Economy at EPA Reference Speed) vs. Average Speed by Powertrain Type, LD Vehicles for Freeways Only

Figure 15 shows the modeled fuel economy for HD vehicles, segmented by powertrain type and vehicle weight. As expected, lighter vehicles have better FE. These FE values trend upward with speed throughout the speed range, unlike for LD vehicles. There appears to be a discontinuity in the data around 30 – 35 mph, which is where the division between freeway and non-freeway driving schedules occurs (though both classes of driving schedules are applied on both facilities).

Figure 16 shows the same HD FE data, normalized to the assumed free-flow freeway MOVES HD driving schedule (see Table 4-6). We again see steadily increasing FE and a discontinuity around 30 – 35 mph. Figure 17 shows the HD FE values normalized to modeled FE at the EPA reference speed (as in Figure 14). The trends are essentially the same as Figure 16, but now high speeds around 60 mph are more efficient than the reference case.

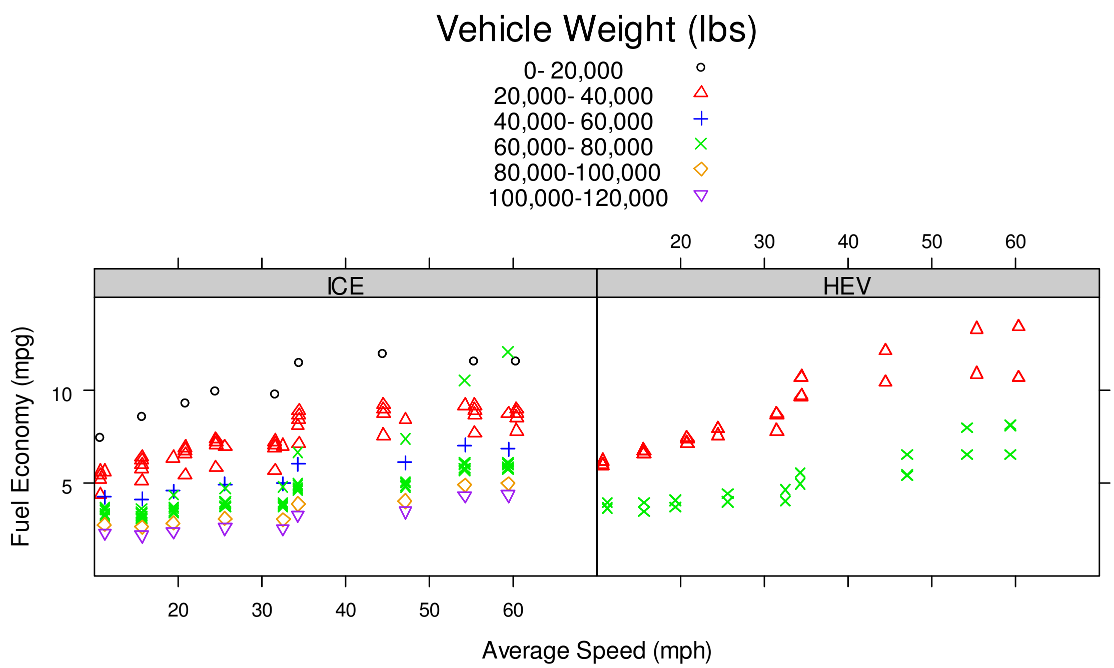

Figure 15. Fuel Economy vs. Average Speed by Powertrain Type with Weight Classes, for HD Vehicles

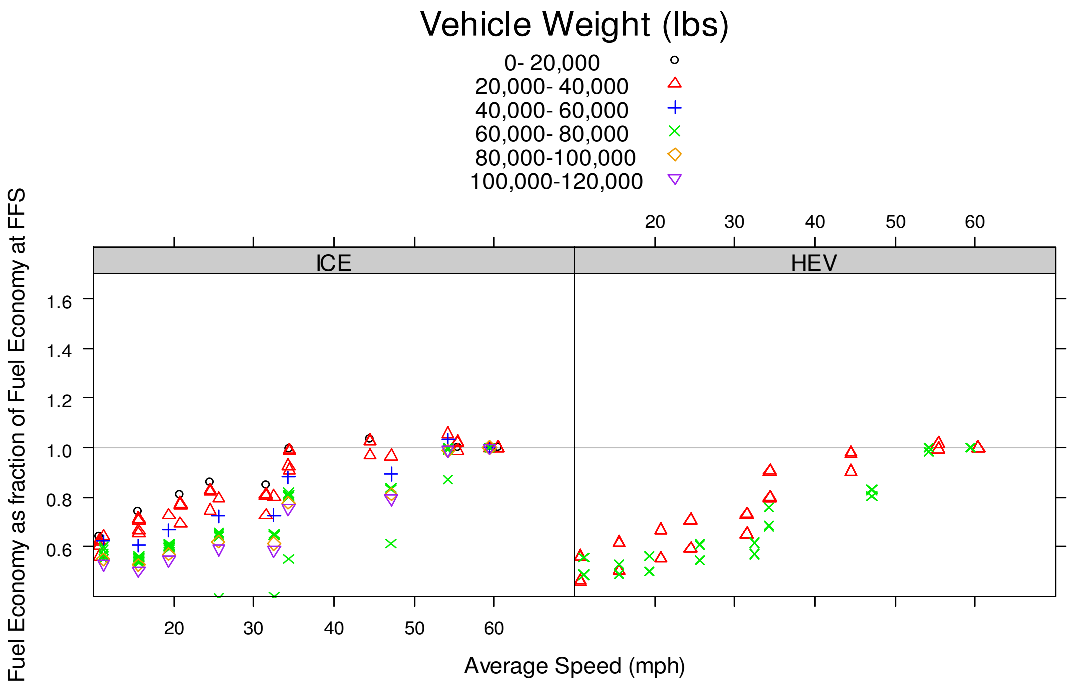

Figure 16. Fuel Economy (Normalized to Free-Flow Speed Fuel Economy) vs. Average Speed by Powertrain Type with Weight Classes, for HD Vehicles

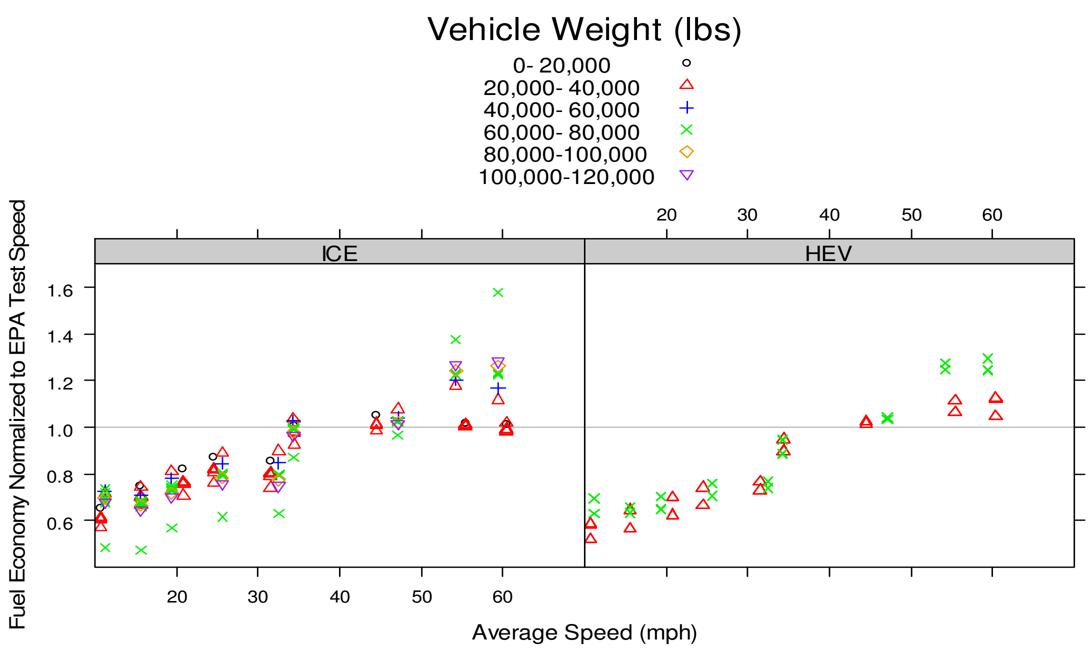

Figure 17. Fuel Economy (Normalized to Fuel Economy at EPA Test Speed) vs. Average Speed by Powertrain Type with Weight Classes, for HD Vehicles

5.4 Fuel Rate Normalization Differences

The normalization differences seen in the preceding section illustrate the importance of selecting a representative reference FE. Figure 18 presents a further comparison of these normalization approaches, with FFS-normalized FE plotted against EPA reference speed normalization in the top panels and EPA-adjusted-FE-normalized FE plotted against EPA reference speed normalization in the bottom panels (each for freeways and arterials, including all vehicles). Points along the diagonal line indicate agreement between the normalization methods, while points nearer to one axis than the other indicate higher normalized FE by that approach.

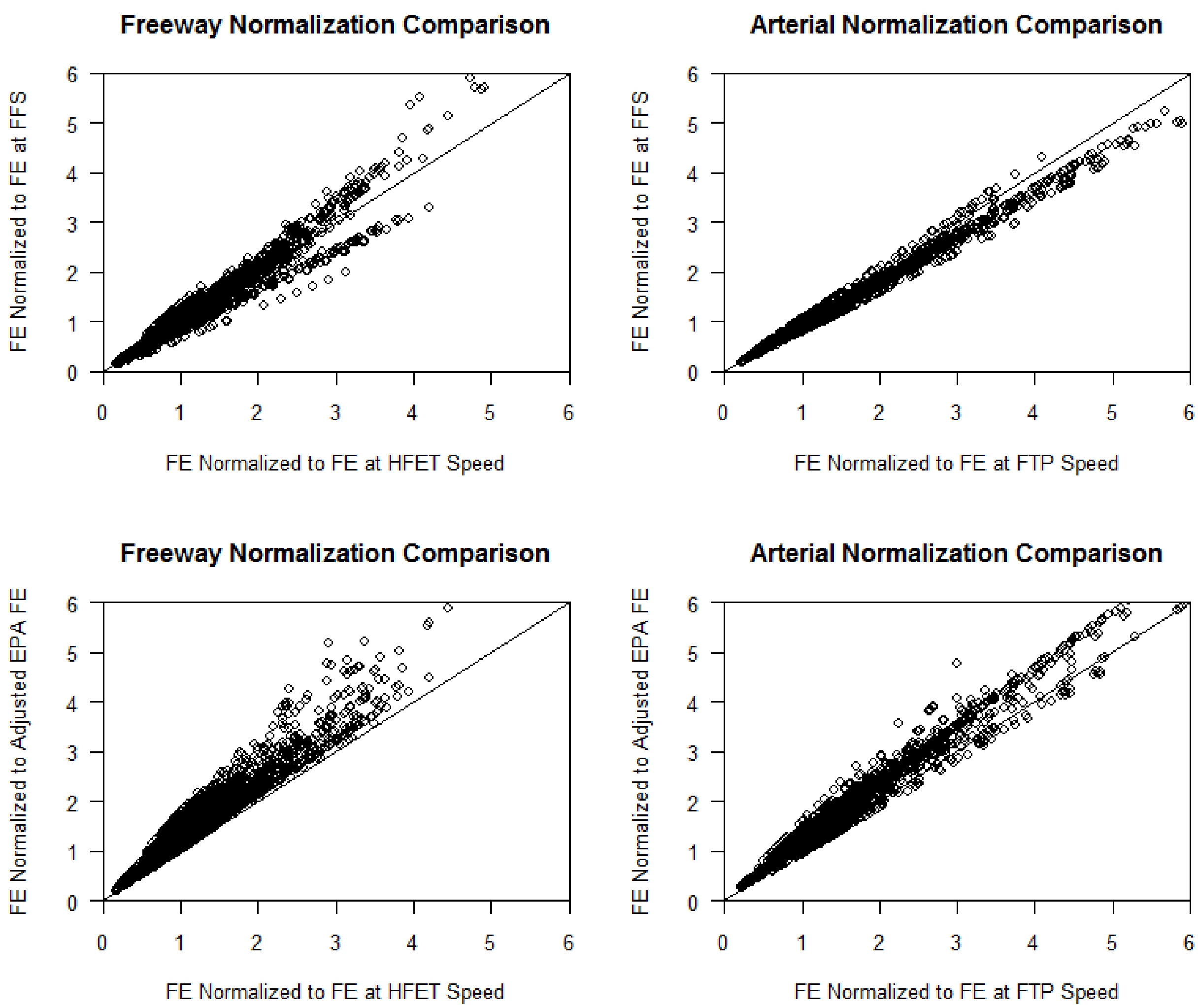

Figure 18. FE Normalized to FE at FFS and to EPA Adjusted FE versus FE Normalized to FE at EPA Reference Speeds

From Figure 18 we see that FFS normalization produces lower normalization values than the EPA reference speed approach on arterials, but no clear bias (and more spread) on freeways. Using the EPA adjusted FE leads to higher normalization values than the EPA reference speed approach. The EPA adjusted FE is lower than the PERE-modeled FE estimates because the EPA adjustment accounts for other factors besides speed profiles (road roughness, surface winds, grades, aggressive driving, etc.). The real-world drive schedules from MOVES account for traffic effects, but neglect these other factors.

5.5 Sensitivity of Fuel Economy in Congestion to Vehicle Characteristics

Fuel economy varies widely among vehicles for any one driving schedule, as illustrated in the preceding figures. This is due to variability in both fuel rates and VSP distributions of operating time, as demonstrated in Sections 5.1 and 5.2. In this section we investigate how vehicle characteristics influence the Fuel-Speed data points. Of particular interest is which vehicle characteristics impact the shape of the FSC – i.e., which characteristics most affect relative vehicle performance in congestion (as compared to free-flow conditions).

This assessment is made using the freeway “Congestion Impact” metric described in Section 4.8. For each vehicle attribute, a comparison of freeway Congestion Impacts is made for vehicles which are identical for every other attribute. Broadly, these sensitivity analyses show that vehicle weight, vehicle power, hybrid threshold, coastdown/road-load coefficients, and accessory load are the vehicle characteristics that have the most impact on the fuel economy effects of congestion. Individual vehicle characteristics are investigated in the following sections.

5.5.1 Vehicle Weight

Vehicle weight impacts fuel consumption by VSP bin and VSP bin distribution of operating time, as described in Section 5.2. Figure 19 shows the freeway Congestion Impact for vehicles of varying weight. The lines in this figure connect vehicles which are identical for all other attributes besides weight. From this figure we see that lower vehicle weights increase the relative fuel economy in congestion. This is logical since higher vehicle weights tend to have higher fuel consumption rates in each VSP bin. This figure excludes the potential relationship between RLC and vehicle weight, which is discussed below.

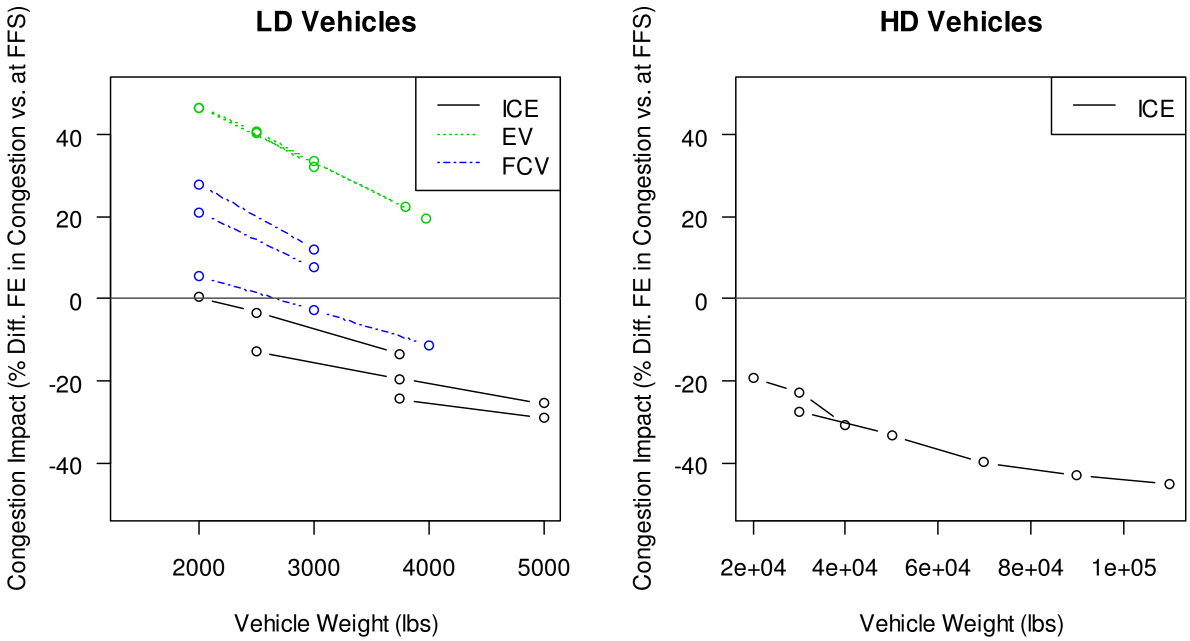

Figure 19. Vehicle Weight and Congestion Impact

5.5.2 Vehicle Power

Figure 20 shows the Congestion Impact of varying engine displacement for both LD and HD vehicles, again connecting vehicles which have all other attributes in common. Here it appears that increasing engine size decreases the FE performance of LD ICE vehicles in congestion, but has no large effect on HD ICE vehicles in congestion. ICE vehicles must continuously run the engine, even when the power is not needed, which consumes more fuel with larger displacement engines. Larger engines are also less efficient at low power requirements. HD vehicle power requirements are higher, so this is less of an issue for them than LD vehicles. HEV (both LD and HD) *improve* their relative FE in congestion with larger engine sizes. This is a logical effect because the HEV can utilize the larger ICE nearer optimum efficiency for high power loads but turn off the combustion engine during low-power driving events in congestion.

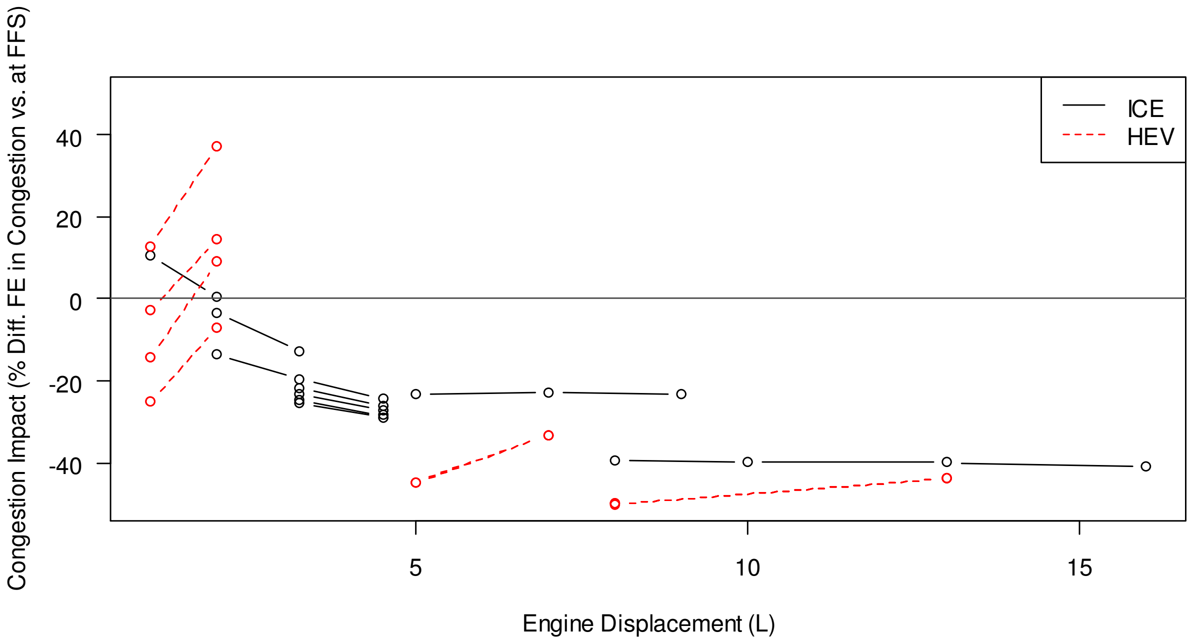

Figure 20. Engine Displacement and Congestion Impact

Figure 21 shows a similar comparison, but for the peak power of the electric motor in EV and HEV. Electric motor peak power has no major effect on the Congestion Impact for HEV or EV. Motors with higher peak power are not assumed to be any less efficient at lower power requirements. For very low power EV (below 50 kW peak power) the low motor peak power slightly reduces FE in congestion. Regenerative braking in PERE is limited by the peak power of the motor (operating as a generator), so lower peak power motors can have less power generation during decelerations in EV (most important during "stop-and-go" driving). In HEV, the internal combustion engine operation is primarily governed by the hybrid threshold, not the motor peak power. The motor peak power could affect the hybrid threshold through the amount of energy generated by regenerative braking, but that is not included in the sensitivity shown in Figure 21.

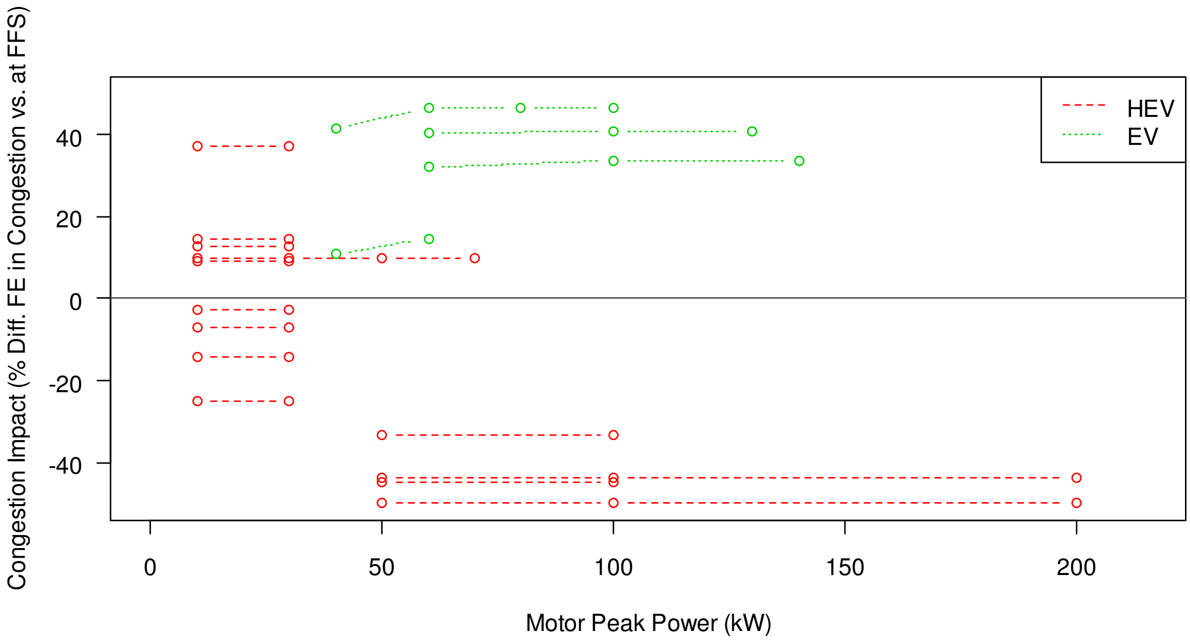

Figure 21. Motor Peak Power and Congestion Impact

Figure 22 shows the Congestion Impact of varying fuel cell power ratings in FCV. Here increasing fuel cell power rating decreases FE in congestion. This is similar to the effect of ICE size, since in PERE the efficiency of fuel cells follows a fitted curve where efficiency decreases at lower power loads (with respect to the power rating of the fuel cell). In other words, larger ICE (in conventional vehicles) and fuel cells are operating less efficiently in congested driving conditions.

