INCORPORATING VEHICLE EMISSION MODELS INTO THE HIGHWAY DESIGN PROCESS

A Dissertation

by

MYUNG-HOON KO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2011

Major Subject: Civil Engineering

Incorporating Vehicle Emission Models into the Highway Design Process

INCORPORATING VEHICLE EMISSION MODELS INTO THE HIGHWAY DESIGN PROCESS

A Dissertation

by

MYUNG-HOON KO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Dominique Lord
Committee Members,	Yunlong Zhang
	Qi Ying
	F. Michael Speed
	Josias Zietsman
Head of Department,	John Niedzwecki

December 2011

Major Subject: Civil Engineering

ABSTRACT

Incorporating Vehicle Emission Models into the Highway Design Process.
(December 2011)
Myung-Hoon Ko, B.S., Korea Aerospace University
Chair of Advisory Committee: Dr. Dominique Lord

Automobile transportation consumes a significant amount of non-reusable energy and emits emissions as by-products of fuel consumption. There has been much progress in the development of vehicle engine technology and alternative fuels to reduce the adverse impact of highway transportation on the environment. However, the research regarding the reduction of the adverse impact through highway design is still in its infancy. Furthermore, highway design manuals/guidebooks do not provide any information on environmentally-friendly designs. The primary objective of this research was to provide the tools and guidelines for a quantitative environmental evaluation in highway design. This research provided the results regarding the quantitative environmental impacts, by means of fuel consumption and emissions, of various highway geometric design conditions on the vertical grades as well as for horizontal and vertical crest curves that could be included in the highway design process. The researcher generated second-by-second speed profiles using the speed prediction models and non-uniform acceleration/deceleration models, and extracted the fuel consumption and emissions rates based on vehicle specific powers and speeds using recently developed motor vehicle emission simulator (MOVES). The generated speed profiles were matched with the extracted rates and aggregated during a trip on the grades and curves. In addition, the researcher conducted the environmental evaluation including a benefit-cost analysis with actual highway geometric data based on the proposed method and processes. The results demonstrated that fuel consumption and emissions could be significantly changed according to highway design conditions on grades and curves. Throughout the analyses, this research provides the guidelines and tools for environmental evaluations related to selected design features as a part of the highway development process. The provided guidelines and tools can reduce the uncertainty associated with the engineering judgment for environmentally-conscious highway design. Finally, this research shows the efficacy of environmentally-friendly design for sustainable (i.e., social, economical, and environmental) transportation.

To my lovely wife, Sunyoung, and my children, Youngmin and Emily

ACKNOWLEDGEMENTS

I would like to sincerely thank my advisor, Dr. Dominique Lord, for his invaluable advice and constant encouragement throughout the completion of this dissertation. His dedicated concern and recommendations allowed this work to be finished. I also would like to express my appreciation to my committee members, Dr. Yunlong Zhang, Dr. Qi Ying, Dr. F. Michael Speed, and Dr. Josias Zietsman, for all their dedicated help and guidance on the dissertation.

I am deeply indebted to the Texas Transportation Institute (TTI) for providing funding throughout the period of my doctoral study. The research experience at TTI has led me to the areas that I could not learn in the classroom and inspired me to think the topic of the dissertation. While working at TTI, I had invaluable help and guidance from Ms. Laura Higgins, Dr. Susan Chrysler, Dr. Troy Walden, Dr. Josias Zietsman, Dr. Doh-Won Lee, and Ms. Tara Ramani. Especially, I would like to thank Dr. Reza Farzaneh for his great help on MOVES issues and Dr. Mark Burris for his information on a cost analysis.

I would like to thank Mr. David Brzezinski of the U.S. Environmental Protection Agency (EPA), Mr. Yusuf Mohamedshah of Highway Safety Information System (HSIS), and Mr. Lou Baker of the Washington Department of Transportation (WSDOT) for their assistance. I also would like to thank my colleagues and friends, Ying Li, Pei-Fen Kuo, Dr. Fan Ye, and Hongsu Park, for their friendship and help during my study.

Finally, I would like to thank my parents, parents-in-law, a sister and a brother for their encouragement and assistance. Above all, I appreciate my lovely wife, Sunyoung, for her continuous support and encouragement to finish my degree.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATION

The following symbols are used in this study unless any specification.