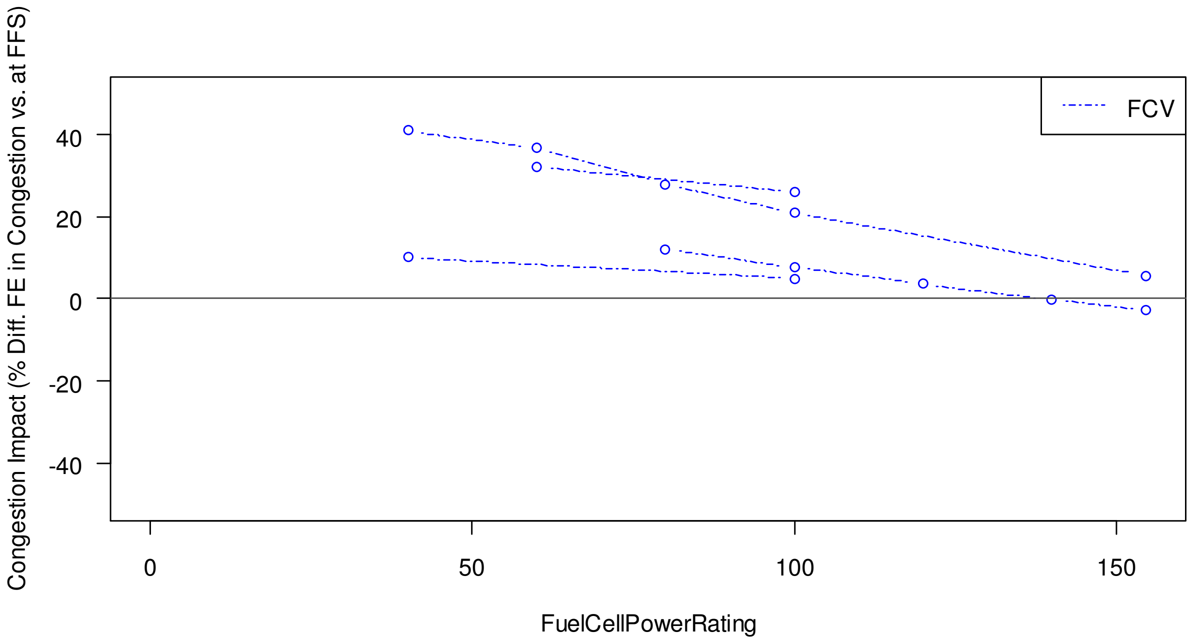

Figure 22. Fuel Cell Power and Congestion Impact

Figure 23 shows combined total peak power (from the combustion engine, electric motor, and fuel cell, as appropriate) and Congestion Impact. Lines connect modeled vehicles with all non-power-related attributes the same. LD ICE vehicles and FCV have decreased fuel efficiency in congestion with more peak power, as indicated in Figure 20 and Figure 22. EV have slightly better performance in congestion with higher peak power motors when the peak power is low, but the effect disappears at higher peak powers as in Figure 21. The effect of total peak power on HEV performance in congestion depends on which powertrain element is being adjusted. Increasing the electric motor peak power does not affect congestion performance (Figure 21), whereas increasing the ICE power improves relative congested FE (Figure 20).

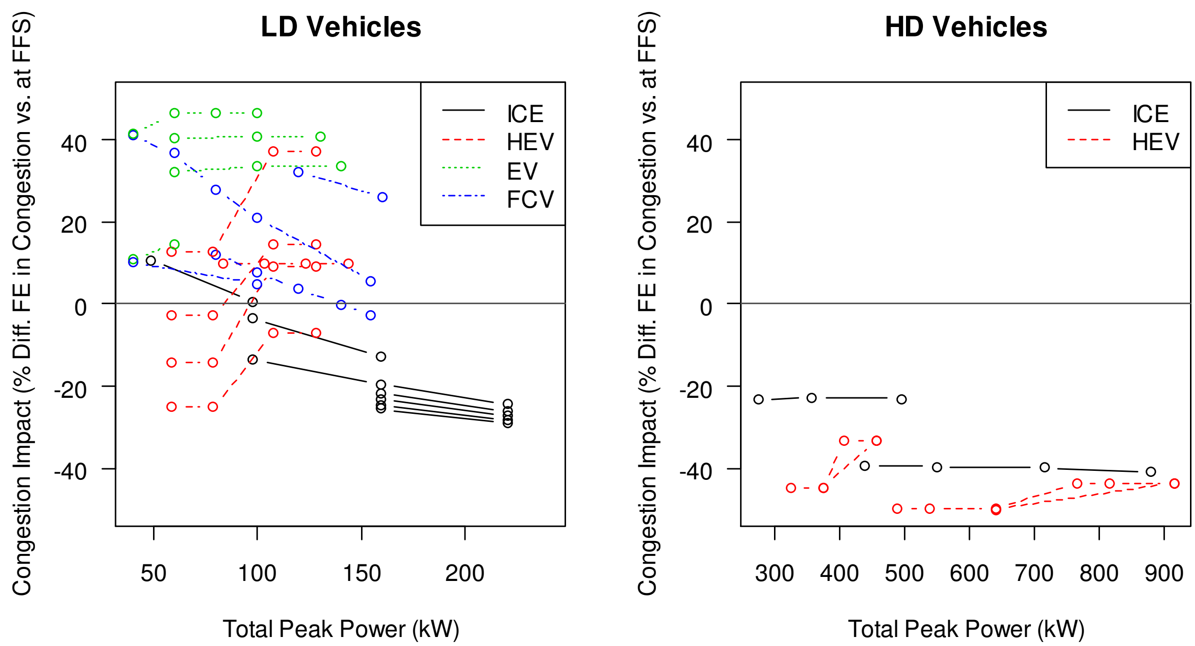

Figure 23. Total Peak Power and Congestion Impact

Figure 24 shows the Congestion Impact of varying vehicle specific peak power. Vehicle specific power is simply the total peak power divided by the vehicle mass. Lines in Figure 24 connect vehicles with all attributes the same except for vehicle weight and those related to power production (engine/motor power, etc., as in Figure 23). The results are much more chaotic than Figure 23. Specific power can increase because of greater peak power or because of lower vehicle weight, and these will each have different influences on the Congestion Impact. Changing vehicle weight causes the CI to increase with specific peak power and changing peak power causes the CI to decrease with increasing specific peak power. Clearly, specific power is not a good indicator of expected congestion impacts for vehicles.

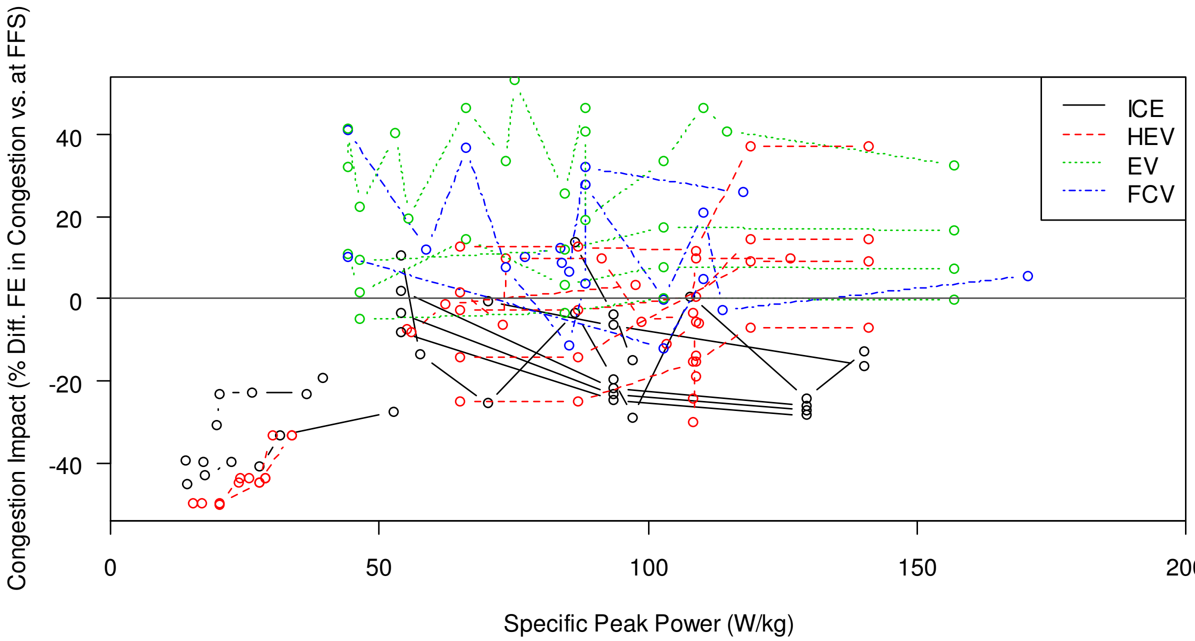

Figure 24. Specific Peak Power and Congestion Impact

5.5.3 Hybrid Threshold

Hybrid threshold is the vehicle power requirement at which the internal combustion engine is required in an HEV. In PERE, for power requirements below the hybrid threshold the vehicle is run off the battery power alone, and for power requirements above the threshold, run off the ICE alone (unless the power requirement exceeds the ICE peak power, in which case the motor is used as power assist). Figure 25 shows the effect of varying hybrid threshold on Congestion Impacts. Increasing the hybrid threshold increases the relative fuel efficiency in congestion for LD vehicles – which is logical since in congestion more vehicle operating time is low-power activity. But hybrid threshold has no noticeable effect on HD vehicles. This is likely because the hybrid threshold range tested is low with respect to the power requirements of HD vehicles. There is little information available about the likely hybrid threshold of HD vehicles, and a more in-depth analysis of the potential hybridization of the HD vehicle fleet is beyond the scope of this study (see Delorme et al.(2010) for research in this area).

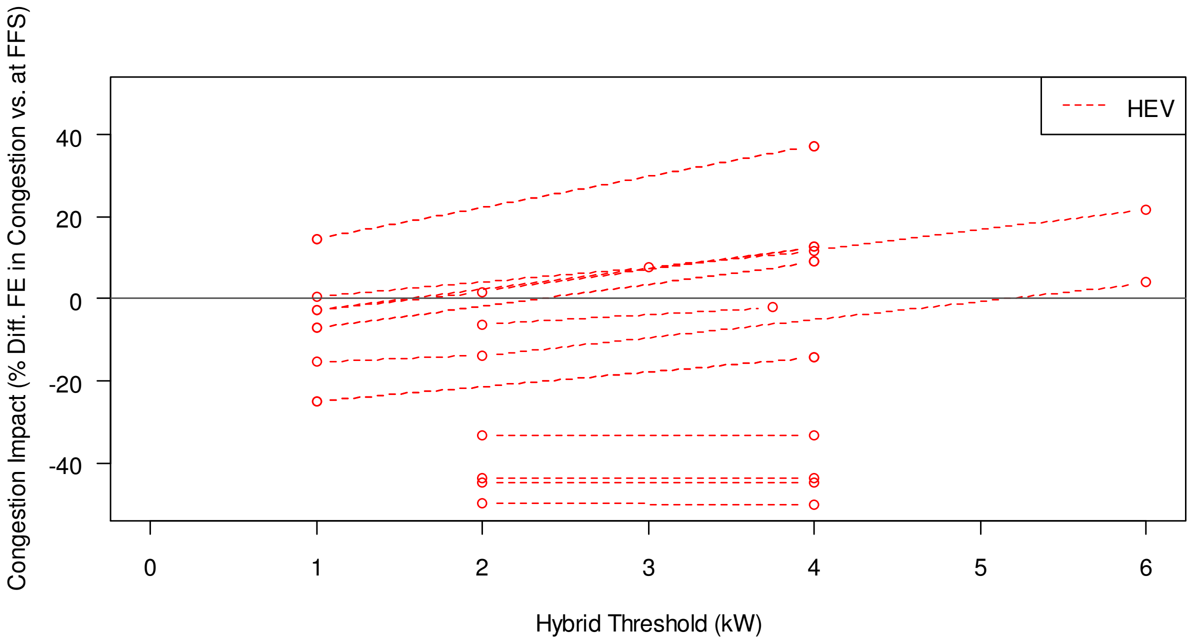

Figure 25. Hybrid Threshold and Congestion Impacts

The key consideration related to hybrid threshold is the State of Charge (SOC) of the HEV battery. In PERE it is suggested that the hybrid threshold is adjusted to achieve a zero change in SOC over the course of the driving schedule – a process referred to as State of Charge balancing (so that total motor contribution does not exceed the generated battery power). But in this study PERE is used not for modeling individual driving schedules but to generate average fuel rates by VSP bin for composite driving schedules – which are not necessarily realistic in their composite form. For this reason SOC balancing was not performed. Instead, we base our hybrid thresholds on research from the literature (Nam & Giannelli 2005).

The true hybrid threshold during vehicle operation would depend not just on vehicle characteristics but also on driving patterns and environmental conditions. Different combinations and orders of driving conditions (idling, "stop-and-go" traffic, high-speed freeway travel, etc.), in different environmental conditions (grades, surface winds, etc.) over the course of a trip will influence the true hybrid threshold. Without know these conditions, we have based our modeled values on the literature. There is the possibility that extended driving in certain traffic conditions will result in higher or lower hybrid thresholds than those modeled.

The hybrid effects described in this section are all for gas-electric HEV. Several fuel cell hybrids were modeled as well (FCV with batteries and electric motors). These fuel cell hybrids were found to be neither more nor less sensitive to congestion than non-hybrid fuel cell vehicles (as indicated by the Congestion Impact). For the remainder of this study all FCV are considered together as one powertrain type, without differentiating the hybrids.

5.5.4 Road Load Coefficients

The Road Load Coefficients (RLC – also known as the coastdown coefficients) describe various vehicle attributes related to the external power requirements. They are based on aerodynamic drag, rotational inertia, and rolling resistance. Greater RLC decrease estimated fuel efficiency by increasing the expected driving power requirements. Broadly, the RLC tend to increase with weight (see the equations for estimating RLC from vehicle weight for LD vehicles (Koupal et al. 2005) and HD vehicles (Nam & Giannelli 2005)). This is due to factors such as less aerodynamic body shapes and bigger wheels in larger (and typically heavier) vehicles. As an example, the recommended default RLC for input to the MOVES model are about 50% higher for passenger trucks than for passenger cars (U.S. Environmental Protection Agency 2010).

Changing the RLC from the passenger car to the passenger truck values (based on EPA documentation) between modeled vehicles #17 and #18 (with all other parameters the same) increases the Congestion Impact from -20% to -4%. Congestion Impact increases (is more positive) with RLC because the RLC have a bigger FE-reducing impact on high speed travel than low speed travel (as discussed in Section 5.2). This effect can be confirmed by inspection of Equation 3, where the RLC are coefficients to speed terms. Less aerodynamic vehicles perform proportionally more poorly at high speeds, and thus are comparatively more efficient at lower speeds.

Since the Congestion Impact increases with RLC but decreases with vehicle weight, and the RLC trend with vehicle weight, these factors will somewhat offset each other in actual vehicles. We can see this effect mathematically in Equation 3, where the RLC are in the numerator and the vehicle mass is in the denominator of the first three terms. If the RLC and mass are positively correlated, each will work to offset the effect of the other. The worst case vehicle attributes for Congestion Impact are a heavy vehicle that is aerodynamic and has efficient (low-resistance) tires – i.e. high mass and low RLC. The best vehicle attributes for Congestion

Impact (though not overall efficiency) is a light, "boxy" vehicle which has low weight impacts in traffic congestion but is inefficient at high speeds.

5.5.5 Fuel and Transmission Types

Diesel engines are generally more fuel efficient than equivalent-powered gasoline engines. Figure 26 shows the Congestion Impact of the two vehicles that were modeled with engines of each fuel type. Both have better relative fuel efficiency in congestion using diesel engines than gasoline engines. In other words, diesel engines have both better overall fuel economy and less sensitivity to congestion.

Figure 26 also shows the Congestion Impact for passenger cars modeled with different transmissions types. PERE models both manual and automatic transmission types (with assumed shift points for each). There are only minor shift point differences between the two, however. From this figure we see that the effect of transmission type on relative fuel economy in congestion is negligible.

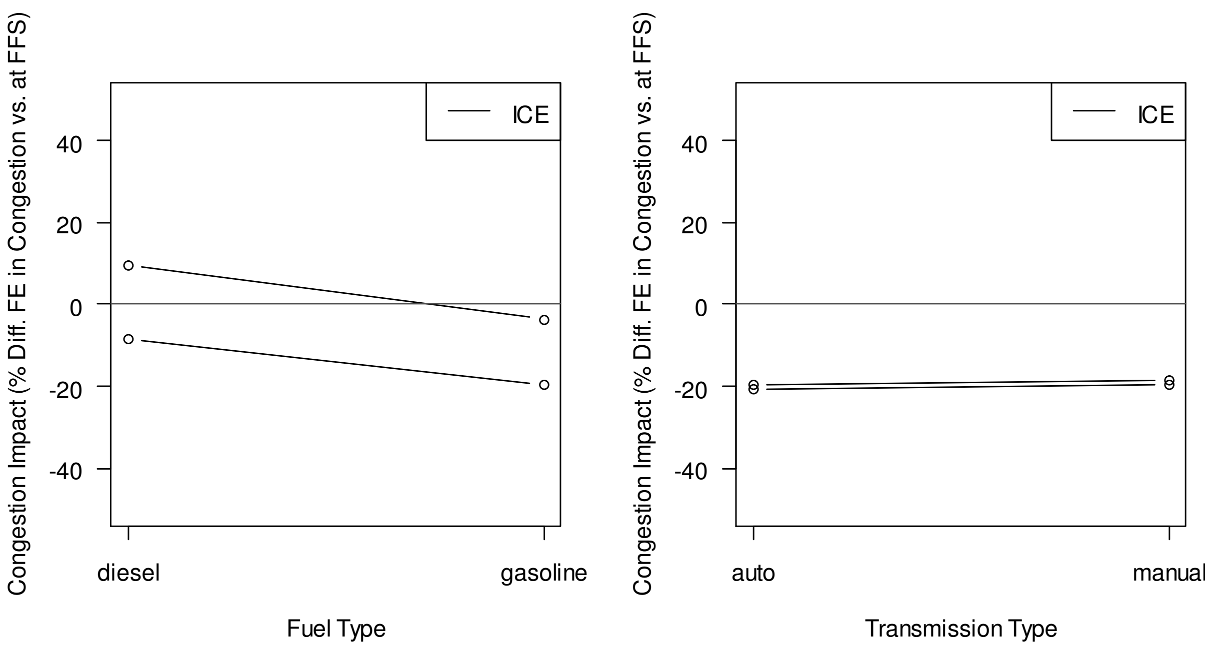

Figure 26. Congestion Impact with Fuel Type and Transmission Type

5.5.6 Engine Efficiency

Figure 27 shows the effect of varying the engine indicated efficiency on Congestion Impact. The engine indicated efficiency is the thermal efficiency of the engine – its ability to convert fuel energy to mechanical energy. Greater efficiency tends to have poorer congestion performance, but the effect is minimal. This is due to the greater efficiency benefitting high-power vehicle activity (during high speed driving) proportionally more than low-power congested driving.

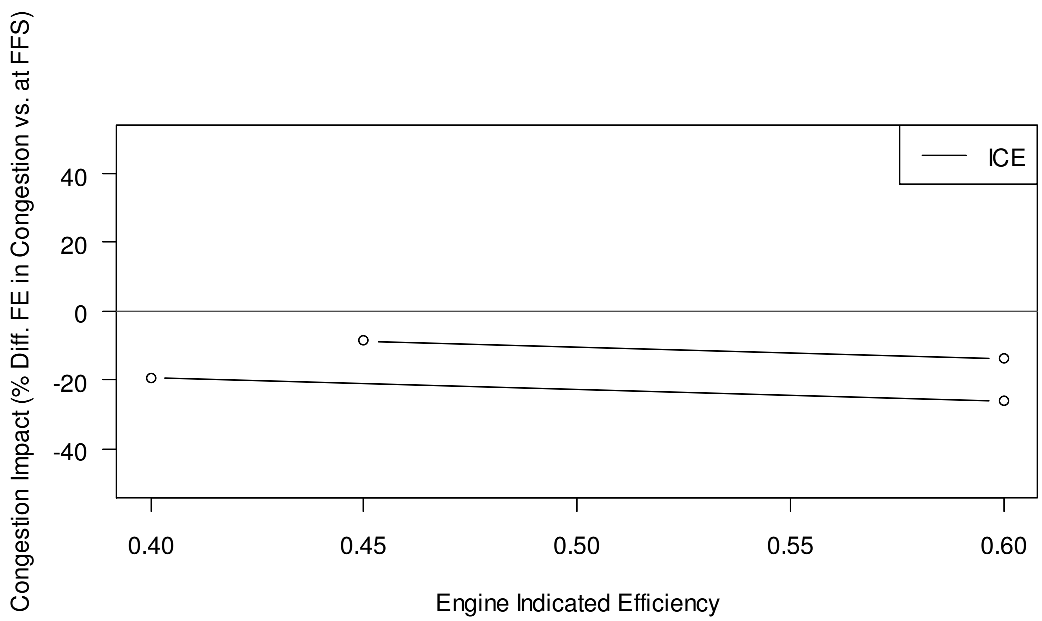

Figure 27. Engine Indicated Efficiency and Congestion Impact

5.5.7 Accessory Loads

Figure 28 shows the Congestion Impact for varying accessory power loads. The range of accessory loads tested is based on previous research, which used maximum thermal cooling electrical loads of 3kW, in addition to the baseline auxiliary loads (Farrington & Rugh 2000). A wider range was tested for HD vehicles because of additional accessories. Higher accessory loads are associated with poorer relative fuel efficiency in congestion for all powertrain types. This is expected, since the relatively small accessory loads are a greater share of total vehicle power requirements during low-speed (low-power) driving. Similarly, the effect of accessory loads is bigger for LD vehicles than for HD vehicles, since the accessory loads represent a greater fraction of total power requirements for LD vehicles.

Higher accessory loads affect the performance in congestion for advanced vehicles (HEV, EV, FCV) more than conventional (ICE) vehicles. This is seen by the steeper downward slopes of the curves in Figure 28 for non-ICE vehicles. This result agrees with previous research, where more fuel efficient vehicles were found to be disproportionately affected by air conditioning power loads (Farrington & Rugh 2000).

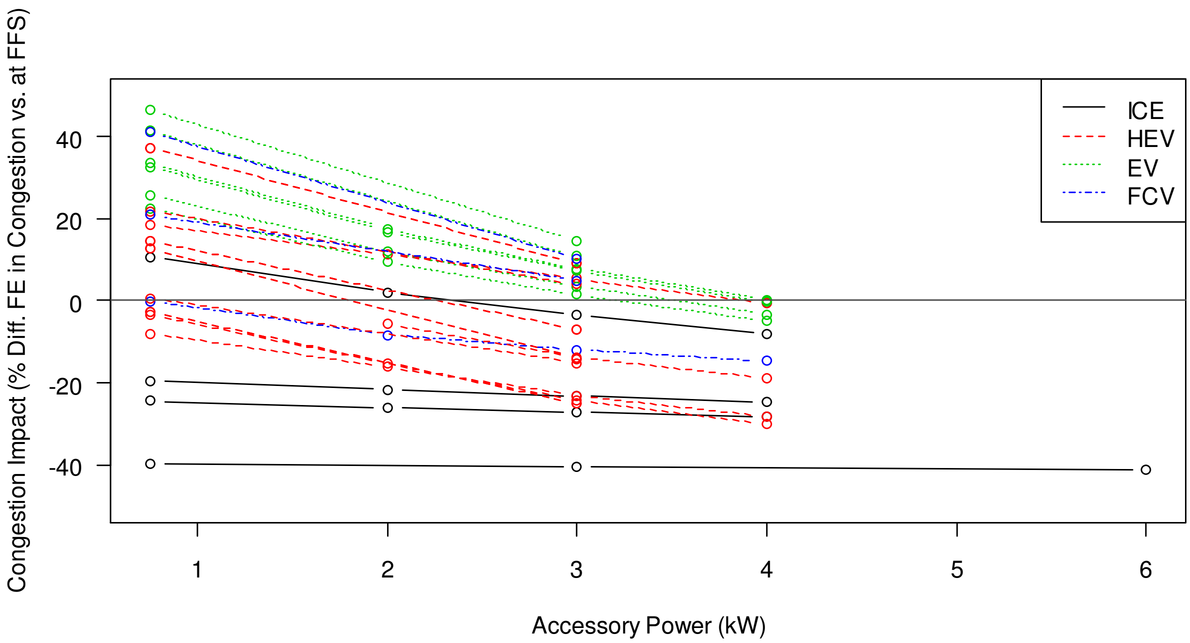

Figure 28. Accessory Power Load and Congestion Impact

5.5.8 Model Year

Figure 29 shows the trends in Congestion Impact for vehicles tested over varying model years. The impact of model year is reflected in PERE by embedded trends in engine mechanical/friction losses and peak torque (for ICE). Other vehicle parameters do not vary with model year because they are custom input for each model run. Based on the trends in the PERE modeling, vehicles are not only getting more efficient overall, but also getting proportionally more efficient in congestion (i.e. the Congestion Impact is increasing) – though the effect is small. This is because for many vehicles the engine losses represent a smaller portion of total losses at higher speeds – where aerodynamic losses increase (Delorme et al. 2010). For the vehicles shown in Figure 29, the Congestion Impact is increasing by about 2% for each 10 model years for LD vehicles, and by less than 0.5% for each 10 model years for HD vehicles. The improvements over time in engine operating efficiency will reduce the expected negative impacts of traffic congestion on fuel efficiency – particularly for LD vehicles. The engine efficiency reflected in Figure 29 relates to friction and mechanical losses – and should not be confused with the thermal efficiency in Figure 27.

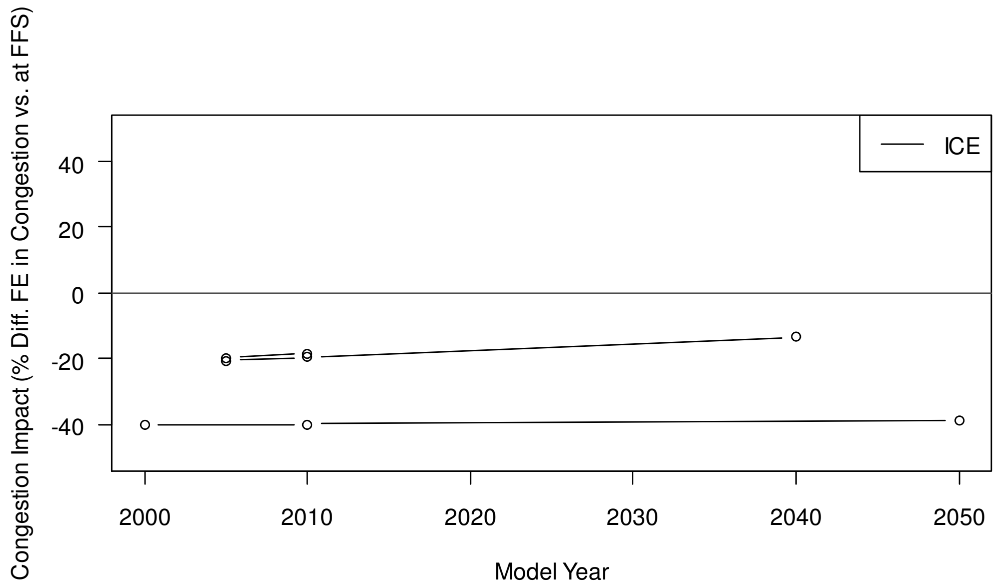

Figure 29. Model Year and Congestion Impact

5.5.9 Arterial Congestion Impacts

The preceding figures look at how the freeway Congestion Impact varies with certain vehicle characteristics. For almost all vehicle characteristics the arterial Congestion Impact shows the same trend, but with less difference since the arterial speed difference between assumed free-flow and congested conditions is smaller. The main exception is for ICE displacement in HEV, where the Congestion Impact improvement seen in Figure 20 no longer exists. Instead, different HEV have either slightly increasing or decreasing Congestion Impacts with varying ICE displacement on arterials.

5.5.10 Vehicle Characteristics Sensitivity Summary

The preceding sections looked at varying vehicle characteristics to see which most affect the relative fuel economy in congestion (as compared to free-flow conditions). This is different from which vehicle characteristics impact overall fuel economy, and sometimes shows opposite effects. For example, vehicle parameters which mostly improve FE at higher speeds (decreased drag coefficients, for example) will result in poorer *relative* FE in congestion.

The vehicle characteristics which most affect the Congestion Impact (and so are most likely to influence the shape of the FSC) are vehicle weight, engine displacement/fuel cell power, hybrid threshold, accessory power load, and the Road Load Coefficients. Vehicle weight, engine power, and RLC vary by vehicle, and so will depend on the purchasing habits of consumers. Compared to ICE cars, ICE passenger trucks/SUV's tend to have more weight and engine power (which reduces performance in congestion), but also higher RLC (which improves *relative* performance in congestion). For HEV the motor and battery characteristics combined with the driving patterns will determine the true hybrid threshold. Assuming HEV improve over time to allow higher hybrid thresholds, the relative HEV performance in congestion will improve as well. High accessory power loads notably degrade the relative efficiency in congestion for fuel efficient vehicles. Improvements over time such as advanced glazings and cabin ventilation (Farrington & Rugh 2000) can thus increase the relative FE in congestion for advanced vehicles by reducing accessory loads.

5.6 Fuel-Speed Curves

In this section we use the modeled fuel economy-average speed data points (as in Figure 11) to fit Fuel-Speed Curves for each modeled vehicle. As described in Section 4.6, we fit the FSC to the modeled data using an exponentiated 4th-order polynomial functional form (Equation 6), following previous emissions modeling research. For each vehicle, separate fits are made for freeway and arterial driving schedules. Freeway driving schedules include MOVES and OR-217 sources for LD vehicles and only MOVES sources for HD vehicles (since the OR-217 driving traces were collected in LD vehicles). Arterial driving schedules are sourced from MOVES only.

Driving schedule 101 (see Table 4-2) was removed from the FSC fits because of its impact on HEV FSC. This driving schedule is for very low speed driving (average speed of 2.5 mph) and produces fuel consumption rates of nearly zero for some of the HEV (which are expected to run entirely off the battery during this activity). This leads to extremely large FE estimates which heavily influence the fitted shape of the FSC. Furthermore, this driving schedule is well below the speeds modeled in GreenSTEP. Driving schedule 101 is also excluded from all further modeling in this study.

Two example fits for freeway FSC are shown in Figure 30. Here, two LD-vehicle fitted FSC are shown along with the base data (using the MOVES and OR-217 driving schedules). The example low congestion efficiency ICE vehicle is #15 (see Appendix B), a heavy, high-powered gasoline-fueled passenger car. The fit has an approximate R-squared value of 0.96 (calculated as Nagelkerke's generalized R-squared). The example high congestion efficiency ICE vehicle is #20 (see Appendix B), a diesel-fueled passenger truck with moderate power and weight. This fit has a generalized R-squared value of 0.86.

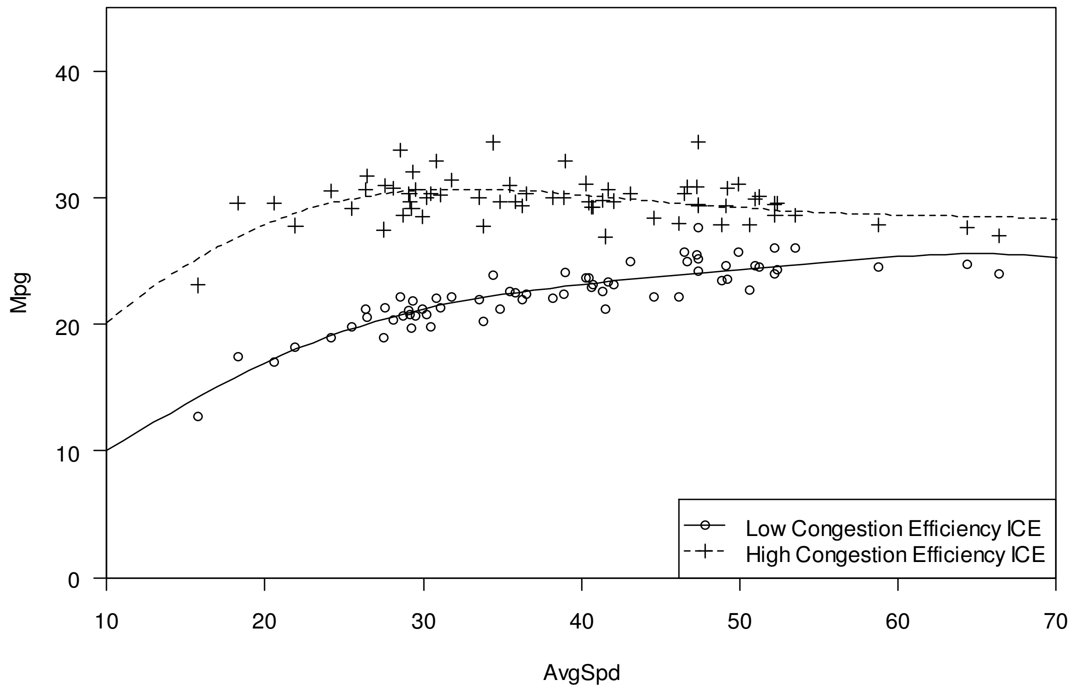

Figure 30. Example FSC Fits for LD Vehicles

The fitted freeway FSC parameters for all modeled vehicles are presented in Appendix D. Figure 31 shows fitted freeway FSC for all modeled LD vehicles segmented by powertrain type. There is a variety of FE values and FSC shapes, as expected from Figure 11. Generally, ICE vehicles have varying relationships with speed (positive or negative) for speeds above 30 mph, and decreasing FE at lower speeds below 30 mph. HEV are less sensitive to congestion, with some vehicles' FE not decreasing until below 20 mph. Some HEV have about the same FE performance as ICE vehicles – particularly those with low hybrid thresholds. LD EV and FCV both show increasing FE with decreasing speed in Figure 31, down to about 20-30 mph.

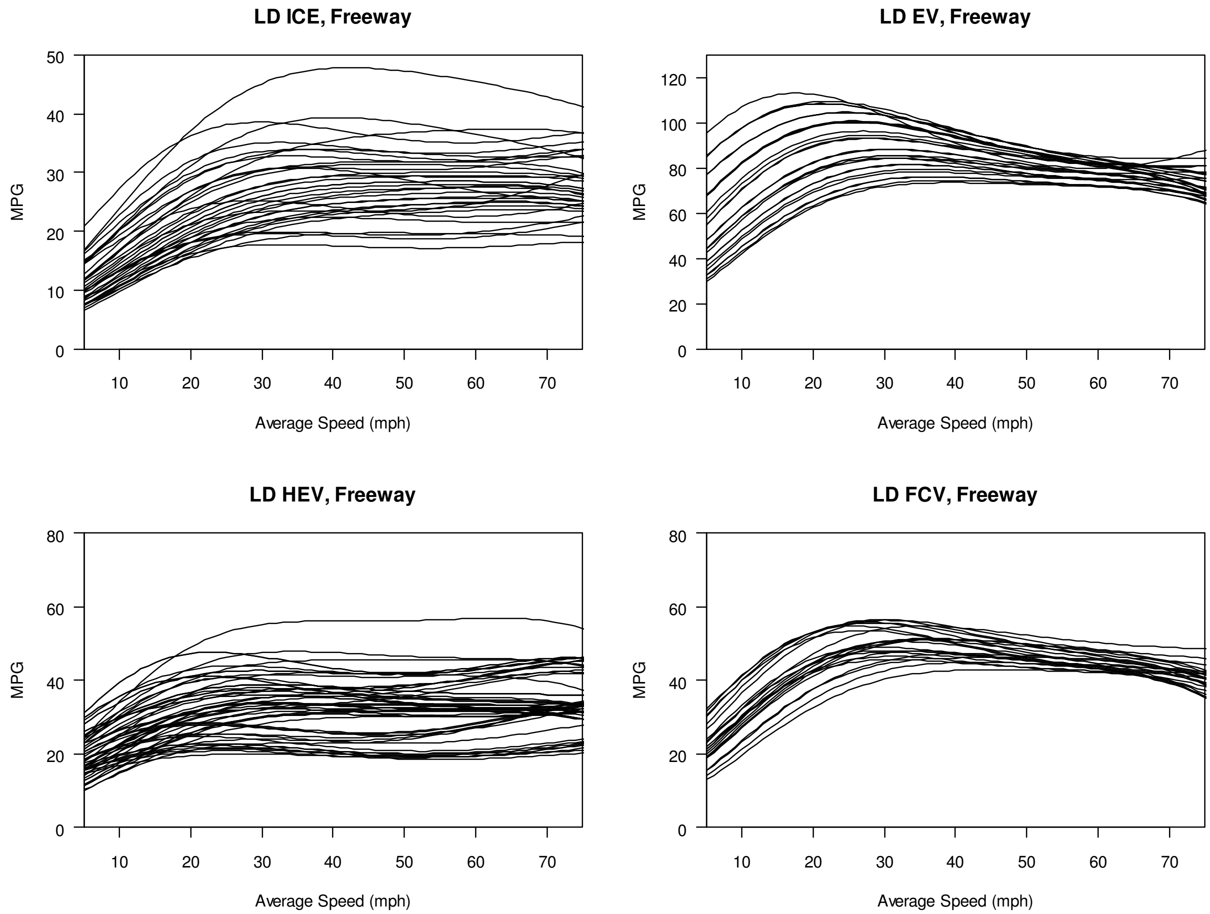

Figure 31. Modeled Individual FSC for LD Freeway Vehicles by Powertrain Type

Including the on-road vehicle data from OR-217 provides much more data points for FSC estimation than only using the MOVES driving schedules. Since they were gathered locally, the OR-217 speed data are expected to be representative of Portland freeway driving conditions. But they were collected on a single roadway with only a handful of passenger cars, and so will be less representative for a broad range of roadway conditions and vehicles (which MOVES drive schedules are designed to represent).

Figure 33 compares the percent difference in FSC that result from using MOVES and OR-217 data together with the FSC based on MOVES driving schedules alone, for all vehicles on freeway facilities. Values above the line indicate better FE from including OR-217 data. Including the OR-217 leads to predominantly higher FE overall. This can be expected from the comparisons in Sections 5.2.1 and 5.2.2 which showed overall more aggressive driving in the

MOVES driving schedules. The OR-217 driving speed data are included here for FSC creation because GreenSTEP is a locally-targeted modeling tool for Oregon.

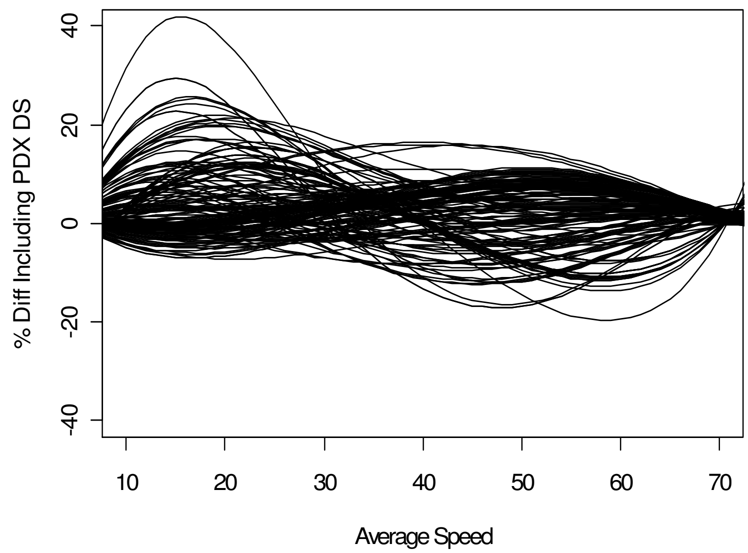

Figure 32. Comparison of FSC Including and Excluding OR-217 Speed Data, as Percent Difference in FE

6 Recommended Fuel-Speed Curves for GreenSTEP

This section describes the recommended FSC for GreenSTEP implementation. Given the range of plausible curve shapes shown in Section 5, the recommended approach is to use minimum/maximum sensitivity curves as the bounds of congestion effects. Interpolating between these normalized extreme curves provides speed-based FE adjustment factors to calculate congestion effects. The interpolation distance is based on a new model input, "Congestion Efficiency", which describes the performance of the vehicle in congestion with respect to "extreme case" vehicles. Congestion Efficiency ranges from 0 for poorest performance to 1 for maximum relative efficiency performance. Using Congestion Efficiency CE and upper and lower bound *normalized* FSC with curve fit parameters $\alpha_{U,i}$ and $\alpha_{L,i}$, respectively, the interpolated normalized FSC curve is calculated

$$FE = CE \cdot \exp\left(\sum_{i=0}^{4} \alpha_{U,i} v^i\right) + (1 - CE)\exp\left(\sum_{i=0}^{4} \alpha_{L,i} v^i\right) \quad . \qquad (9)$$

The determination of CE in scenario analysis is based on the sensitivities shown in Section 5.5. This approach avoids introducing numerous vehicle modeling parameters to the GreenSTEP model, while still allowing some assumptions about the future vehicle fleet to inform the congestion adjustment values. In addition to Congestion Sensitivity, FE adjustments for different advanced vehicle types require additional input assumptions regarding the LD vehicle fleet mix, as described below.

6.1 Selecting Extreme-Case Fuel-Speed Curves

For each of five vehicle/powertrain combinations (LD ICE, LD HEV, LD EV, LD FCV, and HD ICE) the Congestion Impact metric (see Section 4.8) is used to identify the modeled vehicles with the most and least relative efficiency in congestion. Because of uncertainty in likely vehicle characteristics, HD HEV are not included in this or further analysis. Additionally, modeled vehicle #149 (see Appendix B) is excluded from consideration due to unrealistic estimated RLC.

Figure 33 illustrates the selection process for extreme-case LD vehicles on freeways. For each vehicle-powertrain type combination the modeled vehicles are ranked according to their Congestion Impact. The best and worst performing vehicles in congestion are then selected as the first and last in the ranking. This selection process was completed separately for freeway and arterial driving schedules and Congestion Impacts. Some pairs of vehicles had overlapping FSC and equivalent Congestion Impacts – when the varied parameter between them does not affect the shape of the FSC (such as motor peak power for vehicles 122 and 123 – as is demonstrated in Figure 21). In this case the selected vehicle was arbitrary, since the resulting FSC would be the same. Figure 34 shows the same process for LD vehicles on arterials, and Figure 35 shows the selection process for HD vehicles on each facility.

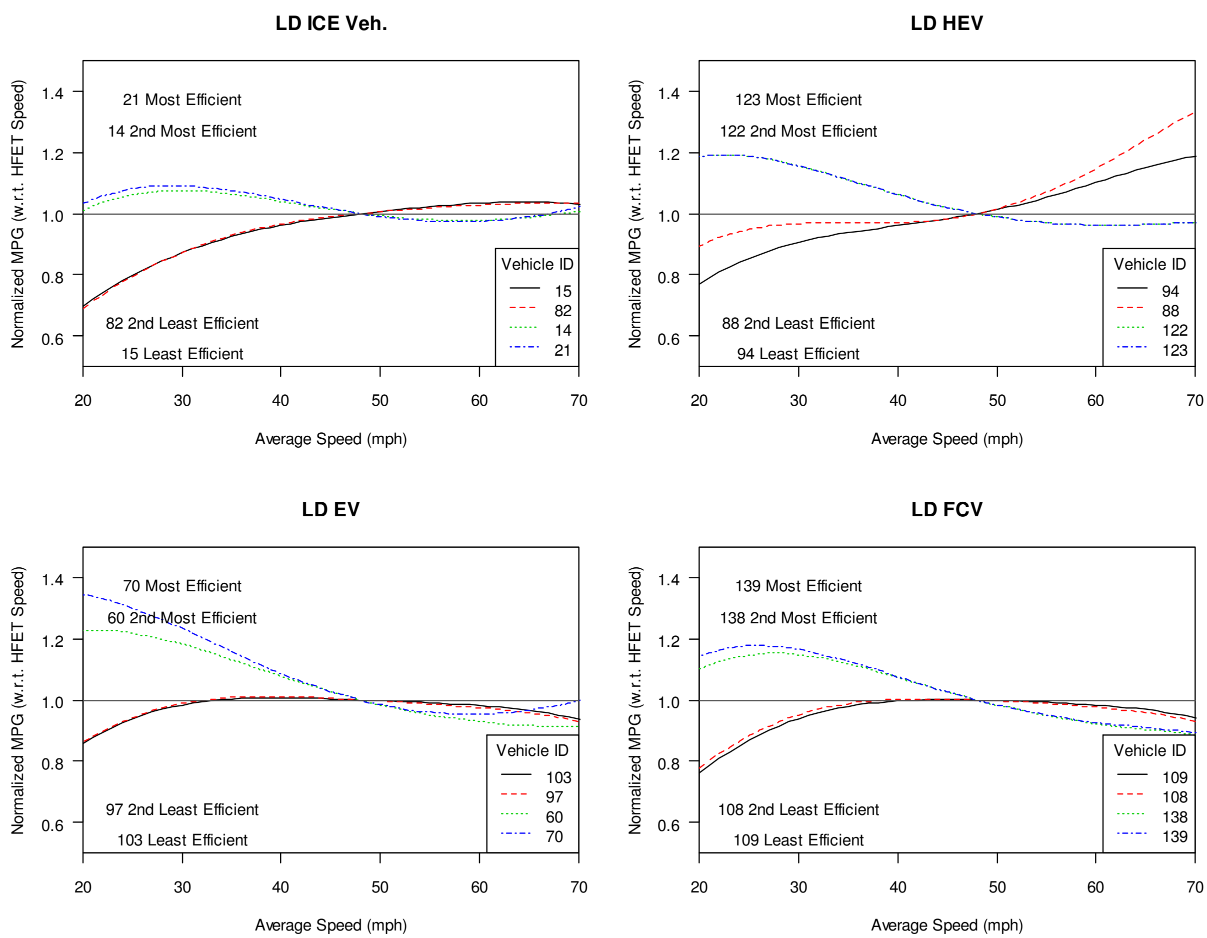

Figure 33. Selection of Vehicles for High/Low-Efficiency Reference LD Freeway FSC