Symbol	Description	Unit
V (V_0)	vehicle speed (initial speed)	m/s
a	vehicle acceleration rate	m/s^2
g	gravitational constant (use 9.81)	m/s^2
I_c	deflection angle	degree
θ	road grade	degree
G	road grade	percent
e	superelevation rate	percent
A	algebraic difference in grades	percent
K	rate of vertical curvature	m/percent
T	braking reaction time	second
t	travel time	second
R	curve radius	m
F	tractive force	N
F_a	accelerating force	N
R_a	aerodynamic resistance	N
R_r	rolling resistance	N
R_g	grade resistance	N
M	vehicle mass	kg
M_e	effective mass	kg
W	vehicle weight	$kg\ m/s^2$
r	engine efficiency factor	-
P	engine generated power	kW
ρ	air density	kg/m^3
A_f	frontal area of the vehicle	m^2
A_r	rolling resistance coefficient	kW/m/s
B	rolling resistance coefficient	$kW/(m/s)^2$
C	air drag resistance coefficient	$kW/(m/s)^3$
C_D	drag coefficient	-
Cr	rolling coefficient	-
C_R	rotating coefficient	s/m

UNIT CONVERSION

	SI (Metric Unit)	Equal US Customary Unit
Length	meter (m)	3.281 feet (ft)
Volume	cubic meter (m^3)	35.31 cubic feet (ft^3)
	cubic meter (m^3)	1.306 cubic yard (yd^3)
Mass	kilogram (kg)	2.205 pounds mass (lb_m)
Speed	km/h	0.621 mph

CHAPTER I

INTRODUCTION

The highway network plays an important role on vehicle trips from origin to destination. The highway system should ideally provide safe mobility and access for every driver. However, its function has been degraded from congestion due to continued increase in driving. Despite chronic underfunding, new construction or reconstruction as one of the strategies for increasing capacity and reducing congestion has been ongoing. This chapter examines the current status of the highway system and outlines the necessity for incorporating environmental considerations into the highway design process.

There exist unique conditions in highway development. First, a highway is a fixed and almost permanent facility; once the highway has been built, it is not easy to redesign and reconstruct due to high costs and a lack of adequate funds. Second, the highway system has historically been developed to keep pace with the increasing travel demand. Regardless, the travel demand has surpassed the capacity of transportation infrastructure for the past few decades. The excessive travel demand on a limited highway capacity has caused saturation, commonly termed congestion. According to the Urban Mobility Report written by Schrank, Lomax, and Eisele (2011), the traffic congestion index had increased in urban areas in the U.S. since 1982, except for the last few years. In 2010, drivers wasted 4.8 billion hours and 1.9 billion gallons of fuel due to congestion, for a total cost of $101 billion.

This dissertation follows the style of Accident Analysis and Prevention.

This serious problem was also noted in the U.S. Government Accountability Office (GAO) report regarding challenges and investment options for the Nation's infrastructure (GAO, 2008). The report concluded that congestion results in decreased performance and reliability of the surface transportation system. Multiple strategies (e.g., public transportation, smart growth, alternative transportation mode, and high-occupancy toll (HOT)/high-occupancy vehicle (HOV) lanes) should be considered to address these challenges. Increasing capacity by constructing new highways, widening existing ones, or improving highway design components (e.g., grade separation at intersection and roundabouts) is also one of the key strategies. As long as there is a demand for new highways or improving old highways, the design and implementation of more socially, economically, and environmentally sustainable highways will be a main objective.

At the 2009 United Nations Climate Change Conference (commonly called the Copenhagen Summit), President Obama warned of the severity of climate change and stressed the need to act against it. His administration created a goal for a 17-percent reduction in emissions of carbon dioxide (CO_2) and other gases commonly known as greenhouse gases (GHGs) by 2020, based on 2005 levels. In the U.S., mobile-sourced emissions have been identified as one of the most significant contributors to GHGs. For example, a report regarding sustainable and energy efficient transportation infrastructure by a U.S. House of Representatives Committee on Science and Technology (2008) concluded that surface transportation is a major contributor to energy consumption and air pollution and accounts for about one-third of GHGs emitted in the U.S. In addition, as much as 95 percent of carbon monoxide (CO) comes from mobile sources, according to the Environmental Protection Agency (EPA) (2010a).