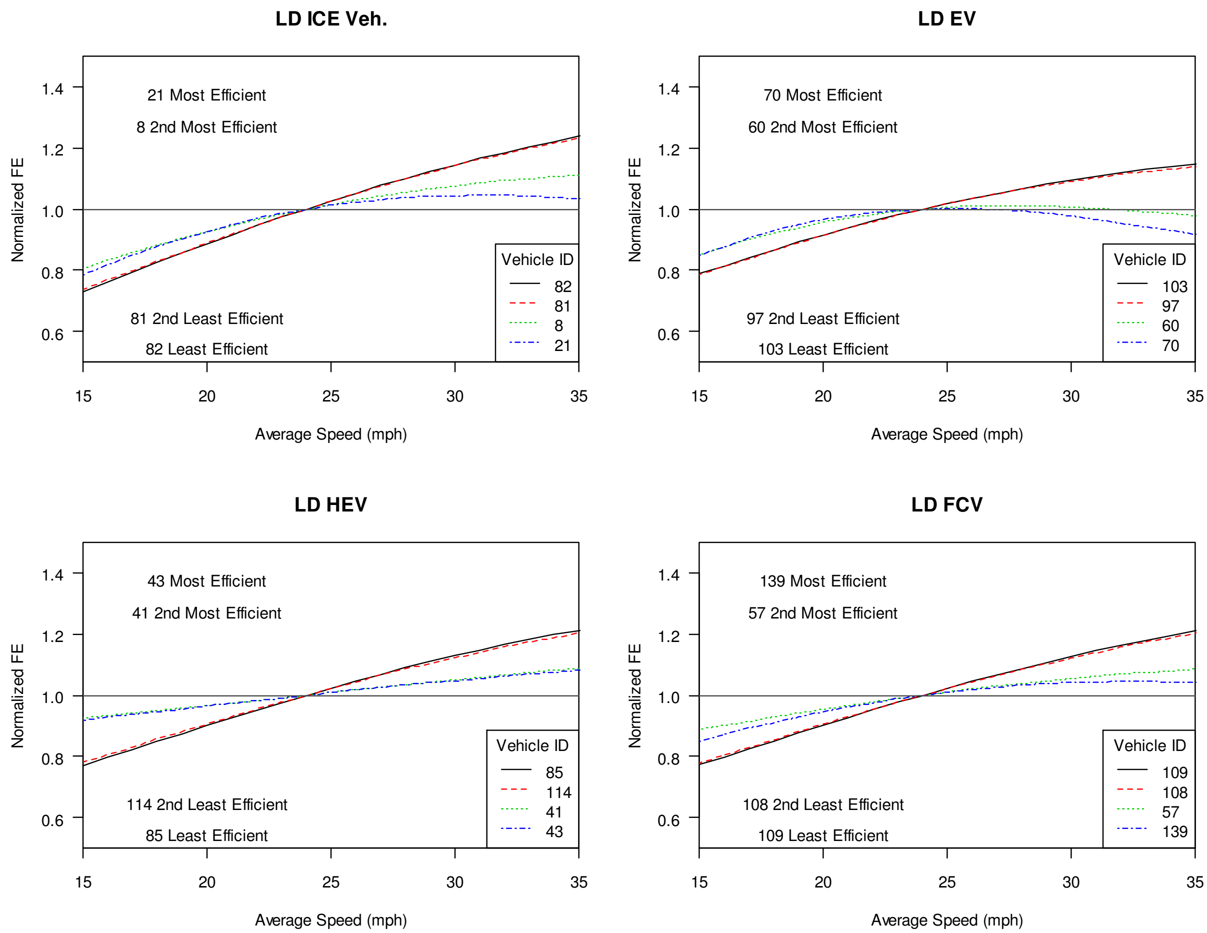

Figure 34. Selection of Vehicles for High/Low-Efficiency Reference LD Arterial FSC

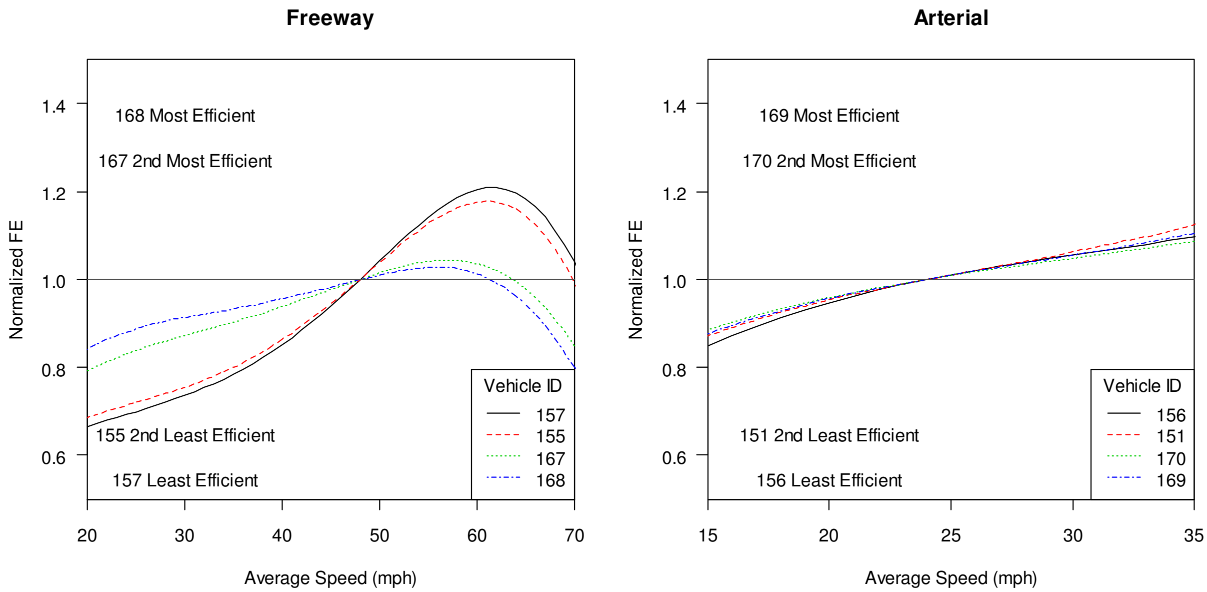

Figure 35. Selection of Vehicles for High/Low-Efficiency Reference HD FSC

The selected vehicle IDs for extreme-case FSC are shown in Table 6-1 (see Appendix B). The key characteristics for the LD vehicles are also shown in Table 6-2. The high- and low-performing normalized FSC for these vehicles are shown in Figure 36 for freeways and Figure 37 for arterials. The low-efficiency LD ICE vehicles are gasoline-powered passenger cars with moderate to heavy weight, large engines, low RLC, and a high accessory power load (on the arterial). The high-efficiency LD ICE vehicle is, on both facilities, a light passenger truck with a small engine, higher RLC, and low accessory load.

Table 6-1. Selected Vehicle IDs for Extreme-Case FSC

Vehicle type	Selected Freeway Vehicle IDs		Selected Arterial Vehicle IDs	
	Low Congestion Efficiency	High Congestion Efficiency	Low Congestion Efficiency	High Congestion Efficiency
LD ICE	15	21	82	21
LD HEV	94	122	85	43
LD EV	103	60	103	60
LD FCV	109	139	109	139
HD ICE	151	168	156	169

Table 6-2. Extreme-Case LD Vehicles: Characteristics and FSC Fit Parameters

	Freeways							
	ICE*		HEV*		EV**		FCV**	
Congestion Efficiency	Low	High	Low	High	Low	High	Low	High
Passenger Car/Truck	Car	Truck	Car	Car	Car	Car	Car	Car
Curb Weight (lbs)	5,000	2,500	2,504	2,000	3,800	2,000	3,000	2,000
Engine Displ. (L)	4.5	2.0	1.1	2.0	NA	NA	NA	NA
RLC: A	156.46	235.01	156.46	156.46	156.46	156.46	156.46	156.46
RLC: B	2.002	3.039	2.002	2.002	2.002	2.002	2.002	2.002
RLC: C	0.493	0.748	0.493	0.493	0.493	0.493	0.493	0.493
Motor Peak Power/ Fuel Cell Rating (kW)	NA	NA	68	10	80	100	140	40
Hybrid Threshold (kW)	NA	NA	2	4	NA	NA	NA	NA
Accessory Power (kW)	0.75	0.75	4	0.75	4	0.75	4	0.75
Total Peak Power (kW)	220	98	123	108	80	100	140	40
Specific Power (W/kg)	97	86	108	119	46	110	103	44
α_0	1.514	2.331	1.892	3.122	2.911	4.236	1.984	3.048
α_1	0.1112	0.0809	0.1321	0.0667	0.1132	0.0511	0.1324	0.0955
α_2	-0.0029	-0.0025	-0.0041	-0.0025	-0.0034	-0.0019	-0.0037	-0.0032
α_3	3.63E-5	2.94E-5	5.78E-5	3.44E-5	4.55E-5	2.41E-5	4.60E-5	4.27E-5
α_4	-1.73E-7	-1.15E-7	-2.90E-7	-1.63E-7	-2.27E-7	-1.04E-7	-2.18E-7	-2.00E-7
	Arterial							
	ICE*		HEV*		EV**		FCV**	
Congestion Efficiency	Low	High	Low	High	Low	High	Low	High
Passenger Car/Truck	Car	Truck	Car	Car	Car	Car	Car	Car
Curb Weight (lbs)	3,750	2,500	3,000	3,020	3,800	2,000	3,000	2,000
Engine Displ. (L)	4.5	2.0	1.8	1.3	NA	NA	NA	NA
RLC: A	156.46	235.01	156.46	154.69	156.46	156.46	156.46	156.46
RLC: B	2.002	3.039	2.002	1.977	2.002	2.002	2.002	2.002
RLC: C	0.493	0.748	0.493	0.487	0.493	0.493	0.493	0.493
Motor Peak Power/ Fuel Cell Rating (kW)	NA	NA	60	10	80	100	140	40
Hybrid Threshold (kW)	NA	NA	2	2	NA	NA	NA	NA
Accessory Power (kW)	4	0.75	4	0.75	4	0.75	4	0.75
Total Peak Power (kW)	220	98	148	76	80	100	140	40
Specific Power (W/kg)	129	86	109	55	46	110	103	44
α_0	1.392	2.331	1.803	2.71	2.911	4.236	1.984	3.048
α_1	0.1145	0.0809	0.1204	0.0765	0.1132	0.0511	0.1324	0.0955
α_2	-0.0029	-0.0025	-0.0034	-0.0031	-0.0034	-0.0019	-0.0037	-0.0032
α_3	3.45E-5	2.94E-5	4.36E-5	4.77E-5	4.55E-5	2.41E-5	4.60E-5	4.27E-5
α_4	-1.55E-7	-1.15E-7	-2.06E-7	-2.42E-7	-2.27E-7	-1.04E-7	-2.18E-7	-2.00E-7

* Gasoline-fueled, automatic transmission, engine indicated efficiency of 0.4, model year 2010

** EV and FCV are the same vehicles for arterials and freeways, model year 2010

The low-efficiency LD HEV have smaller ICE, lower hybrid thresholds, higher accessory loads, and/or lower RLC than their high-efficiency counterparts. For LD EV, vehicle #60 was selected as the high-efficiency vehicle instead of #70 despite the fact that #60 was second to #70 in Congestion Impact (see Figure 33 and Figure 34). Vehicle #70 is based on the Mitsubishi i_MiEV[2] with a curb weight of only 1,080 lbs. The decision to exclude vehicle #70 was made because it is a very small EV similar to a neighborhood electric vehicle, and with incomparable power with respect to the other modeled vehicles. The low-efficiency LD EV is heavier and has a higher accessory load than its high-efficiency counterpart. Similarly, the low-efficiency LD FCV is heavier, has a higher fuel cell power rating, and has a higher accessory load than its high-efficiency counterpart.

For HD ICE vehicles, trucks over 80,000 lbs were excluded from consideration (which includes vehicles #155 and #157 in Figure 35). The next-worst Congestion Impact is vehicle #151 (with a weight of 70,000 lbs), which was selected as the low-efficiency freeway FSC. The low-efficiency freeway HD ICE vehicle is heavier, has a larger engine, and a higher accessory load than its high-efficiency counterpart. The high- and low-efficiency arterial HD ICE vehicles are more similar, with the more efficient vehicle having a smaller engine and heavier weight (which is tied to higher RLC). From Figure 35, however, we can see that the differences between the normalized FSC in the extreme cases on arterials is small.

[2] http://www.mitsubishi-motors.com/special/ev/whatis/index.html

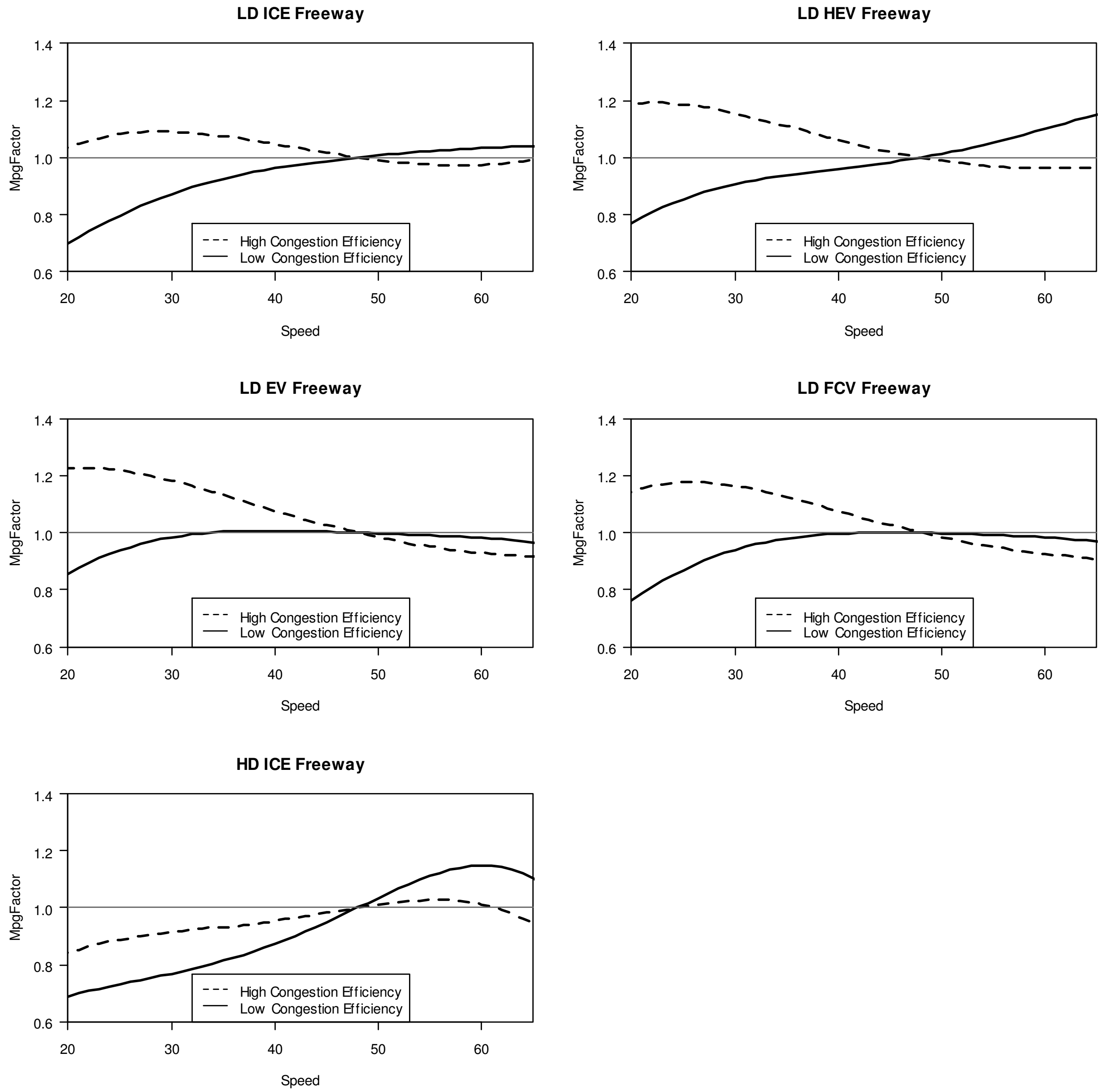

Figure 36. Selected High/Low-Sensitivity Normalized FSC on Freeways

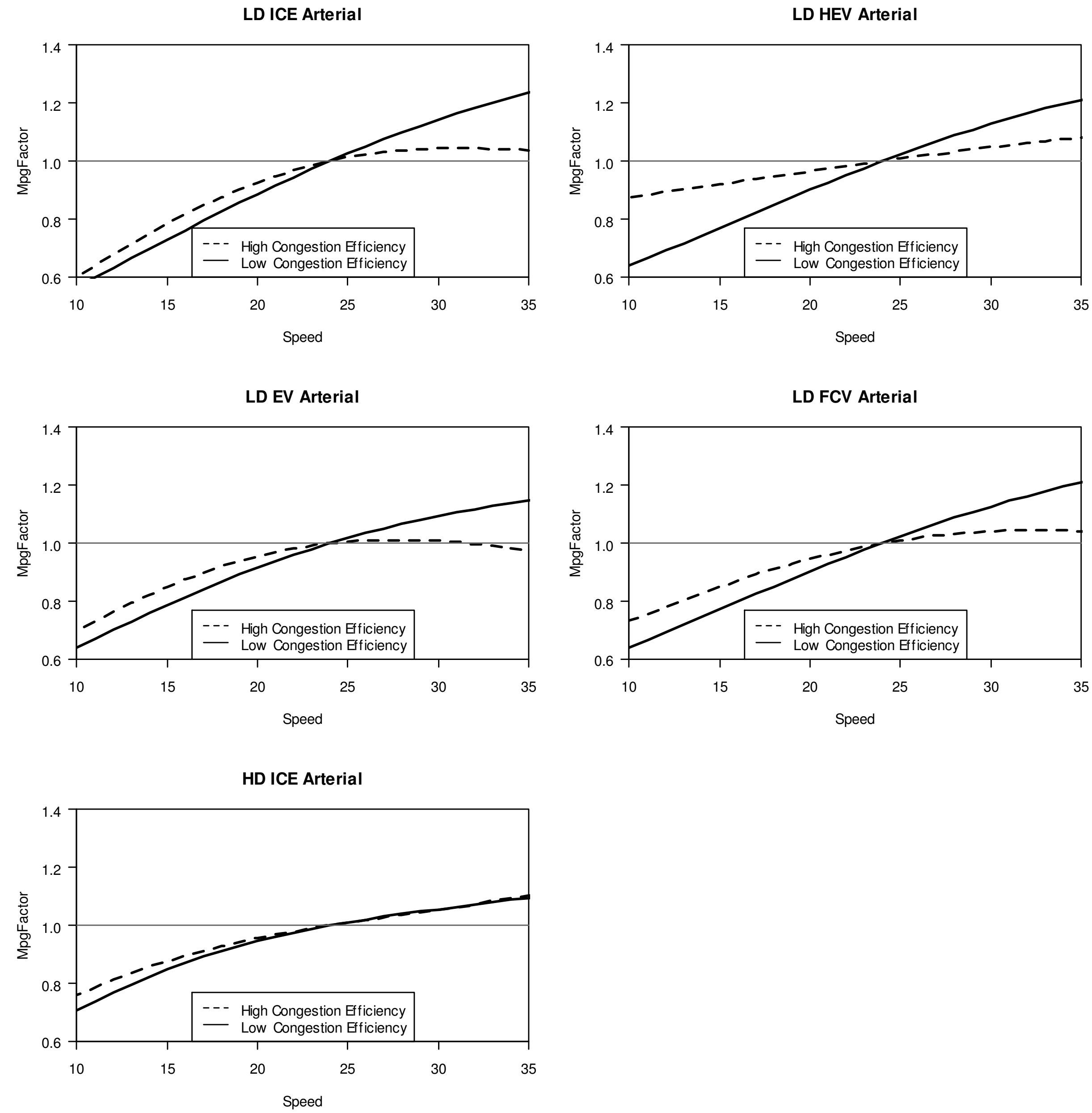

Figure 37. Selected High/Low-Sensitivity Normalized FSC on Arterials

Table 6-3 lists the vehicle characteristics which are expected to impact the relative efficiency in congestion (CE) for each vehicle-powertrain type. This table is based on sensitivity analysis of the modeled vehicle attributes and FSC. Qualitative projection of these attributes can be used to set the new model input, Congestion Efficiency, between 0 and 1. The median Congestion Efficiency value is 0.5, which sets the FE adjustment curve midway between the extreme curves shown in Figure 36 and Figure 37. If we expect, for example, average LD HEV to get lighter over time, we can set the Congestion Efficiency to trend upward. Note again that CE is increased both by attributes that improve FE in congestion and by attributes that disproportionately decrease FE at higher speeds.

Table 6-3. Vehicle Characterisitcs Influencing Relative Congestion Efficiency

Vehicle type	Low Relative Congestion Efficiency	High Relative Congestion Efficiency
LD ICE	heavier weight, larger engine, lower RLC, gasoline fuel, higher accessory loads, earlier model year	lighter weight, smaller engine, higher RLC, diesel fuel, lower accessory loads, later model year
LD HEV	heavier weight, smaller ICE, lower RLC, lower hybrid threshold, gasoline fuel, higher accessory loads, earlier model year	lighter weight, larger ICE, higher RLC, higher hybrid threshold, diesel fuel, lower accessory loads, later model year
LD EV	heavier weight, lower RLC, higher accessory loads	lighter weight, higher RLC, lower accessory loads
LD FCV	heavier weight, higher fuel cell power rating, lower RLC, higher accessory loads	lighter weight, lower fuel cell power rating, higher RLC, lower accessory loads
HD ICE	heavier weight, lower RLC	lighter weight, higher RLC

6.2 Comparison with existing GreenSTEP FSC

Figure 38 compares the new minimum, maximum, and median normalized freeway FSC with the existing GreenSTEP normalized freeway FSC *for ICE vehicles*. The new curves are calculated using Congestion Efficiency values of 0, 0.5, and 1 for minimum, median and maximum efficiency curves, respectively. The GreenSTEP curves are adjusted to be normalized to the assumed EPA reference speeds, and not the free-flow speed (as they currently are in GreenSTEP).

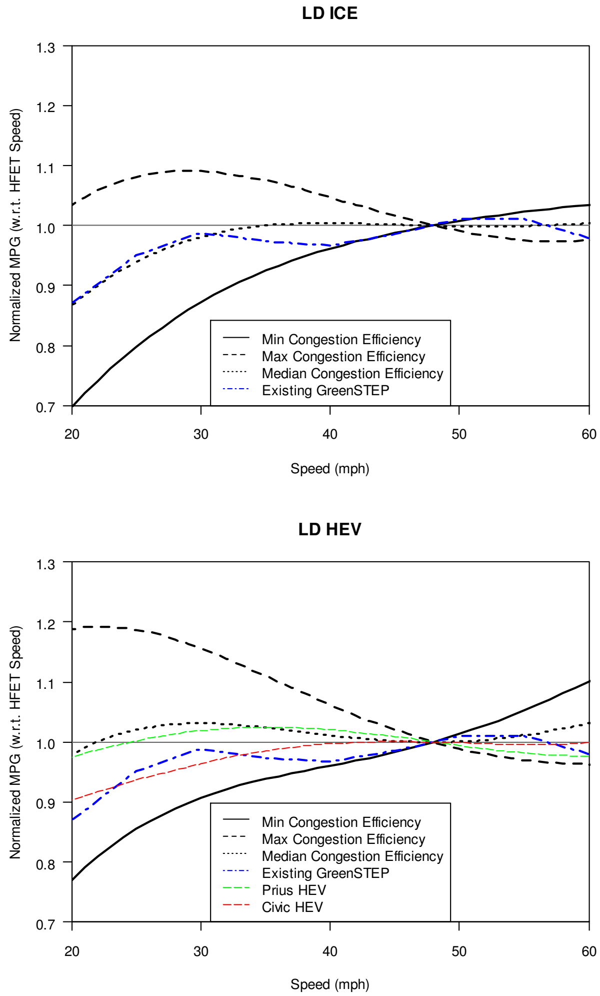

Figure 38. Comparison of Selected FSC and Reference Vehicles with Existing GreenSTEP FSC for ICE vehicles (LD Vehicles on Freeways)

For LD ICE the existing GreenSTEP FSC is similar to the median efficiency curve. The maximum and minimum efficiency curves are 10-20% higher and lower than the median efficiency curve in congestion – which presents a wide range of possible efficiencies. Most modeled LD ICE vehicles showed relatively flat FE from 70 mph down to about 30 mph, at which point the FE began to degrade.

The LD HEV curves are mostly higher than the existing GreenSTEP FSC for ICE vehicles. This is expected, as the modeled HEV performed better in congestion than ICE vehicles overall. Included in this comparison are lines for the modeled 2010 Toyota Prius HEV and 2010

Honda Civic HEV (based on vehicle specifications from Toyota[3] and Honda[4], respectively, and assumptions based on other sources for unavailable parameters). The Prius and Civic are modeled vehicles #37 and #41, respectively. The modeled Prius has close to the median performance for the range of test vehicles, while the modeled Civic has slightly poorer low-speed performance.

The LD EV curves have consistently better efficiency in congestion than the existing GreenSTEP curves for ICE vehicles. Included in this comparison is a line for the modeled 2010 Nissan Leaf EV (based on vehicle specifications from Nissan[5]), which is modeled vehicle #68. The modeled leaf has similar performance in congestion to the median EV efficiency. Note again that GreenSTEP does not currently adjust FE for EV or the portion of PHEV travel on stored electricity.