To reduce the amount of fuel consumed and emissions including GHGs emitted, the Clean Air Act of 2008 requires that each state adopt a plan describing implementation, maintenance, and enforcement efforts to meet the National Ambient Air Quality Standards in each air quality control region. In the transportation sector, the plans mainly focus on 1) vehicle improvements providing higher mileage per fuel gallon, 2) lower emissions using alternative fuels, and 3) fewer vehicle miles traveled (VMT) by adopting strategies such as smart growth. There has been a significant progress in vehicle fuel efficiency and in the development of alternative fuels (Alaska, 2009). However, from 1990 to 2008, transportation emissions rose by 22 percent due to increased demand for travel; the amount of VMT by light-duty motor vehicles increased 37 percent (EPA, 2010a). The increased VMT offset the emissions savings from improved vehicle fuel efficiency and low carbon alternative fuels.

None of the state plans includes vehicle fuel consumption and emission reduction strategies by means of highway geometric design improvements. However, some studies suggested that this could be effective. For example, a vehicle consumes more fuel and produces more emissions when roadway grades are steeper because of the greater demand on the vehicle’s power (Boriboonsomsin and Barth, 2009; Park and Rakha, 2006). Some researchers have demonstrated that reducing the frequency of acceleration/deceleration in vehicle operations is also beneficial (El-Shawarby et al., 2005; Ericsson et al., 2006).

This part of this chapter summarizes the Texas Department of Transportation’s (TxDOT) project development process. The process consists of six stages: planning and programming; preliminary design; environmental; right-of-way and utilities; plans, specifications, and estimates (PS&E) development; and lettings (TxDOT Project Development Process, 2009). More detailed description of each stage will appear in a later chapter. Environmental analyses and evaluations are explicitly considered in four project stages: planning and programming, preliminary design, environmental, and PS&E development as shown in Figure 1.1.

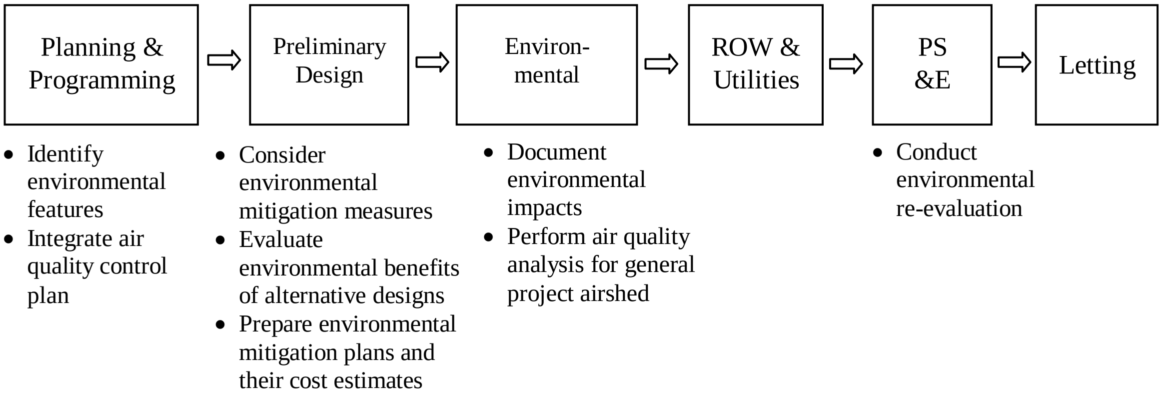


Figure 1.1 Environmental consideration in the project development process (source: TxDOT Highway Development Process, 2009)

According to the Clean Air Act of 2008, each state with a non-attainment area must provide air quality improvement plans in the statewide improvement plan (SIP). In conformance with the SIP, metropolitan planning organizations (MPOs) in non-attainment areas must include detailed strategies in their metropolitan transportation plans (MTP) and transportation improvement programs (TIP). These plans and programs should be integrated in the planning and programming stage during the project development process. In the preliminary design stage, a proposed project must show that it will not lead to higher carbon monoxide (CO) levels using the basic features and preliminary design criteria, via mobile emission models. In addition, similar environmental analysis and evaluation should be done with detailed design criteria in the subsequent program stages. However, these environmental analyses and evaluations do not consider a quantitative relationship with various geometric design criteria and features. Instead, they just focus on mobile emissions inventory prediction in the project.

In a highway project development, the reference most often used by designers and engineers for design features and criteria is the GreenBook, also known as *A Policy on Geometric Design of Highways and Streets*, published by the American Association of State Highway and Transportation Officials (AASHTO, 2004). Although not a design manual, the GreenBook is viewed as a set of national standards; it is a series of guidelines on geometric design, providing a range or a minimum for desirable design standards (FHWA, 2010). When the applied design criteria do not meet these standards, a design exception is required. It provides designers and engineers with flexibility regarding geometric situations in the highway design process. Considering this flexibility, the TxDOT Roadway Design Manual (2010) recommends that use of higher rather than the minimum design standards results in a safer environment, better compensating for drivers' errors.

In highway development, there are critical issues regarding not only how to improve mobility and safety, but also to make roadway travel as environmentally friendly as possible. Considering the degree of the impact of transportation on energy use and GHGs, certainly the improvements in vehicle engine efficiency and alternative fuels must be maintained. Additionally, a sustainable highway geometric design (designing a highway to promote the consumption of less fuel and producing less pollution) should be considered. A quantitative evaluation of various highway geometric design features regarding fuel consumption and emissions may be beneficial for highway designers and engineers. The remainder of this chapter consists of four sections. Section 1.1 presents the problem statement. Section 1.2 describes the scope of this research. Section 1.3 specifies the objectives and goals of this research, and Section 1.4 outlines the dissertation.

1.1 Problem Statement

The primary purpose of the national highway system is to ensure safe mobility and access. The intent of guidebooks or manuals used in the highway development process is to permit sufficient flexibility to designers or engineers by providing a recommended range or minimum values for critical dimensions. If these guidebooks or manuals provide any quantitative analysis of each design criteria/features on safety, it can reduce the uncertainty of an engineering judgment on safety in the selection of design criteria/features. This is because some guidebooks/manuals (e.g., Interactive Highway Safety Design Model (IHSDM), Highway Safety Manual (HSM)) are recently trying to provide quantitative analysis of design criteria and safety features. The TxDOT Roadway Design Manual (2010) specified a vertical alignment design in which the length of ascending grade should take into consideration a heavy truck operation without an undesirable speed reduction, typically 15 km/h. This manual does not provide any quantitative information on the impacts of roadway grades on safety. However, Bonneson et al. (2006) intended to provide quantitative safety design guidelines and evaluation tools to be used by designers and engineers. They concluded that 16 percent more crashes occurred at an eight-percent grade relative to a flat section of freeway. Since a vertical alignment design has a flatter grade than the allowable maximum standard, it costs more at the time of construction—but it increases safety and usefulness substantially throughout the life of the highway.

There is a similar issue in environmental analysis. Although there are several stages of environmental analysis in the highway development process, these analyses are for mobile emission inventory prediction overall, not for evaluating various geometric design criteria. Research on environmentally-friendly highway geometric design concepts is still in its infancy, and highway design manuals/guidebooks do not provide any information regarding the quantitative environmental impacts of highway geometric design features on fuel consumption and emissions. Therefore, the matter of environmental issues related to selected design features is completely dependent on engineering judgment.

1.2 Scope

The researcher sought to quantify the relationship between highway geometric design features (i.e., vertical grades, horizontal curve, and vertical crest curve) and environmental impacts in terms of fuel consumption and vehicle emissions. This research can also be applied to environmental evaluation with actual highway geometric data. Throughout these analyses, this research proposes practical methods and processes on environmental evaluation with highway geometric design features for designers/engineers in order to add information that could be incorporated into the design decision process. Figure 1.2 illustrates the scope of the study.