The LD FCV curve range is similar to the other advanced vehicle types. The FCV curves are most similar to HEV at lower speeds and EV at higher speeds. FCV characteristics are more uncertain than for HEV (which are already in mass production) or even EV. Compared to existing GreenSTEP FSC for ICE vehicles, the modeled FCV (like other advanced vehicles) are expected to be more efficient in congestion.

Figure 39 makes a similar comparison as Figure 38, but for arterial roadways. Arterial speeds in GreenSTEP cover a narrow range, so these curves are less varied. This study suggests slightly more sensitivity to speed for LD ICE vehicles than the current GreenSTEP curve. The current GreenSTEP curve is more in line with the advanced vehicle curves, which are less sensitive to congestion than ICE vehicles at these speeds.

[3] http://www.toyota.com/prius-hybrid/specs.html
[4] http://automobiles.honda.com/civic-hybrid/specifications.aspx
[5] http://www.nissanusa.com/leaf-electric-car/specs-features/index#/leaf-electric-car/specs-features/index

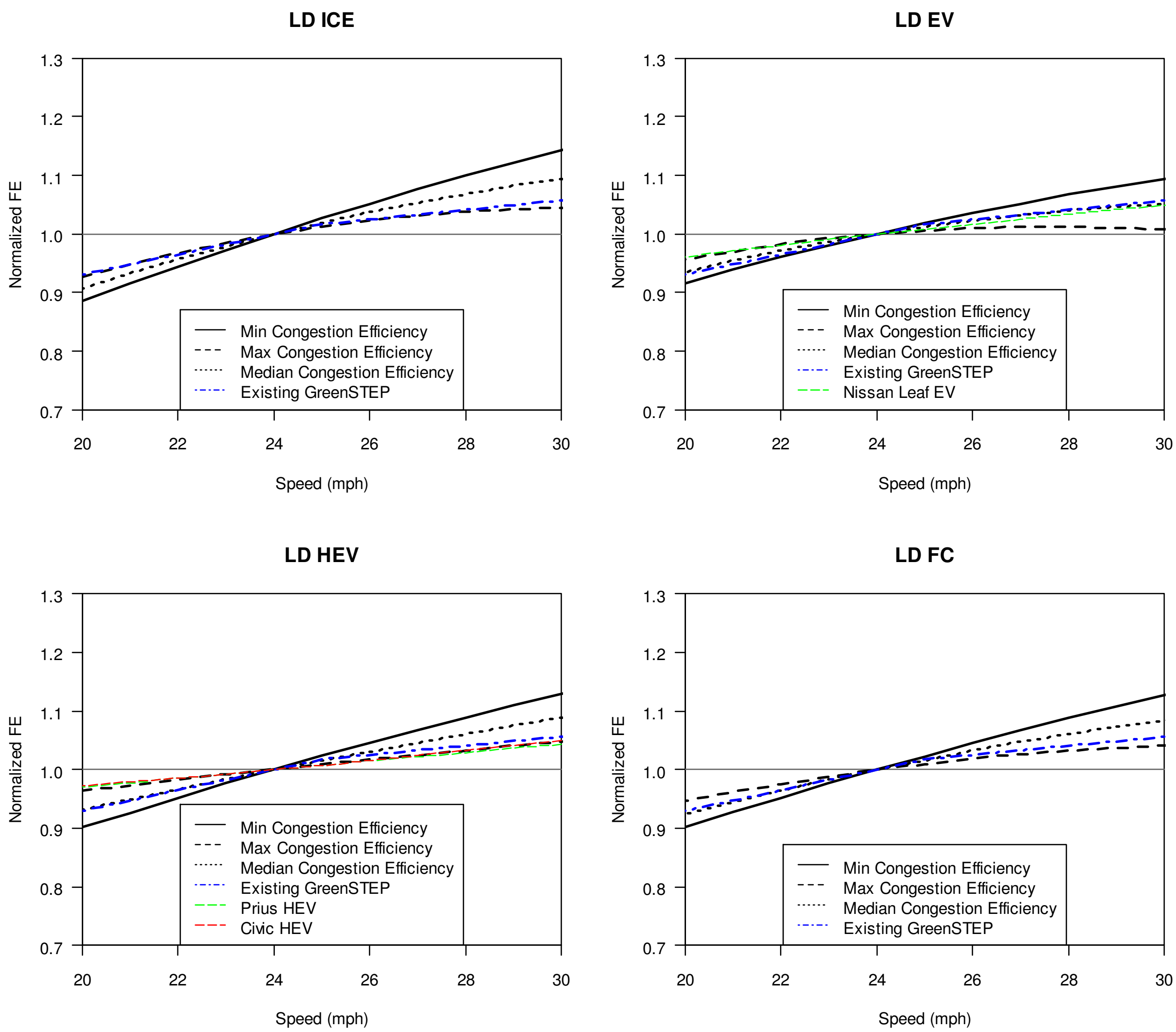

Figure 39. Comparison of Selected FSC and Reference Vehicles with Existing GreenSTEP FSC for ICE Vehicles (LD Vehicles on Arterials)

Figure 40 compares the proposed HD normalized FSC with the existing GreenSTEP truck curves for freeways and arterials (again adjusted to the assumed EPA reference speed). With the exception of the 35-45 mph speed range on freeways, the existing curves agree well with the proposed values. The arterial normalized FSC are virtually identical for the existing GreenSTEP curve and the full range of modeled curves. The wide range of potential efficiencies for low-speed freeway travel presents the opportunity to adjust for evolving vehicle fleet characteristics such as more aerodynamic truck bodies (which would decrease the relative congestion efficiency).

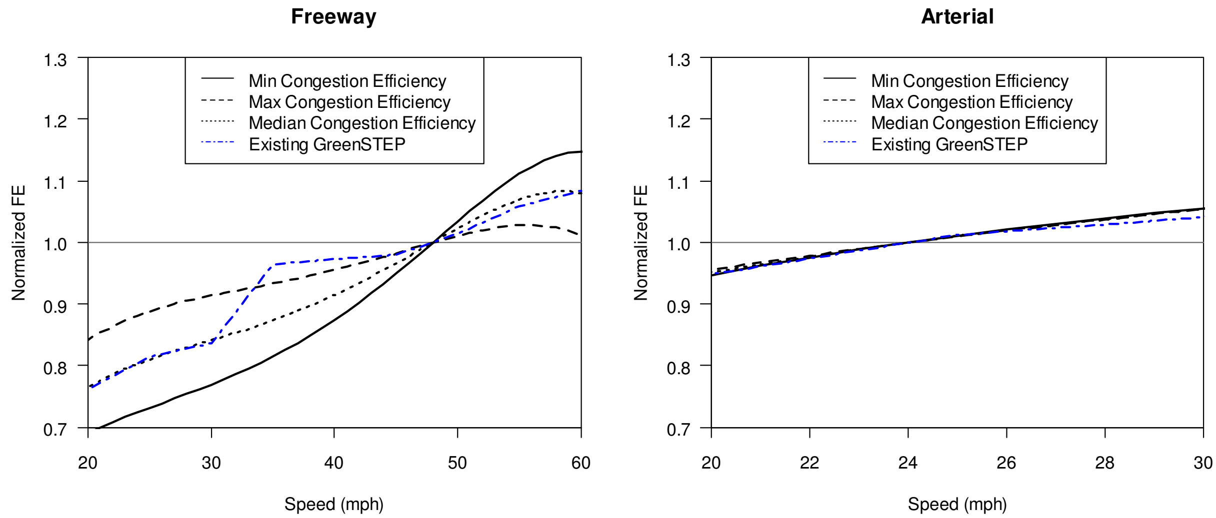

Figure 40. Comparison of Selected FSC with Existing GreenSTEP FSC and Reference Vehicles – HD vehicles, freeway (left) and arterial (right)

6.3 Constant-Speed Comparisons

Constant-speed fuel efficiency was also modeled to see the effect of speed variability in the driving patterns. This was done for a selection of low- and high-efficiency vehicles, again as indicated by Congestion Impact. As described in Section 4.4, fuel consumption for constant-speed driving was modeled directly in PERE – without VSP binning. This comparison is also interesting as an upper-bound estimate on the potential fuel efficacy of eco-driving or speed-smoothing traffic management/operations.

Figure 41 shows the modeled FE using MOVES freeway driving schedules as a fraction of the constant-speed FE (which was estimated at 10 mph intervals for the selected vehicles). The vehicle IDs included in Figure 41 are 15 and 21 (low/high-efficiency LD ICE vehicles), 103 and 60 (low/high-efficiency LD EV), 109 and 139 (low/high-efficiency LD FCV), and 153 and 168 (low/high-efficiency HD ICE vehicles). HEV are not included, since the absence of deceleration events in constant-speed driving produces no battery charge. FE based on real-world transient speed profiles is 20-60% lower than the FE of constant-speed driving for speeds below 50 mph. LD ICE vehicles have the greatest difference around 40 mph, whereas LD EV and HD ICE vehicles have an increasing gap between transient and steady-state driving at lower speeds.

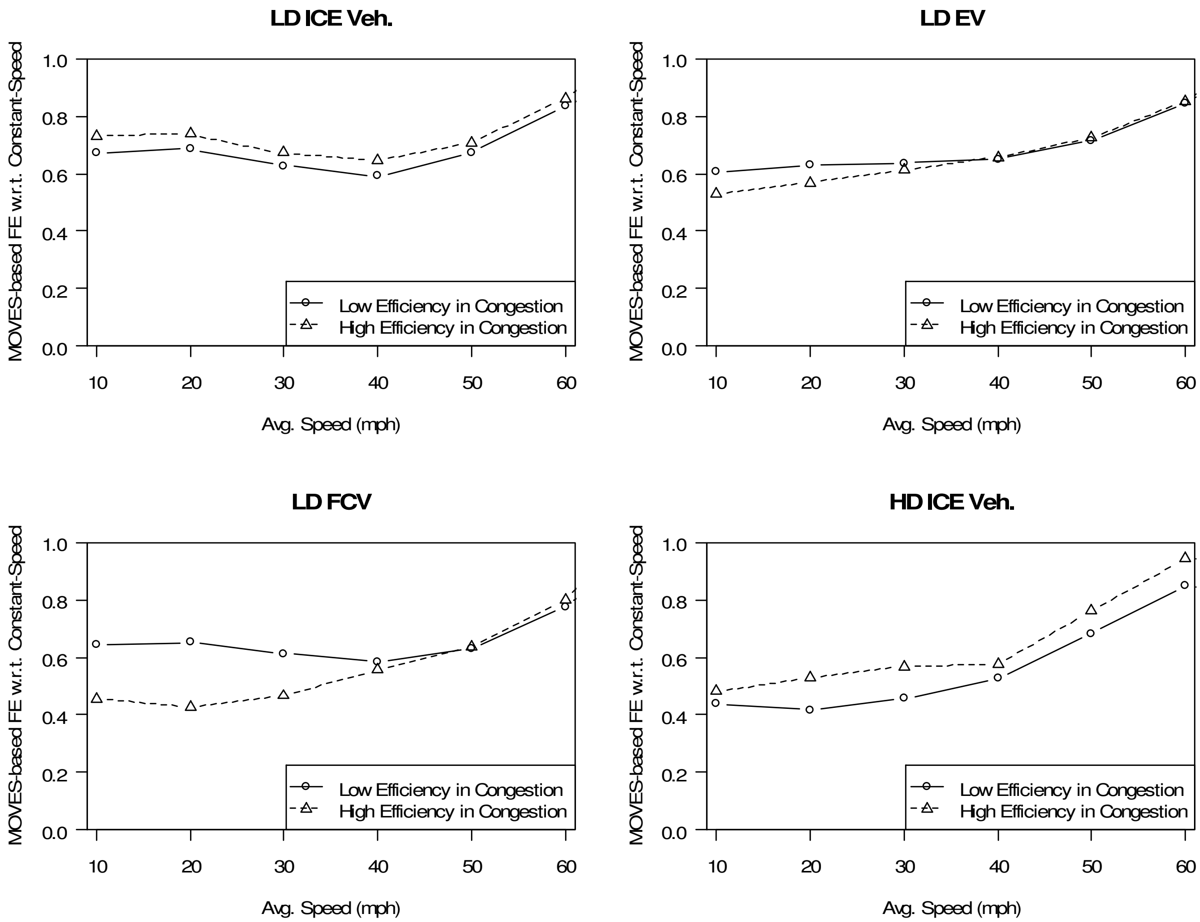

Figure 41. MOVES-Based FSC as Fraction of Constant-Speed FE for Selected Vehicles

As a comparison for these curves, Barth and Boriboonsomsin (2008) modeled carbon dioxide emissions rates for both real-world driving schedules and steady-state driving at a variety of speeds using the CMEM model. They only modeled LD ICE vehicles and found about 70% poorer performance in congestion for real-world driving than steady-state driving. They also found larger real-world/steady-state differences at lower speeds than freeway free-flow speeds – which agrees with Figure 41.

6.4 Other Considerations

6.4.1 Air Conditioning Effects

Air condition usage will increase the power accessory load for all vehicles. Higher accessory loads decrease average fuel economy. As shown in Figure 28, higher accessory loads also disproportionately affect low-speed driving. The amount of air conditioning usage is difficult to predict, as it includes meteorological, vehicle shell, and driver behavior factors. In GreenSTEP, air condition usage is not modeled explicitly. The EPA methodology for FE estimation includes expected average air conditioning effects on average fuel economy. To include more or less air conditioning usage in the FE adjustments for congestion, the value of the Congestion Efficiency input parameter can be decreased or increased, respectively. For example, if Oregon's temperate climate leads to lower average accessory loads than the national average, then that would lead to not only better average overall FE, but also higher Congestion Efficiency.

6.4.2 Plug-in Hybrid Electric Vehicles

Plug-in Hybrid Electric Vehicles (PHEV) have not been explicitly modeled in this research. PHEV act approximately as EV until the pre-trip stored electrical charge expires, then act as HEV. Their average FE is difficult to model with driving schedule approaches because the fuel consumption depends greatly on where the vehicle is with respect to the trip start (which requires prediction of additional parameters). Also, PHEV are likely designed as series-configuration hybrids, which are not modeled by PERE.

In terms of congestion response, their performance depends on how much net pre-trip charge has been depleted before encountering congestion. If enough charge remains they will respond as EV and if the charge is depleted they will respond as HEV. In aggregate, we can expect the PHEV to respond to congestion somewhere between the HEV and EV normalized FSC. Assuming an equivalent distribution of HEV and EV operating modes across congestion levels for the PHEV, interpolation can be performed between the HEV and EV normalized FSC based on the proportion of PHEV travel utilizing pre-trip battery energy on each facility. Alternatively, separate adjustments to fuel economy can be made for the portions of driving as an EV and as an HEV. In GreenSTEP, daily household trip length distributions are used with input PHEV characteristics to estimate the proportion of PHEV travel powered by stored electricity (Gregor 2010). Assuming this proportion is the same on arterial and freeway facilities, the congestion adjustment to FE can be performed for PHEV as well, using the HEV and EV FSC.

6.4.3 Vehicles Modeled in GreenSTEP

GreenSTEP does not currently model FCV or HEV explicitly. HEV are simply represented as more fuel efficient conventional vehicles. Given the similarity of the FE adjustment curves shown in Figure 38 and Figure 39, it is reasonable to assume that congestion effects of FCV can adequately be represented by HEV. But the effects of congestion on ICE vehicle FE are different from the effects on advanced vehicles (again, see Figure 38).

In order to account for these differences in congestion effects, additional input is needed regarding the LD vehicle fleet mix. EV and PHEV ownership and usage is modeled in GreenSTEP. Therefore, the required additional input is the proportion of the LD non-EV, non-PHEV fleet which is HEV, FCV, and ICE vehicle. Then the aggregate congestion impacts can be modeled using a weighted average of the congestion impacts of each vehicle powertrain type (assuming proportional exposure to congestion). If desired, FCV and HEV can be grouped together as "advanced vehicles" for congestion effects estimation. The input average LD fleet fuel economy is assumed to already account for the mix of powertrain types in the LD fleet, if applicable. HD vehicles, for now, are assumed to be all ICE.

6.5 GreenSTEP Sensitivity

Figure 42 shows the MPG adjustment curves that result for a Congestion Efficiency of 0.5 (and assuming half of PHEV operation is on stored electricity). The plotted values are also presented in Table 6-4 and Table 6-5. These curves go down to 5 mph, but from Table 3-3 the lowest speed modeled in GreenSTEP is 20.8 mph. On freeways the minimum modeled speed is 24.8 mph. At this speed the LD ICE FE adjustment factor is 0.94 for Congestion Efficiency of 0.5. The advanced drivetrain vehicles all have FE benefits (adjustments over 1) for speeds down to 25 mph. On arterials the minimum adjustment factor at 20 mph (for LD ICE) is 0.92. Thus, the potential adjustments to FE for congestion are relatively small. With evolving vehicle fleets containing more advanced vehicles, it is unlikely that the net effect of congestion on LD FE will be substantially detrimental – and the net effect could be beneficial. Further exploration of the impacts of these new FSC will be presented in the Task 2 documentation, where the interaction of FSC and the congestion model are investigated. MPG adjustment tables for Congestion Efficiency of 0 and 1 (the extreme cases) on arterials and freeways are presented in Appendix E.

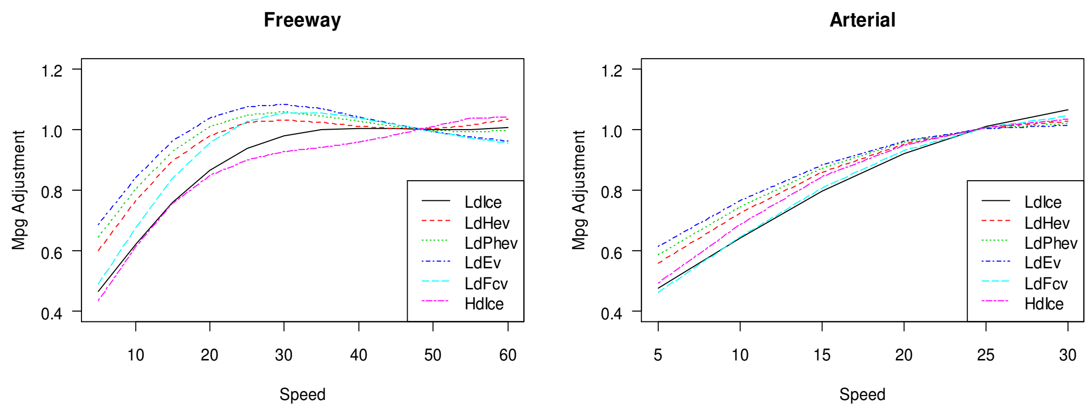

Figure 42. New MPG Adjustment Curves for Congestion Efficiency of 0.5

Table 6-4. Freeway FE Adjustment Factors for Congestion Efficiency of 0.5

Speed (mph)	LD ICE	LD HEV	LD PHEV	LD EV	LD FCV	HD ICE
5	0.47	0.60	0.64	0.69	0.49	0.44
10	0.62	0.77	0.80	0.84	0.68	0.61
15	0.76	0.90	0.93	0.96	0.84	0.76
20	0.86	0.98	1.01	1.04	0.96	0.85
25	0.94	1.02	1.05	1.08	1.03	0.90
30	0.98	1.03	1.06	1.08	1.05	0.93
35	1.00	1.02	1.05	1.07	1.05	0.94
40	1.00	1.01	1.03	1.04	1.04	0.96
45	1.00	1.00	1.01	1.02	1.02	0.98
50	1.00	1.00	1.00	0.99	0.99	1.01
55	1.00	1.01	0.99	0.97	0.97	1.04
60	1.01	1.03	1.00	0.96	0.95	1.04

Table 6-5. Arterial FE Adjustment Factors for Congestion Efficiency of 0.5

Speed (mph)	LD ICE	LD HEV	LD PHEV	LD EV	LD FCV	HD ICE
5	0.48	0.56	0.59	0.62	0.46	0.49
10	0.64	0.73	0.74	0.76	0.65	0.69
15	0.80	0.86	0.87	0.88	0.81	0.84
20	0.92	0.95	0.96	0.96	0.93	0.95
25	1.01	1.00	1.00	1.00	1.01	1.00
30	1.06	1.03	1.02	1.01	1.04	1.03

6.6 Summary of Proposed Method

Before concluding this section of the report, we here present a summary of the proposed method for implementing advanced vehicle fuel economy adjustments in GreenSTEP. Draft R code to execute these calculations (independently of the larger GreenSTEP model execution) has been provided to ODOT staff along with this report.

Input data:

1. Congestion Efficiency for LD ICE vehicles, LD HEV, LD EV, LD FCV, and HD ICE vehicles

   This is an estimated scaling value (from 0 to 1) for each modeled year representing the average performance in congestion for on-road vehicles of each type. It is scaled with respect to the vehicles of that type with the least and most relative efficiency in congestion. Congestion Efficiency estimation can be informed by the FSC sensitivity analysis above.
2. The average proportion of travel using stored electricity for PHEV
3. The proportion of DVMT for non-EV, non-PHEV LD vehicles which is traveled by HEV, FCV, and ICE vehicles, respectively

MPG Adjustment Calculation

1. Run the GreenSTEP congestion module for each metropolitan area and each year to estimate of proportion of DVMT at each congestion level on each facility, and the average speeds for each congestion level.
2. For each facility-congestion level combination:
   a. Calculate the high-end and low-end FE adjustment factors for each vehicle type (except PHEV) using the provided MPG adjustment tables (Appendix E) and the congested average speeds
   b. Interpolate between the low and high FE adjustment values for each vehicle type using the Congestion Efficiency values
   c. Interpolate between the HEV and EV FE adjustment values for PHEV FE adjustment using the average proportion of travel powered stored electricity for PHEV

    d. Combine the non-EV, non-PHEV LD vehicle FE adjustments using a weighted average based on the proportion of DVMT traveled by vehicles of each powertrain type

3. For each remaining vehicle type (LD EV, LD PHEV, other LD, and HD) take a weighted average of the FE adjustment values using the proportion of DVMT at each facility-congestion level combination

This calculation provides an estimate of the FE adjustment factor to be applied to each modeled vehicle type in each metropolitan area for each year.

7 Conclusions

This report describes research undertaken to establish plausible fuel-speed curves for advanced vehicles. We used the PERE fuel consumption model with real-world driving schedules and a range of advanced vehicle characteristics to estimate vehicle fuel economy in varying traffic conditions. These fuel-speed data points were then used to fit fuel economy versus average speed curves for each of the 177 modeled vehicles.

The shape of the Fuel-Speed Curves (FSC) reveals the impacts of congestion on fuel economy. Analysis of the FSC produced the following observations:

- Advanced powertrain vehicles are expected to perform better in congestion than ICE vehicles (with respect to FE at free-flow speeds),
- Many ICE vehicles do not lose fuel efficiency until congestion slows traffic to about 30 mph,
- HEV are less sensitive to congestion than ICE vehicles, and tend to maintain their fuel efficiency in congestion levels down to 20 mph,
- Fuel efficiency *increases* for EV in congestion levels down to about 20-30 mph, and
- The modeled effects of congestion on FCV are similar to the effects on HEV.

These were the general observations for median response curves of each vehicle powertrain type. But congestion effects vary greatly with other vehicle characteristics as well. Relative fuel efficiency in congestion is expected to improve for vehicles with lighter weight, smaller engines (for ICE), higher hybrid thresholds, and lower accessory loads (such as air conditioning). *Relative* performance in congestion can also improve with attributes that disproportionately decrease FE at higher speeds, such as higher aerodynamic drag and rolling resistance factors.

The primary motivation for developing these curves is to enable modeling of advanced powertrain vehicles in the GreenSTEP model. To this end we presented a method for incorporating advanced vehicle FSC into the FE adjustment for congestion in GreenSTEP. The proposed approach uses an estimate of the average Congestion Efficiency of vehicles of each powertrain type, with respect to the least and most congestion-sensitive modeled vehicles of that type. In other words we take a bounded approach, where the applied FE adjustment is an interpolation between extremes. This allows some adjustment for vehicle trends over time without requiring much specificity in the vehicle fleet characteristics. In addition to the

Congestion Efficiency input, two other additional inputs are need to implement the proposed method: the average proportion of travel using stored electricity for PHEV, and the proportion of DVMT for non-EV, non-PHEV LD vehicles which is traveled by HEV, FCV, and ICE vehicles, respectively. The similarity of advanced-drivetrain vehicles' performance in congestion shows that FCV need not be modeled separately in order to represent the impacts of congestion.