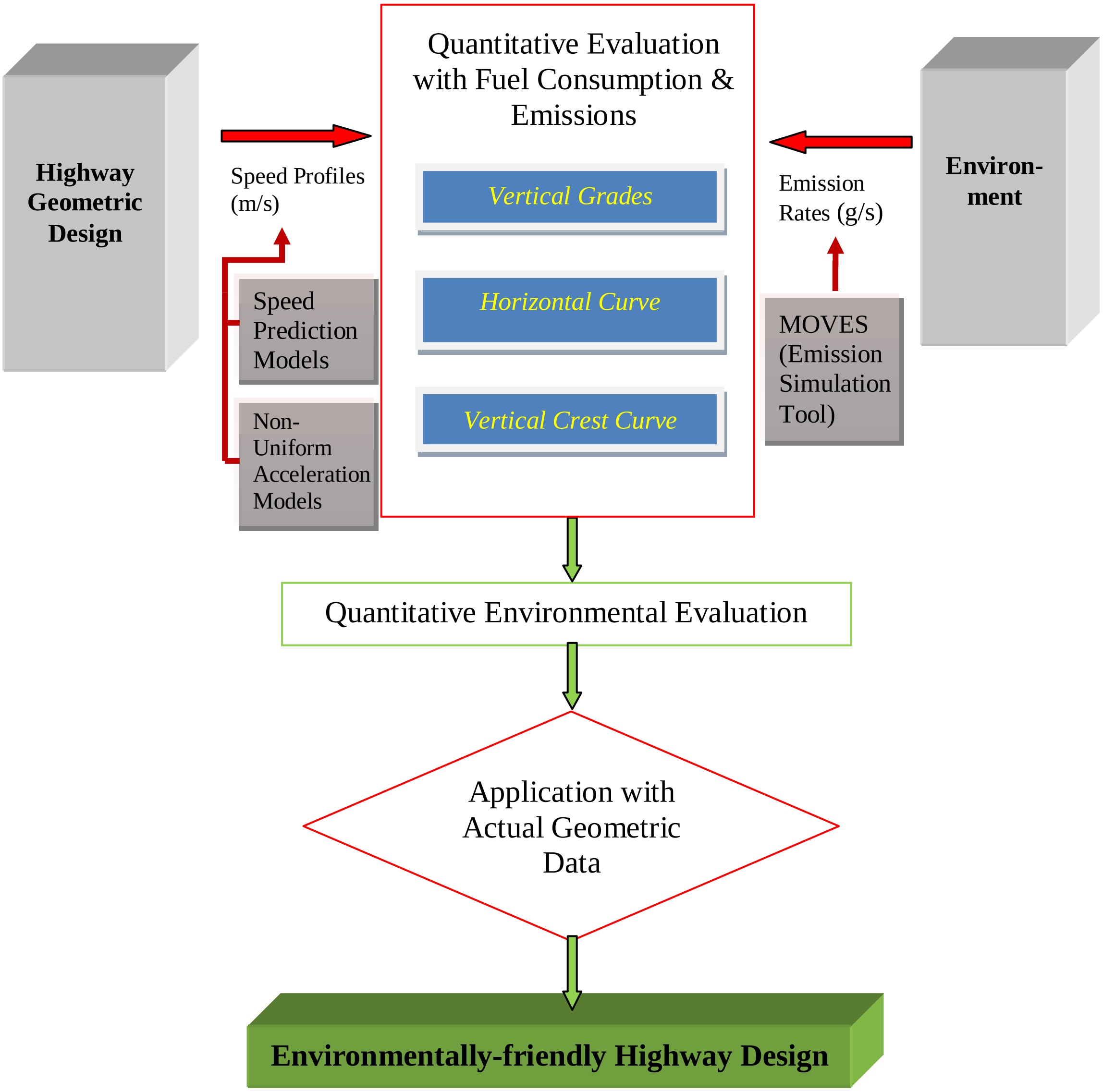


Figure 1.2 Description on scope of the study

1.3 Objectives and Goals

The objectives of this research were to: 1) identify environmental issues (i.e., unintentional and unnecessary fuel consumption and emissions) affecting highway geometric design features, 2) analyze the quantitative impacts of various highway geometric design features on fuel consumption and emissions using most recently developed vehicle emission model and speed profiles generated by speed prediction models and non-uniform acceleration models, 3) show what degree of fuel consumption and emissions can be changed by the variation of specific highway geometric design values with the conceptual evaluation tool like modification factors, 4) evaluate the adaptability of environmentally-friendly design components with actual highway geometric data, and 5) propose practical methods and processes of speed profiles and emission rates for designers/engineers in order to add information for the design decision process.

There are two goals to be accomplished from this research. As the primary goal, the results provided in this research are beneficial for highway designers and engineers by providing the evaluation tools and guidelines on the quantitative environmental impacts related to the selection of highway geometric design features during the project development process; therefore, it can reduce the uncertainty in engineering judgment for environmentally conscious highway design. Second, this research shows the importance of the environmental effect of highway design and supports the statement that environmentally-friendly highway design can be one strategy for sustainable transportation.

1.4 Outline

The rest of this dissertation is organized as follows:

Chapter II summarizes current environmental consideration in the highway development process and the key highway geometric design features. The chapter also reviews the literature on the factors affecting fuel consumption and emissions.

Chapter III describes the methodology for predicting operating speeds on horizontal and vertical crest curves and roadway vertical grades. The methods are used to generate second-by-second speed profiles along various geometric design features. A part of this chapter presents the method for fuel consumption and emission rates related to vehicle operating conditions. In addition, this chapter explains the process for matching the speed profiles with fuel consumption and emission rates for aggregating fuel consumption and emissions.

Chapter IV specifies the hypothetical conditions on highway design features for the quantitative evaluation of fuel consumption and emissions. This chapter, in turn, explains the application process for speed profiles on the geometric design features according to the methods introduced in Chapter III.

Chapter V carries out simulations on fuel consumption and emissions related to highway geometric design features. In addition, this chapter demonstrates the degree to which the results on fuel consumption and emissions can be changed throughout figures of modification factors.

Chapter VI describes how to incorporate the proposed methods and processes into the design process. In addition, the step-by-step procedure for extracting fuel consumption and emissions rates in MOVES is demonstrated. Chapter VII shows the application of the environmental evaluations to actual highway geometric data obtained from the Washington Department of Transportation and Highway Safety Information System (HSIS). Finally, Chapter VIII presents the main findings and a discussion of this research along with the recommendations and directions for future research.

CHAPTER II

BACKGROUND

This chapter starts with a review of environmentally conscious highway design, and is followed by a review of fuel consumption and emissions. Several key highway geometric design features are then reviewed. This chapter concludes with a review of the effects of highway geometric design features on fuel consumption and emissions.

2.1 Environmental Design Considerations in Highway Design Process

The following highway design process described is based on the TxDOT manual, and different states may have different steps. As already shown in Figure 1.1 and Appendix A, the TxDOT highway project development process consists of six stages: planning and programming; preliminary design; environmental; right-of-way and utilities; plans, specifications, and estimates (PS&E) development; and lettings (TxDOT Project Development Process Manual, 2009).

In the planning and programming stages, the feasibility of a project is analyzed and documented based on the purpose, need, and scope for a project identified with the integration of local, regional and statewide plans. In addition, potential construction funding sources are considered. The 2008 Clean Air Act requires each urban area in non-attainment for air quality to develop a plan to improve air quality. The mobile source control plans (e.g., traffic signal improvement, intersection improvements, and intelligent vehicle/highway system elements) should be considered in the planning and programming stage.

In the preliminary design stage, the basic features and preliminary design criteria of the project are established for making engineering and environmental decisions under the review of previous or adjacent projects, traffic and accident data, and cost effectiveness. These features and criteria include number and type of lanes (e.g., single- versus high-occupancy vehicle lanes), shoulders, type and range of median width, possible frontage roads, and range of offset to right-of-way (ROW) limits. Within the stage, public meetings should be conducted after the geometric schematic is reviewed by district staff and stakeholders to ensure that design criteria, project needs, and commitments are met but before it is submitted to the Design Division for approval. In terms of environmental concerns during this stage, non-attainment counties are required to include a CO analysis using mobile emission models in environmental documents and demonstrate that a proposed project will not lead to higher CO levels or a level exceeding the CO standard.

After the preliminary environmental issues have been identified and assessed regarding a project’s environmental variables (e.g., environmental constraints, potentially sensitive areas, historic structures, habitats, and landscapes, impacts of highway encroachments on waterways and floodplains, and impacts of air quality), an appropriate level of public involvement is planned. An air quality analysis must be performed for projects adding capacity, resulting in travel lanes being closer to ROW line, or having a design year average daily traffic (ADT) of 20,000 or more in both attainment and non-attainment counties in accordance with the TxDOT Air Quality Guidelines. The air quality analysis is not conducted for various alternatives, but performed for the general project airshed. The approval by the Environmental Affairs Division or FHWA is needed for the project to advance to the next stage of project development.