One final note from this analysis is that consideration of advanced vehicles reduces the fuel efficiency losses associated with congestion. HEV have less sensitivity to congestion than conventional ICE vehicles because of recaptured braking energy. EV have generally *improved* fuel economy down to heavy levels of congestion because of braking energy regeneration and the insensitivity of motor efficiency to low speed driving. As vehicles become more advanced and internally efficient, it is the external forces which begin to dominate the variation in fuel economy (aerodynamic drag in particular, which increases strongly with speed). Hence, with more advanced vehicles in the fleet we could even see net FE *benefits* from moderate levels of congestion.

This concludes the documentation on Task1 of this project. Documentation on Task 2, the incorporation of ITS/operational improvements, is presented in a companion report. These two tasks are related because the FSC results from this task influence the impact of varying adjustments for congestion in GreenSTEP. Additionally, the constant-speed FSC comparisons in Section 6.3 inform estimation of the potential impacts of speed-smoothing strategies in Task 2.

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Appendix A: Review of Fuel-Speed Models

PSAT

The Powertrain Systems Analysis Toolkit (PSAT) was developed in the early 2000's by the Argonne National Labs (ANL), and sponsored by the U.S. Department of Energy (DOE). **NOTE: this model has been phased out by ANL, and replaced with Autonomie** (see below). The model is therefore no longer readily available.

AUTONOMIE

Autonomie is a vehicle modeling tool developed by the Argonne National Labs (ANL) with funding from the U.S. DOE. Information on the model is available online[6]. A license for the model for university/research applications is $2,000-$7,000. It is the next-generation model following the PSAT model, also developed by ANL. Although this is a relatively new model, it builds on the widely-used PSAT model and shows strong early adoption. These models simulate vehicle control operations and can follow driving schedules to estimate on-road engine loads based on various vehicle parameters. Autonomie allows automated powertrain configuration building, and includes several hundred pre-defined configurations including conventional, EV, HEV, and fuel cells. These are forward simulating models, where drive schedules determine power needs, which are applied by a simulated vehicle controller controlling the propulsion components. The outputs are vehicle performance and fuel consumption over time for the driving schedules. Both Autonomie and PSAT are essentially individual-vehicle models intended for fairly detailed vehicle modeling and geared toward use by automakers and suppliers. The data needs are particularly challenging for use in modeling whole fleets of vehicles where the knowledge of individual vehicle attributes is low.

ADVISOR

The ADvanced Vehicle SImulatOR (ADVISOR) was developed by the National Renewable Energy Lab (NREL) for the U.S. DOE. ADVISOR was designed to look at the impact of interactions between vehicle components on hybrid vehicle performance and fuel economy. This is another detailed vehicle model with various scalable system component

[6] http://www.autonomie.net

modules and the capability for vehicle system optimization. Like Autonmie and PSAT, ADVISOR can perform analysis of driving schedule tests. It has been commercialized and is now only available through the company AVL[7]. ADVISOR is NREL's "Exploratory Level" vehicle model, oriented toward strategic modeling of powertrain configurations and vehicle component sizing. NREL contrasts this with "High Level" models such as GREET or VISION (see below) and with more detailed vehicle models, which are also available but not applicable for this project.

PERE

The Physical Emission Rate Estimator (PERE) model was created by the U.S. Environmental Protection Agency (EPA). According to PERE documentation it is intended "to fill data gaps in MOVES and to provide a tool to extrapolate to future projections of energy and emissions" (Nam & Giannelli 2005). It is a physical modeling approach adapted from the Comprehensive Modal Emissions Model (CMEM), a microscopic emissions model developed at the University of California, Riverside which is described below (Barth et al. 2000). One of the justifications for developing PERE was that the individual vehicle models (such as ADVISOR) are more detailed and complex, and not designed for modeling fleets of vehicles (Nam & Giannelli 2005).

PERE models "Pump-to-Wheel" fuel consumption rates for light-duty vehicles, heavy-duty vehicles, and motorcycles. It is implemented as a Microsoft Excel file, freely downloaded from the EPA[8]. The engine/powertrain technologies modeled are ICE, HEV, FCV, and EV. Fully electric vehicles are modeled simply as HEV without an ICE, though this module is not yet validated.

PERE users input driving schedule and vehicle parameters to generate fuel consumption rates, which can be either time-averaged or binned by Vehicle Specific Power (VSP). VSP is a primary causal variable for fuel consumption and emissions (a measure of power demand), and equations and references can be found in Rakha, Park, & Marr (2010). The VSP bin output allows PERE to be easily integrated with an average-speed emissions model (such as MOVES) which apportions vehicle activities by VSP bin.

[7] https://www.avl.com/produkte
[8] http://www.epa.gov/otaq/models/moves/movesback.htm#moves2004

PERE requires a set of vehicle parameters and a driving schedule as inputs. The model is most sensitive to vehicle engine size, weight, and efficiency, followed by frontal area and drag coefficient. The powertrain component sizing and configuration is not explicitly modeled as in the individual vehicle models, but instead summarized with several efficiency parameters. The vehicle performance is fuel-specific for gas and diesel, but not for other fuels (such as CNG). The model allows for differing fuel weight densities (mass per volume) and energy intensities (energy per mass) – which can be used to model alternative fuels. The PERE model has had some implementation in the literature (H. Christopher Frey et al. 2007; Rakha et al. 2010), though (as mentioned earlier) the EV estimates are not yet validated.

CMEM

The Comprehensive Modal Emissions Model (CMEM) was developed at the University of California Riverside to provide detailed motor vehicle emissions and fuel consumption estimates (Barth et al. 2000). It can be freely obtained from UC Riverside, and more information is available online[9]. It employs a physical approach which relies less on vehicle testing than empirical emissions models. CMEM requires extensive vehicle attributes for input, in addition to second-by-second operating data. CMEM does not model advanced powertrains explicitly, but it does model different fuel types. While the physical approach of CMEM is ideal for advanced vehicles for which test data are not available, the modeling data requirements are extensive for an uncertain vehicle fleet. Furthermore, regenerative braking, state-of-charge, and other factors relevant to advanced powertrain vehicles are not included. PERE exploits the CMEM methodology in a simplified way, which is tailored for advanced and uncertain vehicle fleets (although as a consequence the model estimates have more uncertainty). PERE has also incorporated hybrid powertrain factors and attributes into the physical modeling framework.

MOVES

The MOVES 2010 (MOtor Vehicle Emissions Simulator) model is an average-speed emissions model developed by the EPA, mandated in the U.S. for Clean Air Act conformity analysis. It has both regional and project-level components, which can model on a broad regional

[9] http://www.cert.ucr.edu/cmem/model.html

scale or at the individual roadway level. At the core of the processing, MOVES uses driving schedules to bin vehicle activity by VSP then applies VSP-bin emissions or fuel rates to estimate total emissions or fuel consumption. MOVES is freely available from the EPA[10]. MOVES does estimate speed-based fuel/energy consumption, but because the emissions rates are empirically derived, most advanced technology vehicles are not included in the emissions rate database. In fact, the EPA developed PERE to provide physically-modeled emissions rates estimates that could “fill holes” in the MOVES database.

VISION

VISION is a high-level modeling tool developed by ANL[11] to model the impacts of advanced vehicles on total fuel consumption over long time scales. Although it can provide some validation reference for overall fuel economy, the fuel economy is not speed-related or congestion-related, so not applicable to this project.

GREET

The GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) was developed by ANL for the U.S. DOE. The foci of the model are vehicle and fuel lifecycles, and it is comprised of a model for each. GREET models three light-duty vehicle classes, with more than 80 vehicle/fuel system combinations covering ICE, HEV, Plug-in Hybrid Electric Vehicles (PHEV), EV, and FCV technologies. It also covers a wide range of detailed fuel types. It is implemented in a Microsoft Excel file, freely downloadable from ANL[12].

GREET uses PSAT modeling for some of the advanced vehicle performance characteristics. The modeling output is energy consumption per vehicle-mile of travel (over the entire fuel life-cycle). The key for this project is that, like VISION, GREET does not model fuel economy in relation to speed. It incorporates advanced vehicle characteristics, but not driving schedules. It can potentially provide projections for future vehicle characteristics and reference fuel economy, but not fuel-speed curves.

[10] http://www.epa.gov/otaq/models/moves/index.htm
[11] http://www.transportation.anl.gov/modeling_simulation/VISION/index.html
[12] http://greet.es.anl.gov/

Appendix B: Test Vehicle Matrix

Veh. ID	Veh. Type	Veh. Class	Fuel Type	Transm. Type	P/T Type	Model Year	Vehicle Weight lbs	Engine Displ. L	Road Load Method	Road Load A	Road Load B	Road Load C	Eff. (gas)	Eff. (diesel)	Motor Peak Power kW	Hybrid Threshold kW	Fuel Cell Power kW	Acc. Power kW
1	LD	PC	g	a	c	2005	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
2	LD	PC	g	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
3	LD	PC	g	m	c	2005	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
4	LD	PC	g	m	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
5	LD	PC	d	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
6	LD	PC	g	a	c	2040	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
7	LD	PC	g	a	c	2010	2500	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
8	LD	PC	g	a	c	2010	2500	3.25	1	131.96	1.687	0.415	0.4	0.45	NA	NA	NA	0.75
9	LD	PC	g	a	c	2010	3750	3.25	1	172.47	2.205	0.543	0.4	0.45	NA	NA	NA	0.75
10	LD	PC	g	a	c	2010	5000	3.25	1	212.99	2.723	0.670	0.4	0.45	NA	NA	NA	0.75
11	LD	PC	g	a	c	2010	5000	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
12	LD	PC	g	a	c	2010	2500	2	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
13	LD	PC	g	a	c	2010	3750	2	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
14	LD	PC	g	a	c	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
15	LD	PC	g	a	c	2010	5000	4.5	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
16	LD	PC	g	a	c	2010	3750	4.5	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
17	LD	PT	g	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
18	LD	PT	g	a	c	2010	3750	3.25	3	235.01	3.039	0.748	0.4	0.45	NA	NA	NA	0.75
19	LD	PT	g	a	c	2010	3750	3.25	1	208.45	2.665	0.656	0.4	0.45	NA	NA	NA	0.75
20	LD	PT	d	a	c	2010	3750	3.25	3	235.01	3.039	0.748	0.4	0.45	NA	NA	NA	0.75
21	LD	PT	g	a	c	2010	2500	2	3	235.01	3.039	0.748	0.4	0.45	NA	NA	NA	0.75
22	LD	PT	g	a	c	2010	5000	4.5	3	235.01	3.039	0.748	0.4	0.45	NA	NA	NA	0.75
23	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	10	1	NA	0.75
24	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	10	2	NA	0.75
25	LD	PC	g	a	h	2010	2500	1.5	3	156.46	2.002	0.493	0.4	0.45	10	2	NA	0.75
26	LD	PC	g	a	h	2010	2500	1.5	3	156.46	2.002	0.493	0.4	0.45	30	2	NA	0.75
27	LD	PC	g	a	h	2010	2500	1.5	3	156.46	2.002	0.493	0.4	0.45	50	2	NA	0.75
28	LD	PC	g	a	h	2010	2500	1.5	3	156.46	2.002	0.493	0.4	0.45	70	2	NA	0.75
29	LD	PC	g	a	h	2010	3750	2	3	156.46	2.002	0.493	0.4	0.45	70	2	NA	0.75
30	LD	PC	g	a	h	2010	4000	2.5	3	156.46	2.002	0.493	0.4	0.45	10	2	NA	0.75
31	LD	PC	g	a	h	2010	4000	2.5	3	156.46	2.002	0.493	0.4	0.45	10	3.75	NA	0.75
32	LD	PC	g	a	h	2010	4000	2.5	3	156.46	2.002	0.493	0.4	0.45	30	5.5	NA	0.75
33	LD	PC	g	a	h	2010	4000	2.5	3	156.46	2.002	0.493	0.4	0.45	50	5.75	NA	0.75
34	LD	PC	g	a	h	2010	4000	2.5	3	156.46	2.002	0.493	0.4	0.45	70	5.72	NA	0.75
35	LD	PC	d	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	50	2	NA	0.75
36	LD	PC	d	a	h	2010	4000	2.5	3	156.46	2.002	0.493	0.4	0.45	50	2	NA	0.75
37	LD	PC	g	a	h	2010	3342	1.8	1	165.75	2.119	0.521	0.4	0.45	60	2	NA	0.75
38	LD	PC	g	a	h	2010	3563	2.5	1	173.34	2.216	0.545	0.4	0.45	105	4.7	NA	0.75
39	LD	PC	g	a	h	2010	4246	2.7	1	196.81	2.516	0.619	0.4	0.45	140	4.8	NA	0.75
40	LD	PT	g	a	h	2010	4246	2.7	1	236.20	3.020	0.743	0.4	0.45	140	2	NA	0.75

41	LD	PC	g	a	h	2010	3177	1.34	1	160.08	2.046	0.504	0.4	0.45	15	2	NA	0.75
42	LD	PC	g	a	h	2010	2950	1.5	1	152.28	1.947	0.479	0.4	0.45	10	2	NA	0.75
43	LD	PC	g	a	h	2010	3020	1.34	1	154.69	1.977	0.487	0.4	0.45	10	2	NA	0.75
44	LD	PT	g	a	h	2011	3990	2.5	1	226.17	2.891	0.712	0.4	0.45	70	2	NA	0.75
45	LD	PC	g	a	h	2011	4020	2.5	1	189.05	2.417	0.595	0.4	0.45	26	3.8	NA	0.75
46	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	154.7	0.75
47	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	154.7	0.75
48	LD	PC	g	a	f	2010	4000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	154.7	0.75
49	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	80	0.75
50	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	100	0.75
51	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	120	0.75
52	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	140	0.75
53	LD	PC	g	a	f	2010	3827	NA	3	156.46	2.002	0.493	0.4	0.45	65	2	80	0.75
54	LD	PC	g	a	f	2010	4401	NA	3	156.46	2.002	0.493	0.4	0.45	80	2	90	0.75
55	LD	PC	g	a	f	2010	4048	NA	3	156.46	2.002	0.493	0.4	0.45	60	2	94	0.75
56	LD	PC	g	a	f	2010	4013	NA	3	156.46	2.002	0.493	0.4	0.45	60	2	80	0.75
57	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	60	2	60	0.75
58	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	60	2	100	0.75
59	LD	PC	g	a	e	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	80	0	0	0.75
60	LD	PC	g	a	e	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	100	0	0	0.75
61	LD	PC	g	a	e	2010	2500	NA	3	156.46	2.002	0.493	0.4	0.45	100	0	0	0.75
62	LD	PC	g	a	e	2010	2500	NA	3	156.46	2.002	0.493	0.4	0.45	130	0	0	0.75
63	LD	PC	g	a	e	2010	2500	NA	3	156.46	2.002	0.493	0.4	0.45	60	0	0	0.75
64	LD	PC	g	a	e	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	100	0	0	0.75
65	LD	PC	g	a	e	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	60	0	0	0.75
66	LD	PC	g	a	e	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	140	0	0	0.75
67	LD	PC	g	a	e	2010	3982	NA	3	156.46	2.002	0.493	0.4	0.45	100	0	0	0.75
68	LD	PC	g	a	e	2010	3800	NA	3	156.46	2.002	0.493	0.4	0.45	80	0	0	0.75
69	LD	PC	g	a	e	2010	3023	NA	3	156.46	2.002	0.493	0.4	0.45	215	0	0	0.75
70	LD	PC	g	a	e	2010	1380	NA	3	156.46	2.002	0.493	0.4	0.45	47	0	0	0.75
71	LD	PC	g	a	e	2010	4000	NA	3	156.46	2.002	0.493	0.4	0.45	160	0	0	0.75
72	LD	PC	g	a	e	2010	3525	NA	3	156.46	2.002	0.493	0.4	0.45	135	0	0	0.75
73	LD	PC	g	a	h	2010	2504	1.1	3	156.46	2.002	0.493	0.4	0.45	68	2	0	0.75
74	LD	PC	g	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	2
75	LD	PC	g	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	3
76	LD	PC	g	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	4
77	LD	PC	g	a	c	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	2
78	LD	PC	g	a	c	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	3
79	LD	PC	g	a	c	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	4
80	LD	PC	g	a	c	2010	3750	4.5	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	2
81	LD	PC	g	a	c	2010	3750	4.5	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	3
82	LD	PC	g	a	c	2010	3750	4.5	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	4
83	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	2	0	2
84	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	2	0	3
85	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	2	0	4
86	LD	PC	g	a	h	2010	3177	1.34	1	160.08	2.046	0.504	0.4	0.45	15	2	NA	2

87	LD	PC	g	a	h	2010	3177	1.34	1	160.08	2.046	0.504	0.4	0.45	15	2	NA	3
88	LD	PC	g	a	h	2010	3177	1.34	1	160.08	2.046	0.504	0.4	0.45	15	2	NA	4
89	LD	PC	g	a	h	2010	3563	2.5	1	173.34	2.216	0.545	0.4	0.45	105	4.7	NA	2
90	LD	PC	g	a	h	2010	3563	2.5	1	173.34	2.216	0.545	0.4	0.45	105	4.7	NA	3
91	LD	PC	g	a	h	2010	3563	2.5	1	173.34	2.216	0.545	0.4	0.45	105	4.7	NA	4
92	LD	PC	g	a	h	2010	2504	1.1	3	156.46	2.002	0.493	0.4	0.45	68	2	0	2
93	LD	PC	g	a	h	2010	2504	1.1	3	156.46	2.002	0.493	0.4	0.45	68	2	0	3
94	LD	PC	g	a	h	2010	2504	1.1	3	156.46	2.002	0.493	0.4	0.45	68	2	0	4
95	LD	PC	g	a	e	2010	3525	NA	3	156.46	2.002	0.493	0.4	0.45	135	0	0	2
96	LD	PC	g	a	e	2010	3525	NA	3	156.46	2.002	0.493	0.4	0.45	135	0	0	3
97	LD	PC	g	a	e	2010	3525	NA	3	156.46	2.002	0.493	0.4	0.45	135	0	0	4
98	LD	PC	g	a	e	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	140	0	0	2
99	LD	PC	g	a	e	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	140	0	0	3
100	LD	PC	g	a	e	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	140	0	0	4
101	LD	PC	g	a	e	2010	3800	NA	3	156.46	2.002	0.493	0.4	0.45	80	0	0	2
102	LD	PC	g	a	e	2010	3800	NA	3	156.46	2.002	0.493	0.4	0.45	80	0	0	3
103	LD	PC	g	a	e	2010	3800	NA	3	156.46	2.002	0.493	0.4	0.45	80	0	0	4
104	LD	PC	g	a	e	2010	3023	NA	3	156.46	2.002	0.493	0.4	0.45	215	0	0	2
105	LD	PC	g	a	e	2010	3023	NA	3	156.46	2.002	0.493	0.4	0.45	215	0	0	3
106	LD	PC	g	a	e	2010	3023	NA	3	156.46	2.002	0.493	0.4	0.45	215	0	0	4
107	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	140	2
108	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	140	3
109	LD	PC	g	a	f	2010	3000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	140	4
110	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	1	0	0.75
111	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	3	0	0.75
112	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	4	0	0.75
113	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	6	0	0.75
114	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	1	0	3
115	LD	PC	g	a	h	2010	3000	1.8	3	156.46	2.002	0.493	0.4	0.45	60	6	0	3
116	LD	PC	g	a	c	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	NA	NA	NA	0.75
117	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	10	1	NA	0.75
118	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	30	1	NA	0.75
119	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	30	1	NA	0.75
120	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	10	4	NA	0.75
121	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	30	4	NA	0.75
122	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	10	4	NA	0.75
123	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	30	4	NA	0.75
124	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	10	4	NA	3
125	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	30	4	NA	3
126	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	10	4	NA	3
127	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	30	4	NA	3
128	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	10	1	NA	3
129	LD	PC	g	a	h	2010	2000	1	3	156.46	2.002	0.493	0.4	0.45	30	1	NA	3
130	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	10	1	NA	3
131	LD	PC	g	a	h	2010	2000	2	3	156.46	2.002	0.493	0.4	0.45	30	1	NA	3
132	LD	PC	g	a	e	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	40	0	0	0.75

133	LD	PC	g	a	e	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	60	0	0	0.75
134	LD	PC	g	a	e	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	40	0	0	3
135	LD	PC	g	a	e	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	60	0	0	3
136	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	100	0.75
137	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	80	0.75
138	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	60	0.75
139	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	40	0.75
140	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	100	3
141	LD	PC	g	a	f	2010	2000	NA	3	156.46	2.002	0.493	0.4	0.45	0	0	40	3
142	LD	PC	g	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.6	0.45	NA	NA	NA	0.75
143	LD	PC	d	a	c	2010	3750	3.25	3	156.46	2.002	0.493	0.4	0.6	NA	NA	NA	0.75
144	LD	PC	g	a	h	2010	3750	2	3	156.46	2.002	0.493	0.6	0.45	20	2	NA	0.75
145	LD	PC	d	a	h	2010	3750	2	3	156.46	2.002	0.493	0.4	0.6	20	2	NA	0.75
146	HD	HDT	d	m	c	2000	70000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
147	HD	HDT	d	m	c	2010	70000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
148	HD	HDT	d	m	c	2050	70000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
149	HD	HDT	d	m	c	2010	70000	13	3	125.58	-0.900	0.447	0.4	0.48	NA	NA	NA	0.75
150	HD	HDT	d	m	c	2010	70000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	3
151	HD	HDT	d	m	c	2010	70000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	6
152	HD	HDT	d	m	c	2010	70000	10	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
153	HD	HDT	d	m	c	2010	70000	16	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
154	HD	HDT	d	m	c	2010	50000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
155	HD	HDT	d	m	c	2010	90000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
156	HD	HDT	d	m	c	2010	30000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
157	HD	HDT	d	m	c	2010	110000	13	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
158	HD	HDT	d	m	c	2010	70000	8	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
159	HD	HDT	d	m	h	2010	70000	13	1	NA	NA	NA	0.4	0.48	50	2	NA	0.75
160	HD	HDT	d	m	h	2010	70000	8	1	NA	NA	NA	0.4	0.48	50	2	NA	0.75
161	HD	HDT	d	m	h	2010	70000	13	1	NA	NA	NA	0.4	0.48	100	2	NA	0.75
162	HD	HDT	d	m	h	2010	70000	8	1	NA	NA	NA	0.4	0.48	100	2	NA	0.75
163	HD	HDT	d	m	h	2010	70000	13	1	NA	NA	NA	0.4	0.48	200	2	NA	0.75
164	HD	HDT	d	m	h	2010	70000	8	1	NA	NA	NA	0.4	0.48	200	2	NA	0.75
165	HD	HDT	d	m	h	2010	70000	13	1	NA	NA	NA	0.4	0.48	200	4	NA	0.75
166	HD	HDT	d	m	h	2010	70000	8	1	NA	NA	NA	0.4	0.48	200	4	NA	0.75
167	HD	MDV	d	m	c	2010	30000	7	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
168	HD	MDV	d	m	c	2010	20000	7	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
169	HD	MDV	d	m	c	2010	40000	7	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
170	HD	MDV	d	m	c	2010	30000	5	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
171	HD	MDV	d	m	c	2010	30000	9	1	NA	NA	NA	0.4	0.48	NA	NA	NA	0.75
172	HD	MDV	d	m	h	2010	30000	7	1	NA	NA	NA	0.4	0.48	50	2	NA	0.75
173	HD	MDV	d	m	h	2010	30000	5	1	NA	NA	NA	0.4	0.48	50	2	NA	0.75
174	HD	MDV	d	m	h	2010	30000	7	1	NA	NA	NA	0.4	0.48	100	2	NA	0.75
175	HD	MDV	d	m	h	2010	30000	5	1	NA	NA	NA	0.4	0.48	100	2	NA	0.75
176	HD	MDV	d	m	h	2010	30000	7	1	NA	NA	NA	0.4	0.48	100	4	NA	0.75
177	HD	MDV	d	m	h	2010	30000	5	1	NA	NA	NA	0.4	0.48	100	4	NA	0.75

Appendix C: Average Fuel Consumption Rates by VSP Bin for Modeled Vehicles (in Gasoline-Equivalent grams per second)

Veh. ID	Bin_0	Bin_1	Bin_11	Bin_12	Bin_13	Bin_14	Bin_15	Bin_16	Bin_21	Bin_22	Bin_23	Bin_24	Bin_25	Bin_26	Bin_33	Bin_35	Bin_36
1	0.368	0.235	0.353	0.483	1.002	1.435	1.815	2.498	0.385	0.603	0.921	1.254	1.572	2.408	0.786	1.559	2.605
2	0.345	0.219	0.331	0.465	0.977	1.408	1.788	2.468	0.361	0.579	0.897	1.230	1.548	2.381	0.756	1.529	2.572
3	0.368	0.235	0.353	0.451	0.886	1.245	1.562	2.093	0.385	0.590	0.885	1.193	1.488	2.226	0.766	1.485	2.456
4	0.345	0.219	0.331	0.432	0.861	1.218	1.534	2.065	0.361	0.566	0.861	1.169	1.463	2.200	0.737	1.454	2.423
5	0.165	0.092	0.162	0.308	0.744	1.137	1.491	2.091	0.168	0.374	0.672	0.983	1.284	2.035	0.508	1.230	2.185
6	0.239	0.148	0.230	0.378	0.863	1.285	1.662	2.331	0.250	0.467	0.785	1.119	1.437	2.257	0.621	1.390	2.424
7	0.345	0.219	0.327	0.421	0.793	1.085	1.345	1.769	0.358	0.523	0.731	0.958	1.171	1.705	0.655	1.191	2.096
8	0.345	0.219	0.329	0.420	0.792	1.089	1.355	1.768	0.358	0.520	0.735	0.958	1.167	1.695	0.658	1.192	1.989
9	0.345	0.219	0.331	0.466	0.978	1.406	1.790	2.473	0.358	0.580	0.899	1.230	1.548	2.391	0.764	1.537	2.621
10	0.345	0.219	0.332	0.514	1.162	1.722	2.224	3.292	0.360	0.639	1.060	1.504	1.930	3.194	0.847	1.867	3.265
11	0.345	0.219	0.331	0.509	1.153	1.707	2.228	3.314	0.362	0.624	1.060	1.495	1.932	3.200	0.826	1.862	3.157
12	0.213	0.151	0.201	0.315	0.648	0.928	1.181	1.681	0.220	0.384	0.592	0.818	1.031	1.631	0.489	1.015	1.906
13	0.212	0.151	0.204	0.359	0.831	1.249	1.646	2.507	0.222	0.439	0.756	1.091	1.428	2.478	0.578	1.345	2.387
14	0.110	0.096	0.099	0.210	0.460	0.672	0.895	1.364	0.110	0.249	0.417	0.593	0.787	1.411	0.320	0.733	1.621
15	0.477	0.288	0.459	0.615	1.298	1.866	2.391	3.278	0.502	0.764	1.200	1.634	2.072	3.168	1.007	2.051	3.350
16	0.477	0.288	0.458	0.570	1.122	1.567	1.951	2.565	0.499	0.718	1.037	1.369	1.687	2.465	0.934	1.713	2.769
17	0.345	0.219	0.331	0.465	0.977	1.408	1.788	2.468	0.361	0.579	0.897	1.230	1.548	2.381	0.756	1.529	2.572
18	0.346	0.219	0.327	0.472	0.981	1.403	1.784	2.496	0.358	0.582	0.895	1.236	1.555	2.418	0.753	1.537	2.884
19	0.345	0.219	0.329	0.469	0.976	1.408	1.797	2.488	0.357	0.578	0.901	1.235	1.548	2.400	0.745	1.532	2.752
20	0.166	0.092	0.160	0.316	0.750	1.139	1.495	2.105	0.166	0.376	0.669	0.987	1.285	2.066	0.510	1.242	2.453
21	0.226	0.151	0.200	0.314	0.656	0.919	1.167	1.670	0.220	0.375	0.598	0.814	1.033	1.660	0.477	0.995	2.389
22	0.477	0.288	0.457	0.622	1.307	1.880	2.399	3.293	0.496	0.778	1.205	1.646	2.067	3.190	1.041	2.071	3.537
23	0.005	0.001	0.000	0.199	0.470	0.693	0.950	1.378	0.000	0.243	0.432	0.622	0.835	1.481	0.290	0.768	1.299
24	0.004	0.000	0.000	0.142	0.470	0.693	0.950	1.378	0.000	0.189	0.432	0.622	0.835	1.481	0.278	0.768	1.299
25	0.001	0.000	0.000	0.205	0.609	0.902	1.183	1.777	0.000	0.277	0.555	0.795	1.024	1.771	0.353	0.983	1.753
26	0.001	0.000	0.000	0.205	0.609	0.902	1.183	1.777	0.000	0.277	0.555	0.795	1.024	1.771	0.353	0.983	1.753
27	0.001	0.000	0.000	0.205	0.609	0.902	1.183	1.777	0.000	0.277	0.555	0.795	1.024	1.771	0.353	0.983	1.753
28	0.001	0.000	0.000	0.205	0.609	0.902	1.183	1.777	0.000	0.277	0.555	0.795	1.024	1.771	0.353	0.983	1.753
29	0.000	0.000	0.000	0.299	0.856	1.296	1.738	2.597	0.000	0.399	0.788	1.139	1.513	2.644	0.491	1.405	2.315
30	0.000	0.000	0.000	0.341	0.955	1.429	1.869	2.818	0.000	0.457	0.874	1.248	1.623	2.745	0.546	1.550	2.590
31	0.000	0.000	0.000	0.246	0.955	1.429	1.869	2.818	0.000	0.338	0.874	1.248	1.623	2.745	0.516	1.550	2.590
32	0.000	0.000	0.000	0.155	0.955	1.429	1.869	2.818	0.000	0.179	0.874	1.248	1.623	2.745	0.462	1.550	2.590

33	0.000	0.000	0.000	0.142	0.955	1.429	1.869	2.818	0.000	0.161	0.874	1.248	1.623	2.745	0.454	1.550	2.590
34	0.000	0.000	0.000	0.146	0.955	1.429	1.869	2.818	0.000	0.162	0.874	1.248	1.623	2.745	0.456	1.550	2.590
35	0.000	0.000	0.000	0.183	0.555	0.871	1.266	1.713	0.000	0.224	0.511	0.783	1.106	2.001	0.325	0.963	1.490
36	0.000	0.000	0.000	0.243	0.733	1.157	1.665	2.331	0.000	0.310	0.674	1.026	1.453	2.634	0.406	1.266	1.994
37	0.000	0.000	0.000	0.270	0.771	1.161	1.555	2.318	0.000	0.353	0.710	1.023	1.347	2.383	0.464	1.271	2.126
38	0.000	0.000	0.000	0.168	0.895	1.317	1.701	2.500	0.000	0.216	0.818	1.152	1.472	2.424	0.481	1.435	2.467
39	0.000	0.000	0.000	0.219	1.021	1.521	1.979	2.975	0.000	0.294	0.932	1.332	1.721	2.915	0.551	1.652	2.825
40	0.001	0.000	0.000	0.386	1.023	1.524	1.994	2.988	0.000	0.488	0.936	1.342	1.720	2.926	0.609	1.656	2.931
41	0.000	0.000	0.000	0.231	0.680	1.054	1.498	2.013	0.000	0.299	0.635	0.941	1.321	2.312	0.409	1.161	1.763
42	0.000	0.000	0.000	0.230	0.672	1.014	1.371	2.031	0.000	0.290	0.618	0.897	1.197	2.129	0.397	1.112	1.841
43	0.000	0.000	0.000	0.224	0.658	1.012	1.443	1.969	0.000	0.285	0.610	0.901	1.248	2.203	0.391	1.111	1.737
44	0.001	0.000	0.000	0.360	0.960	1.431	1.873	2.807	0.000	0.454	0.875	1.257	1.611	2.752	0.564	1.553	2.757
45	0.000	0.000	0.000	0.249	0.960	1.433	1.869	2.814	0.000	0.341	0.878	1.257	1.622	2.756	0.535	1.555	2.660
46	0.132	0.133	0.132	0.237	0.421	0.630	0.884	1.390	0.132	0.267	0.429	0.634	0.879	1.570	0.302	0.777	1.687
47	0.133	0.133	0.132	0.215	0.343	0.460	0.591	0.890	0.132	0.237	0.347	0.462	0.592	1.016	0.267	0.549	1.274
48	0.132	0.133	0.132	0.257	0.507	0.832	1.238	1.912	0.132	0.290	0.524	0.835	1.226	2.144	0.338	1.048	2.203
49	0.094	0.094	0.094	0.166	0.378	0.681	0.982	1.503	0.094	0.191	0.389	0.685	0.977	1.704	0.253	0.855	1.860
50	0.106	0.107	0.106	0.186	0.380	0.652	0.960	1.461	0.106	0.211	0.390	0.656	0.955	1.647	0.262	0.830	1.791
51	0.117	0.117	0.117	0.205	0.392	0.635	0.927	1.436	0.117	0.232	0.400	0.638	0.921	1.616	0.275	0.804	1.743
52	0.126	0.127	0.126	0.224	0.408	0.629	0.899	1.410	0.126	0.252	0.416	0.632	0.894	1.588	0.290	0.785	1.709
53	0.000	0.000	0.000	0.140	0.477	0.880	1.250	2.008	0.000	0.196	0.500	0.883	1.241	2.274	0.264	1.077	2.349
54	0.000	0.000	0.000	0.162	0.543	1.008	1.437	2.329	0.000	0.229	0.576	1.010	1.423	2.631	0.289	1.229	2.690
55	0.000	0.000	0.000	0.156	0.497	0.916	1.321	2.063	0.000	0.211	0.521	0.921	1.310	2.336	0.272	1.129	2.415
56	0.000	0.000	0.000	0.145	0.501	0.925	1.311	2.133	0.000	0.199	0.526	0.930	1.302	2.417	0.272	1.130	2.480
57	0.000	0.000	0.000	0.104	0.386	0.705	0.984	1.599	0.000	0.151	0.399	0.709	0.979	1.822	0.221	0.867	1.965
58	0.000	0.000	0.000	0.131	0.385	0.647	0.955	1.458	0.000	0.186	0.394	0.651	0.949	1.644	0.227	0.825	1.787
59	-0.065	0.018	0.012	0.056	0.160	0.261	0.354	0.525	-0.008	0.071	0.162	0.260	0.356	0.590	0.093	0.324	0.749
60	-0.065	0.018	0.012	0.056	0.160	0.261	0.354	0.525	-0.008	0.071	0.162	0.260	0.356	0.590	0.093	0.324	0.749
61	-0.099	0.018	0.008	0.065	0.194	0.322	0.443	0.649	-0.022	0.083	0.198	0.323	0.439	0.726	0.107	0.395	0.834
62	-0.099	0.018	0.008	0.065	0.194	0.322	0.443	0.649	-0.022	0.083	0.198	0.323	0.439	0.726	0.107	0.395	0.834
63	-0.099	0.018	0.008	0.065	0.194	0.322	0.443	0.649	-0.022	0.083	0.198	0.323	0.439	0.723	0.107	0.395	0.827
64	-0.131	0.018	0.002	0.074	0.228	0.382	0.529	0.774	-0.035	0.095	0.235	0.383	0.523	0.863	0.128	0.473	0.939
65	-0.131	0.018	0.002	0.074	0.228	0.382	0.529	0.773	-0.035	0.095	0.235	0.383	0.523	0.856	0.128	0.473	0.924
66	-0.131	0.018	0.002	0.074	0.228	0.382	0.529	0.774	-0.035	0.095	0.235	0.383	0.523	0.864	0.128	0.473	0.939
67	-0.194	0.018	-0.008	0.090	0.293	0.497	0.697	1.023	-0.058	0.117	0.304	0.496	0.688	1.123	0.141	0.606	1.165
68	-0.182	0.018	-0.006	0.086	0.281	0.477	0.666	0.975	-0.053	0.114	0.291	0.478	0.660	1.069	0.138	0.581	1.113
69	-0.133	0.018	0.002	0.074	0.229	0.384	0.532	0.779	-0.035	0.096	0.237	0.386	0.527	0.870	0.129	0.475	0.944
70	-0.020	0.018	0.017	0.045	0.116	0.183	0.247	0.370	0.009	0.054	0.120	0.184	0.252	0.425	0.079	0.231	0.671

71	-0.195	0.018	-0.008	0.090	0.294	0.499	0.700	1.027	-0.058	0.119	0.305	0.499	0.692	1.133	0.141	0.608	1.171
72	-0.164	0.018	-0.003	0.082	0.264	0.445	0.616	0.903	-0.045	0.110	0.274	0.447	0.612	1.001	0.132	0.541	1.055
73	0.001	0.000	0.000	0.181	0.551	0.840	1.187	1.628	0.000	0.241	0.509	0.758	1.042	1.829	0.317	0.925	1.443
74	0.345	0.287	0.331	0.536	1.048	1.479	1.859	2.560	0.361	0.650	0.968	1.301	1.619	2.461	0.807	1.600	2.643
75	0.346	0.340	0.331	0.592	1.105	1.536	1.916	2.625	0.361	0.707	1.024	1.358	1.676	2.521	0.847	1.656	2.701
76	0.346	0.394	0.331	0.649	1.161	1.593	1.973	2.691	0.361	0.763	1.081	1.415	1.732	2.587	0.887	1.713	2.758
77	0.112	0.164	0.099	0.281	0.531	0.746	0.993	1.457	0.110	0.320	0.488	0.667	0.880	1.509	0.372	0.805	1.693
78	0.113	0.218	0.099	0.338	0.588	0.809	1.069	1.515	0.110	0.377	0.545	0.732	0.962	1.587	0.414	0.862	1.750
79	0.114	0.273	0.099	0.395	0.644	0.881	1.139	1.572	0.110	0.434	0.602	0.797	1.037	1.666	0.456	0.922	1.808
80	0.478	0.355	0.458	0.641	1.193	1.638	2.022	2.641	0.499	0.789	1.108	1.440	1.758	2.540	0.984	1.784	2.840
81	0.478	0.409	0.458	0.698	1.250	1.695	2.079	2.698	0.499	0.846	1.165	1.497	1.814	2.599	1.025	1.841	2.897
82	0.478	0.463	0.458	0.755	1.307	1.751	2.136	2.762	0.499	0.903	1.222	1.553	1.871	2.658	1.065	1.897	2.954
83	0.000	0.019	0.000	0.393	0.785	1.143	1.491	2.206	0.000	0.460	0.731	1.013	1.302	2.199	0.498	1.240	2.067
84	0.013	0.269	0.098	0.449	0.836	1.196	1.560	2.262	0.043	0.517	0.788	1.070	1.367	2.284	0.551	1.297	2.110
85	0.023	0.326	0.175	0.503	0.887	1.247	1.621	2.321	0.089	0.573	0.844	1.128	1.436	2.370	0.609	1.354	2.150
86	0.000	0.017	0.000	0.358	0.741	1.123	1.571	2.048	0.000	0.419	0.706	1.029	1.419	2.405	0.471	1.232	1.782
87	0.011	0.244	0.080	0.410	0.790	1.184	1.620	2.071	0.042	0.476	0.762	1.105	1.504	2.464	0.523	1.289	1.794
88	0.020	0.301	0.148	0.457	0.838	1.249	1.663	2.092	0.078	0.533	0.820	1.181	1.588	2.537	0.575	1.343	1.803
89	0.000	0.000	0.000	0.268	0.964	1.387	1.771	2.586	0.000	0.369	0.889	1.223	1.543	2.522	0.559	1.506	2.532
90	0.000	0.000	0.000	0.375	1.018	1.443	1.827	2.665	0.000	0.506	0.946	1.280	1.602	2.599	0.624	1.563	2.584
91	0.000	0.000	0.000	0.509	1.071	1.499	1.889	2.738	0.000	0.622	1.003	1.337	1.663	2.679	0.678	1.620	2.634
92	0.001	0.015	0.000	0.311	0.615	0.916	1.265	1.668	0.000	0.362	0.582	0.847	1.146	1.920	0.389	0.999	1.460
93	0.013	0.231	0.091	0.361	0.663	0.976	1.313	1.694	0.046	0.419	0.639	0.921	1.224	1.995	0.443	1.055	1.468
94	0.026	0.285	0.160	0.402	0.711	1.037	1.360	1.716	0.090	0.475	0.697	0.990	1.299	2.072	0.496	1.109	1.473
95	-0.134	0.048	0.027	0.112	0.294	0.475	0.646	0.933	-0.015	0.140	0.303	0.476	0.642	1.031	0.161	0.571	1.084
96	-0.111	0.072	0.051	0.136	0.318	0.499	0.670	0.957	0.008	0.164	0.327	0.500	0.666	1.055	0.185	0.595	1.108
97	-0.087	0.096	0.075	0.160	0.342	0.523	0.694	0.981	0.032	0.188	0.351	0.524	0.690	1.079	0.209	0.619	1.132
98	-0.101	0.048	0.032	0.104	0.258	0.411	0.558	0.804	-0.005	0.125	0.265	0.413	0.553	0.894	0.158	0.503	0.969
99	-0.077	0.072	0.056	0.128	0.282	0.435	0.582	0.828	0.019	0.149	0.289	0.437	0.577	0.918	0.182	0.527	0.993
100	-0.053	0.096	0.080	0.152	0.306	0.459	0.606	0.852	0.043	0.173	0.313	0.461	0.601	0.942	0.206	0.551	1.017
101	-0.152	0.048	0.024	0.116	0.311	0.507	0.696	1.005	-0.023	0.144	0.321	0.508	0.690	1.099	0.168	0.611	1.143
102	-0.128	0.072	0.048	0.140	0.335	0.531	0.720	1.028	0.001	0.168	0.345	0.532	0.714	1.123	0.192	0.635	1.167
103	-0.104	0.096	0.072	0.164	0.359	0.555	0.744	1.052	0.025	0.191	0.369	0.556	0.738	1.147	0.216	0.659	1.191
104	-0.103	0.048	0.032	0.104	0.259	0.414	0.562	0.809	-0.005	0.126	0.267	0.416	0.557	0.900	0.158	0.505	0.974
105	-0.079	0.072	0.056	0.128	0.283	0.438	0.586	0.833	0.019	0.150	0.291	0.440	0.581	0.924	0.182	0.529	0.997
106	-0.055	0.096	0.080	0.152	0.307	0.462	0.610	0.857	0.043	0.174	0.315	0.464	0.605	0.948	0.206	0.553	1.021
107	0.194	0.194	0.194	0.261	0.443	0.676	0.955	1.467	0.194	0.286	0.451	0.679	0.949	1.644	0.334	0.837	1.766
108	0.225	0.225	0.225	0.287	0.472	0.714	1.000	1.513	0.225	0.311	0.481	0.718	0.995	1.689	0.363	0.880	1.812

109	0.251	0.251	0.251	0.311	0.502	0.754	1.047	1.558	0.251	0.335	0.512	0.758	1.041	1.734	0.391	0.924	1.857
110	0.000	0.003	0.000	0.310	0.719	1.075	1.411	2.112	0.000	0.373	0.660	0.942	1.222	2.097	0.444	1.169	2.012
111	0.000	0.000	0.000	0.194	0.719	1.075	1.411	2.112	0.000	0.256	0.660	0.942	1.222	2.097	0.416	1.169	2.012
112	0.000	0.000	0.000	0.137	0.719	1.075	1.411	2.112	0.000	0.174	0.660	0.942	1.222	2.097	0.389	1.169	2.012
113	0.000	0.000	0.000	0.022	0.719	1.075	1.411	2.112	0.000	0.000	0.622	0.942	1.222	2.097	0.323	1.169	2.012
114	0.018	0.269	0.145	0.449	0.836	1.196	1.560	2.262	0.075	0.517	0.788	1.070	1.367	2.284	0.564	1.297	2.110
115	0.000	0.000	0.000	0.191	0.836	1.196	1.560	2.262	0.000	0.248	0.788	1.070	1.367	2.284	0.469	1.297	2.110
116	0.216	0.151	0.199	0.294	0.577	0.798	1.002	1.354	0.220	0.359	0.528	0.706	0.878	1.337	0.449	0.867	1.760
117	0.007	0.002	0.000	0.276	0.595	0.829	1.046	1.427	0.000	0.345	0.543	0.732	0.914	1.399	0.383	0.903	1.780
118	0.005	0.001	0.000	0.199	0.470	0.693	0.950	1.378	0.000	0.243	0.432	0.622	0.835	1.481	0.290	0.768	1.299
119	0.007	0.002	0.000	0.276	0.595	0.829	1.046	1.427	0.000	0.345	0.543	0.732	0.914	1.399	0.383	0.903	1.780
120	0.002	0.000	0.000	0.031	0.470	0.693	0.950	1.378	0.000	0.005	0.432	0.622	0.835	1.481	0.226	0.768	1.299
121	0.002	0.000	0.000	0.031	0.470	0.693	0.950	1.378	0.000	0.005	0.432	0.622	0.835	1.481	0.226	0.768	1.299
122	0.002	0.000	0.000	0.042	0.595	0.829	1.046	1.427	0.000	0.007	0.543	0.732	0.914	1.399	0.291	0.903	1.780
123	0.002	0.000	0.000	0.042	0.595	0.829	1.046	1.427	0.000	0.007	0.543	0.732	0.914	1.399	0.291	0.903	1.780
124	0.005	0.000	0.000	0.224	0.582	0.817	1.092	1.468	0.000	0.301	0.559	0.767	1.010	1.651	0.366	0.897	1.321
125	0.005	0.000	0.000	0.224	0.582	0.817	1.092	1.468	0.000	0.301	0.559	0.767	1.010	1.651	0.366	0.897	1.321
126	0.007	0.000	0.000	0.290	0.722	0.957	1.174	1.579	0.000	0.383	0.671	0.860	1.042	1.546	0.454	1.031	1.904
127	0.007	0.000	0.000	0.290	0.722	0.957	1.174	1.579	0.000	0.383	0.671	0.860	1.042	1.546	0.454	1.031	1.904
128	0.030	0.225	0.143	0.331	0.582	0.817	1.092	1.468	0.076	0.381	0.559	0.767	1.010	1.651	0.407	0.897	1.321
129	0.030	0.225	0.143	0.331	0.582	0.817	1.092	1.468	0.076	0.381	0.559	0.767	1.010	1.651	0.407	0.897	1.321
130	0.039	0.280	0.201	0.426	0.722	0.957	1.174	1.579	0.112	0.491	0.671	0.860	1.042	1.546	0.514	1.031	1.904
131	0.039	0.280	0.201	0.426	0.722	0.957	1.174	1.579	0.112	0.491	0.671	0.860	1.042	1.546	0.514	1.031	1.904
132	-0.065	0.018	0.012	0.056	0.160	0.261	0.354	0.524	-0.008	0.071	0.162	0.260	0.356	0.585	0.093	0.324	0.717
133	-0.065	0.018	0.012	0.056	0.160	0.261	0.354	0.525	-0.008	0.071	0.162	0.260	0.356	0.589	0.093	0.324	0.747
134	-0.011	0.072	0.066	0.110	0.213	0.314	0.408	0.578	0.045	0.125	0.216	0.314	0.410	0.639	0.147	0.378	0.770
135	-0.011	0.072	0.066	0.110	0.213	0.314	0.408	0.578	0.045	0.125	0.216	0.314	0.410	0.643	0.147	0.378	0.801
136	0.107	0.106	0.106	0.166	0.286	0.430	0.601	0.951	0.106	0.183	0.290	0.432	0.602	1.080	0.220	0.546	1.347
137	0.094	0.094	0.094	0.146	0.271	0.435	0.627	0.978	0.094	0.163	0.275	0.437	0.628	1.108	0.204	0.566	1.394
138	0.079	0.079	0.079	0.126	0.263	0.457	0.658	1.006	0.079	0.142	0.269	0.460	0.659	1.150	0.192	0.593	1.475
139	0.062	0.061	0.061	0.106	0.274	0.484	0.666	1.098	0.061	0.124	0.281	0.487	0.667	1.260	0.190	0.608	1.528
140	0.183	0.183	0.183	0.224	0.351	0.514	0.701	1.054	0.183	0.240	0.356	0.517	0.702	1.182	0.286	0.641	1.451
141	0.118	0.117	0.117	0.175	0.378	0.578	0.773	1.223	0.117	0.200	0.384	0.580	0.773	1.343	0.274	0.710	1.477
142	0.345	0.205	0.331	0.401	0.777	1.076	1.334	1.803	0.361	0.507	0.719	0.940	1.152	1.726	0.658	1.179	1.889
143	0.165	0.082	0.162	0.264	0.604	0.904	1.177	1.815	0.168	0.323	0.546	0.779	1.013	1.766	0.439	0.984	1.718
144	0.000	0.000	0.000	0.241	0.648	0.949	1.255	1.874	0.000	0.328	0.600	0.833	1.090	1.912	0.390	1.035	1.657
145	0.000	0.000	0.000	0.179	0.525	0.839	1.220	1.553	0.000	0.231	0.490	0.761	1.114	1.962	0.302	0.912	1.314
146	0.909	0.320	0.826	2.604	8.016	12.920	18.707	28.631	1.137	3.787	8.276	13.128	18.269	31.095	3.612	16.894	36.092

147	0.824	0.255	0.747	2.523	7.926	12.818	18.564	28.464	1.038	3.688	8.178	13.023	18.129	30.917	3.511	16.771	35.925
148	0.597	0.080	0.533	2.307	7.685	12.541	18.179	28.013	0.774	3.422	7.914	12.741	17.754	30.440	3.240	16.441	35.476
149	0.824	0.254	0.753	2.380	7.833	12.930	18.612	28.441	1.044	3.139	8.114	12.695	18.675	31.396	2.674	15.254	34.537
150	0.824	0.361	0.747	2.632	8.035	12.940	18.672	28.572	1.038	3.796	8.286	13.131	18.279	31.026	3.561	16.880	36.033
151	0.824	0.504	0.747	2.777	8.179	13.090	18.854	28.717	1.038	3.941	8.431	13.276	18.437	31.170	3.628	17.024	36.178
152	0.634	0.204	0.574	2.350	7.764	12.999	18.563	27.858	0.799	3.446	7.949	13.189	18.355	30.300	3.262	16.636	35.322
153	1.014	0.305	0.919	2.697	8.130	12.849	18.201	28.629	1.278	3.930	8.417	13.115	17.850	31.134	3.759	16.674	36.243
154	0.825	0.254	0.747	2.025	5.918	9.295	12.964	20.411	1.027	2.909	6.114	9.430	12.822	22.526	3.099	12.036	25.612
155	0.824	0.255	0.747	3.026	10.022	16.758	23.854	35.804	1.035	4.412	10.168	16.912	23.650	38.924	3.974	21.632	47.068
156	0.825	0.254	0.741	1.559	3.932	5.925	7.971	12.314	1.023	2.162	4.099	6.138	8.237	13.540	2.451	7.294	15.650
157	0.824	0.255	0.747	3.524	12.182	20.648	28.552	43.145	1.034	5.112	12.321	20.953	28.461	46.747	4.446	25.819	56.496
158	0.507	0.171	0.459	2.236	7.740	13.106	18.167	27.454	0.639	3.285	7.887	13.404	18.118	29.843	3.119	16.534	34.919
159	0.000	-0.005	0.000	2.548	8.343	13.628	19.631	24.956	0.000	3.800	8.578	13.821	19.315	26.724	3.012	16.974	25.480
160	0.000	-0.003	0.000	2.286	8.186	13.574	15.784	15.985	0.000	3.403	8.318	14.080	17.271	17.154	2.848	13.457	15.979
161	0.000	-0.005	0.000	2.548	8.343	13.628	19.631	24.956	0.000	3.800	8.578	13.821	19.315	26.724	3.012	16.974	25.480
162	0.000	-0.003	0.000	2.286	8.186	13.574	15.784	15.985	0.000	3.403	8.318	14.080	17.271	17.154	2.848	13.457	15.979
163	0.000	-0.005	0.000	2.548	8.343	13.628	19.631	24.956	0.000	3.800	8.578	13.821	19.315	26.724	3.012	16.974	25.480
164	0.000	-0.003	0.000	2.286	8.186	13.574	15.784	15.985	0.000	3.403	8.318	14.080	17.271	17.154	2.848	13.457	15.979
165	0.000	0.000	0.000	2.528	8.343	13.628	19.631	24.956	0.000	3.790	8.578	13.821	19.315	26.724	2.978	16.974	25.480
166	0.000	0.000	0.000	2.270	8.186	13.574	15.784	15.985	0.000	3.396	8.318	14.080	17.271	17.154	2.826	13.457	15.979
167	0.435	0.154	0.419	1.257	3.556	5.611	8.079	13.486	0.391	1.504	3.437	5.595	7.827	13.298	1.915	6.778	14.710
168	0.435	0.153	0.418	1.001	2.535	3.857	5.229	8.444	0.393	1.157	2.464	3.840	5.226	8.920	1.324	4.243	10.127
169	0.435	0.154	0.415	1.491	4.593	7.686	11.207	17.497	0.391	1.872	4.467	7.413	10.472	17.363	2.088	8.403	18.948
170	0.311	0.120	0.298	1.139	3.473	5.891	8.725	13.410	0.279	1.393	3.351	5.636	7.887	13.017	1.761	6.629	14.550
171	0.559	0.187	0.539	1.384	3.672	5.648	7.902	13.001	0.502	1.616	3.546	5.635	7.790	13.389	2.069	6.926	14.871
172	0.000	0.000	0.000	1.272	3.746	5.954	8.608	14.026	0.000	1.558	3.610	5.912	8.148	10.785	1.737	6.756	7.853
173	0.000	0.000	0.000	1.160	3.674	6.237	9.196	12.706	0.000	1.448	3.530	5.950	7.622	8.191	1.644	5.319	5.609
174	0.000	0.000	0.000	1.272	3.746	5.954	8.608	14.026	0.000	1.558	3.610	5.912	8.148	10.785	1.737	6.756	7.853
175	0.000	0.000	0.000	1.160	3.674	6.237	9.196	12.706	0.000	1.448	3.530	5.950	7.622	8.191	1.644	5.319	5.609
176	0.000	0.000	0.000	1.227	3.746	5.954	8.608	14.026	0.000	1.542	3.610	5.912	8.148	10.785	1.737	6.756	7.853
177	0.000	0.000	0.000	1.124	3.674	6.237	9.196	12.706	0.000	1.435	3.530	5.950	7.622	8.191	1.644	5.319	5.609

Appendix D: Fitted Freeway FSC Parameters for Modeled Vehicles

Vehicle ID	a_0	a_1	a_2	a_3	a_4
1	1.783213	0.106157	-0.002793	3.333E-05	-1.518E-07
2	1.824491	0.105618	-0.002793	3.343E-05	-1.526E-07
3	1.851279	0.107154	-0.002866	3.460E-05	-1.584E-07
4	1.895435	0.106611	-0.002870	3.476E-05	-1.596E-07
5	2.244790	0.100253	-0.002529	2.748E-05	-1.154E-07
6	2.038824	0.102380	-0.002787	3.389E-05	-1.566E-07
7	2.054452	0.091436	-0.002282	2.439E-05	-9.426E-08
8	1.976539	0.102943	-0.003216	4.183E-05	-1.853E-07
9	1.881214	0.097106	-0.002998	3.808E-05	-1.659E-07
10	1.724705	0.100663	-0.003120	4.028E-05	-1.839E-07
11	1.640955	0.116033	-0.003220	4.137E-05	-2.028E-07
12	2.310467	0.091566	-0.002476	2.839E-05	-1.183E-07
13	1.986791	0.112366	-0.003221	4.116E-05	-1.979E-07
14	2.647460	0.091345	-0.002873	3.627E-05	-1.592E-07
15	1.514043	0.111216	-0.002934	3.625E-05	-1.725E-07
16	1.656099	0.103542	-0.002613	3.014E-05	-1.332E-07
17	1.824491	0.105618	-0.002793	3.343E-05	-1.526E-07
18	1.914211	0.088989	-0.002373	2.672E-05	-1.089E-07
19	1.896987	0.094755	-0.002916	3.649E-05	-1.559E-07
20	2.351990	0.079158	-0.001973	1.899E-05	-6.253E-08
21	2.330680	0.080886	-0.002479	2.937E-05	-1.149E-07
22	1.568577	0.099609	-0.002612	3.031E-05	-1.322E-07
23	3.057061	0.066832	-0.002258	3.130E-05	-1.497E-07
24	3.062790	0.074183	-0.002654	3.821E-05	-1.892E-07
25	2.940162	0.063293	-0.001942	2.435E-05	-1.091E-07
26	2.940162	0.063293	-0.001942	2.435E-05	-1.091E-07
27	2.940162	0.063293	-0.001942	2.435E-05	-1.091E-07
28	2.940162	0.063293	-0.001942	2.435E-05	-1.091E-07
29	2.438161	0.091232	-0.002846	3.876E-05	-1.950E-07
30	2.356559	0.090689	-0.002765	3.706E-05	-1.854E-07
31	2.341082	0.100811	-0.003242	4.495E-05	-2.291E-07
32	2.322169	0.111865	-0.003749	5.326E-05	-2.752E-07
33	2.319168	0.113490	-0.003825	5.451E-05	-2.823E-07
34	2.319984	0.113069	-0.003804	5.416E-05	-2.803E-07
35	2.766462	0.094392	-0.002911	3.826E-05	-1.841E-07
36	2.396023	0.112646	-0.003473	4.679E-05	-2.347E-07
37	2.654868	0.066629	-0.002553	3.703E-05	-1.766E-07
38	2.631336	0.068038	-0.002656	3.818E-05	-1.809E-07
39	2.433790	0.074888	-0.002818	4.025E-05	-1.939E-07
40	2.430380	0.062825	-0.002191	2.911E-05	-1.294E-07
41	2.667211	0.078435	-0.003156	4.890E-05	-2.500E-07
42	2.737650	0.071865	-0.002884	4.371E-05	-2.172E-07
43	2.709889	0.076542	-0.003091	4.773E-05	-2.423E-07
44	2.510618	0.059809	-0.002107	2.795E-05	-1.224E-07
45	2.500726	0.069326	-0.002580	3.634E-05	-1.711E-07
46	2.434315	0.117066	-0.003337	4.156E-05	-1.965E-07
47	2.714601	0.101231	-0.002803	3.221E-05	-1.343E-07

48	2.166183	0.136175	-0.004187	5.745E-05	-2.973E-07
49	2.537854	0.120394	-0.003728	4.878E-05	-2.375E-07
50	2.503017	0.120701	-0.003655	4.722E-05	-2.280E-07
51	2.472466	0.120080	-0.003556	4.533E-05	-2.173E-07
52	2.449176	0.118482	-0.003430	4.312E-05	-2.051E-07
53	2.690532	0.115772	-0.003971	5.737E-05	-3.054E-07
54	2.556691	0.118478	-0.003996	5.755E-05	-3.057E-07
55	2.674265	0.112946	-0.003816	5.491E-05	-2.925E-07
56	2.644969	0.116820	-0.003999	5.793E-05	-3.093E-07
57	3.025211	0.093834	-0.003175	4.322E-05	-2.156E-07
58	3.108886	0.085692	-0.002794	3.702E-05	-1.811E-07
59	4.236186	0.051136	-0.001874	2.405E-05	-1.038E-07
60	4.236186	0.051136	-0.001874	2.405E-05	-1.038E-07
61	4.113757	0.054689	-0.001853	2.356E-05	-1.068E-07
62	4.113757	0.054689	-0.001853	2.356E-05	-1.068E-07
63	4.113281	0.054872	-0.001859	2.365E-05	-1.074E-07
64	3.933246	0.068015	-0.002315	3.074E-05	-1.477E-07
65	3.931530	0.068447	-0.002330	3.102E-05	-1.493E-07
66	3.932803	0.068060	-0.002317	3.077E-05	-1.479E-07
67	3.634907	0.088990	-0.003075	4.377E-05	-2.291E-07
68	3.704548	0.083578	-0.002883	4.070E-05	-2.108E-07
69	3.925838	0.068254	-0.002318	3.076E-05	-1.478E-07
70	4.358944	0.049310	-0.002066	2.798E-05	-1.191E-07
71	3.631751	0.088805	-0.003063	4.360E-05	-2.282E-07
72	3.779496	0.077536	-0.002639	3.637E-05	-1.843E-07
73	2.894970	0.078733	-0.002662	3.774E-05	-1.888E-07
74	1.693503	0.111251	-0.002952	3.558E-05	-1.633E-07
75	1.599811	0.115022	-0.003055	3.697E-05	-1.702E-07
76	1.512789	0.118423	-0.003149	3.825E-05	-1.766E-07
77	2.372608	0.103585	-0.003188	4.046E-05	-1.806E-07
78	2.194489	0.110594	-0.003363	4.281E-05	-1.929E-07
79	2.041505	0.116052	-0.003494	4.455E-05	-2.021E-07
80	1.546917	0.108220	-0.002748	3.201E-05	-1.426E-07
81	1.467005	0.111483	-0.002841	3.329E-05	-1.490E-07
82	1.391944	0.114459	-0.002926	3.445E-05	-1.549E-07
83	2.622549	0.064668	-0.001709	1.942E-05	-8.147E-08
84	1.925584	0.118892	-0.003457	4.431E-05	-2.101E-07
85	1.803077	0.120354	-0.003429	4.359E-05	-2.058E-07
86	2.536762	0.076992	-0.002942	4.484E-05	-2.267E-07
87	1.900439	0.128260	-0.004599	6.852E-05	-3.496E-07
88	1.758886	0.133377	-0.004697	6.970E-05	-3.558E-07
89	2.564275	0.062669	-0.002336	3.261E-05	-1.495E-07
90	2.510408	0.057471	-0.002031	2.729E-05	-1.194E-07
91	2.458029	0.051639	-0.001692	2.138E-05	-8.592E-08
92	2.756831	0.072123	-0.002234	3.039E-05	-1.475E-07
93	2.040880	0.127714	-0.004039	5.637E-05	-2.826E-07
94	1.891605	0.132100	-0.004133	5.775E-05	-2.902E-07
95	3.386981	0.094633	-0.003000	4.016E-05	-1.999E-07
96	3.149788	0.103252	-0.003152	4.151E-05	-2.045E-07
97	2.955972	0.109313	-0.003242	4.212E-05	-2.059E-07

98	3.500270	0.087894	-0.002755	3.559E-05	-1.687E-07
99	3.243944	0.097692	-0.002939	3.735E-05	-1.755E-07
100	3.036903	0.104503	-0.003048	3.822E-05	-1.783E-07
101	3.328226	0.099494	-0.003207	4.395E-05	-2.235E-07
102	3.099044	0.107562	-0.003343	4.504E-05	-2.267E-07
103	2.910908	0.113246	-0.003420	4.546E-05	-2.270E-07
104	3.495650	0.087942	-0.002753	3.553E-05	-1.684E-07
105	3.240367	0.097688	-0.002936	3.728E-05	-1.751E-07
106	3.034006	0.104473	-0.003044	3.815E-05	-1.780E-07
107	2.177458	0.129112	-0.003668	4.595E-05	-2.184E-07
108	2.067793	0.131386	-0.003697	4.618E-05	-2.192E-07
109	1.983941	0.132355	-0.003695	4.604E-05	-2.182E-07
110	2.731988	0.066027	-0.001843	2.178E-05	-9.479E-08
111	2.729524	0.078798	-0.002492	3.284E-05	-1.572E-07
112	2.722032	0.086333	-0.002861	3.905E-05	-1.921E-07
113	2.700761	0.103674	-0.003693	5.294E-05	-2.698E-07
114	1.929594	0.116074	-0.003327	4.223E-05	-1.988E-07
115	2.616788	0.082109	-0.002670	3.634E-05	-1.782E-07
116	2.394581	0.089854	-0.002500	2.827E-05	-1.099E-07
117	3.095574	0.039164	-0.001006	8.573E-06	-1.478E-08
118	3.057061	0.066832	-0.002258	3.130E-05	-1.497E-07
119	3.095574	0.039164	-0.001006	8.573E-06	-1.478E-08
120	3.061638	0.091763	-0.003566	5.400E-05	-2.793E-07
121	3.061638	0.091763	-0.003566	5.400E-05	-2.793E-07
122	3.122058	0.066735	-0.002487	3.443E-05	-1.626E-07
123	3.122058	0.066735	-0.002487	3.443E-05	-1.626E-07
124	2.896636	0.069162	-0.002374	3.440E-05	-1.716E-07
125	2.896636	0.069162	-0.002374	3.440E-05	-1.716E-07
126	2.962777	0.040792	-0.001080	1.029E-05	-2.654E-08
127	2.962777	0.040792	-0.001080	1.029E-05	-2.654E-08
128	2.124467	0.124132	-0.003942	5.487E-05	-2.718E-07
129	2.124467	0.124132	-0.003942	5.487E-05	-2.718E-07
130	2.111232	0.100952	-0.002788	3.258E-05	-1.357E-07
131	2.111232	0.100952	-0.002788	3.258E-05	-1.357E-07
132	4.221495	0.053337	-0.001948	2.541E-05	-1.121E-07
133	4.235876	0.051218	-0.001876	2.408E-05	-1.040E-07
134	3.393893	0.092554	-0.002835	3.534E-05	-1.561E-07
135	3.405492	0.090901	-0.002778	3.422E-05	-1.490E-07
136	2.835524	0.103985	-0.003135	3.834E-05	-1.690E-07
137	2.899444	0.102847	-0.003213	4.021E-05	-1.805E-07
138	2.982869	0.098791	-0.003203	4.088E-05	-1.861E-07
139	3.047591	0.095516	-0.003235	4.271E-05	-2.001E-07
140	2.417497	0.118642	-0.003442	4.188E-05	-1.857E-07
141	2.616243	0.109496	-0.003454	4.513E-05	-2.121E-07
142	1.997996	0.104830	-0.002648	3.067E-05	-1.360E-07
143	2.364278	0.105158	-0.002680	2.989E-05	-1.286E-07
144	2.760577	0.086845	-0.002651	3.558E-05	-1.768E-07
145	2.729706	0.110589	-0.003483	4.793E-05	-2.421E-07
146	0.133351	0.124467	-0.004751	8.044E-05	-4.867E-07
147	0.181035	0.122150	-0.004691	7.973E-05	-4.836E-07

148	0.320360	0.115040	-0.004502	7.742E-05	-4.732E-07
149	0.159322	0.137767	-0.004841	7.664E-05	-4.136E-07
150	0.138557	0.124363	-0.004748	8.041E-05	-4.867E-07
151	0.084242	0.127122	-0.004816	8.119E-05	-4.901E-07
152	0.277424	0.117475	-0.004590	7.894E-05	-4.826E-07
153	0.092311	0.126174	-0.004773	8.037E-05	-4.845E-07
154	0.398214	0.123193	-0.004623	7.709E-05	-4.648E-07
155	0.022623	0.116985	-0.004486	7.598E-05	-4.557E-07
156	0.649008	0.125167	-0.004512	7.327E-05	-4.373E-07
157	-0.116109	0.113515	-0.004340	7.352E-05	-4.388E-07
158	0.347464	0.113502	-0.004481	7.765E-05	-4.771E-07
159	0.392996	0.108324	-0.004281	7.557E-05	-4.704E-07
160	0.507420	0.106979	-0.004211	7.607E-05	-4.814E-07
161	0.392996	0.108324	-0.004281	7.557E-05	-4.704E-07
162	0.507420	0.106979	-0.004211	7.607E-05	-4.814E-07
163	0.392996	0.108324	-0.004281	7.557E-05	-4.704E-07
164	0.507420	0.106979	-0.004211	7.607E-05	-4.814E-07
165	0.397730	0.108141	-0.004280	7.566E-05	-4.714E-07
166	0.511737	0.106797	-0.004210	7.614E-05	-4.822E-07
167	0.923135	0.116140	-0.004316	7.135E-05	-4.315E-07
168	1.129694	0.124330	-0.004590	7.567E-05	-4.619E-07
169	0.720046	0.121301	-0.004669	7.960E-05	-4.893E-07
170	1.056168	0.107948	-0.004093	6.882E-05	-4.216E-07
171	0.800474	0.122375	-0.004460	7.272E-05	-4.355E-07
172	1.147864	0.099393	-0.003715	6.366E-05	-3.922E-07
173	1.195178	0.100013	-0.003719	6.536E-05	-4.088E-07
174	1.147864	0.099393	-0.003715	6.366E-05	-3.922E-07
175	1.195178	0.100013	-0.003719	6.536E-05	-4.088E-07
176	1.179435	0.097118	-0.003647	6.271E-05	-3.872E-07
177	1.221772	0.098098	-0.003661	6.455E-05	-4.045E-07

Appendix E: Upper and Lower Bound MPG Adjustments

Table E-1: Freeway MPG Adjustments for Congestion Efficiency of 0.0

Freeway Speed (mph)	LD ICE	LD HEV	LD EV	LD FCV	HD ICE
5	0.30	0.33	0.41	0.30	0.42
10	0.44	0.49	0.58	0.46	0.59
15	0.57	0.64	0.73	0.62	0.73
20	0.70	0.77	0.85	0.77	0.82
25	0.80	0.85	0.94	0.87	0.87
30	0.87	0.90	0.98	0.94	0.89
35	0.92	0.93	1.00	0.98	0.91
40	0.96	0.96	1.01	1.00	0.94
45	0.99	0.98	1.00	1.00	0.97
50	1.01	1.01	1.00	1.00	1.02
55	1.02	1.05	0.99	0.99	1.06
60	1.03	1.11	0.99	0.98	1.10

Table E-2: Freeway MPG Adjustments for Congestion Efficiency of 1.0

Freeway Speed (mph)	LD ICE	LD HEV	LD EV	LD FCV	HD ICE
5	0.63	0.87	0.96	0.96	0.68
10	0.80	1.04	1.10	1.10	0.89
15	0.94	1.15	1.19	1.19	1.05
20	1.03	1.19	1.22	1.22	1.15
25	1.08	1.19	1.21	1.21	1.18
30	1.09	1.16	1.18	1.18	1.17
35	1.07	1.11	1.13	1.13	1.13
40	1.05	1.07	1.08	1.08	1.08
45	1.02	1.02	1.03	1.03	1.03
50	0.99	0.99	0.99	0.99	0.99
55	0.98	0.97	0.95	0.95	0.95
60	0.98	0.96	0.93	0.93	0.93

Table E-3: Arterial MPG Adjustments for Congestion Efficiency of 0.0

Arterial Speed (mph)	LD ICE	LD HEV	LD EV	LD FCV	HD ICE
5	0.37	0.39	0.39	0.44	0.35
10	0.54	0.57	0.57	0.62	0.54
15	0.72	0.75	0.75	0.79	0.72
20	0.88	0.90	0.90	0.92	0.89
25	1.01	1.01	1.01	1.01	1.01
30	1.11	1.08	1.08	1.06	1.09

Table E-3: Arterial MPG Adjustments for Congestion Efficiency of 1.0

Arterial Speed (mph)	LD ICE	LD HEV	LD EV	LD FCV	HD ICE
5	0.58	0.72	0.79	0.79	0.58
10	0.74	0.88	0.91	0.91	0.75
15	0.87	0.97	0.98	0.98	0.89
20	0.96	1.00	1.00	1.00	0.97
25	1.00	1.00	1.00	1.00	1.00
30	1.01	0.97	0.97	0.97	0.99