During the stage of ROW and utilities, the ROW and utilities data are collected to determine ROW limits, restrictions to State ROW ownership, ownership of the properties that abut State ROW, and ownership of any properties to be acquired. When the project is likely to affect utilities, adjustments with utility owners (companies) are necessary.

In the stage of PS&E development, the features and design criteria decided in the preliminary design stage are reviewed at the design conference to finalize detail design. Setting final horizontal and vertical alignments should be performed to optimize the design, minimize environmental impacts, enhance safety, and improve operation. The finalized alignments provide the baseline for the design of roadway, operations, bridge, and drainage, retaining/noise walls and miscellaneous structures, and traffic control plan. At the end of this stage, there should be a final environmental re-evaluation, integrated project plan, updated cost estimates, and funding agreements before TxDOT receives construction bids (letting).

The environmental analysis and evaluation for air quality in the project are explicitly considered in four stages: planning and programming, preliminary design, environmental, and PS&E development. However, the analysis and evaluation are performed for the general project airshed, not for various geometric design factors.

2.2 Fuel Consumption and Emissions

Vehicles move because of the power generated from burning fuel in the engine combustion process. Emissions are exhausted from by-products of this combustion process. In a perfect engine, all burned fuel would convert oxygen to CO_2 and water. However, in reality, the combustion process cannot be perfect, and it produces several types of pollutants, such as hydrocarbons (HC), CO, nitrogen oxides (NO_x), and particulate matter (PM). Cappiello et al. (2002) provided detailed information on the pollutants:

- CO_2 is mainly proportional to fuel consumption rates and the principal production from the fuel combustion process. CO_2 does not affect human health, but it contributes to global warming by trapping the earth's heat (EPA, 2010a)

- CO is sensitive to acceleration. Under enrichment conditions, the combustion is not complete due to the lack of oxygen. Much of the carbon present in the excess fuel is partially oxidized to CO instead of CO_2. According to EPA (1994), CO reduces the flow of oxygen in the bloodstream, and this adverse effect is particular dangerous to people with a heart disease.
- HC is a production of incomplete combustion and is also usually proportional to fuel consumption rates. Under enleanment conditions (too much oxygen in the combustion process), HC emissions can be higher. In long deceleration events, the dramatic drop in fuel results in a cessation of combustion, and virtually all of the remaining fuel is emitted unburned. Ground-level ozone is formed when HC and NO_x interact with sunlight and causes cancer, asthma attacks, lungs damage, and respiratory problem (Maine, 2011). For example, children who are more exposed to vehicle emissions have a higher risk of respiratory symptoms, according to Kim et al. (2004) and Middleton et al. (2010).
- NO_x depend on the combustion temperature. High temperatures generate NO and NO_2. Under enleanment conditions, the excess oxygen facilitates the formation of more NO. According to EPA (1994), NO_x are not only precursors to the formation of ground-level ozone, but also contribute to the formation of acid rain.
- PM is the term for solid or liquid particles found in the air. Mobile source PM consists mainly of tiny particles, less than 2.5 microns in diameter, also known as $PM_{2.5}$ (EPA, 1994). PM can cause a serious health problem for people with respiratory and heart diseases (Maine, 2011).

Fuel consumption and emissions vary with six factors: 1) vehicle-operating factor such as vehicle speed, 2) travel-related factor such as VMT, 3) driver-related factor such as speeding or aggressive acceleration, 4) highway characteristics-related factor such as roadway grades, 5) vehicle characteristics factor such as vehicle size and weight, engine technology, and 6) weather condition factor such as temperature (Park and Rakha, 2006; Zhai et al., 2008). Recently, some researchers have used vehicle-specific power (VSP) in their studies, because VSP quantifies vehicle emissions and fuel consumption related to various vehicle characteristics and operating conditions (Song and Yu, 2009; Zhang and Frey, 2006; Zhai et al., 2008). VSP (kW/ton) is defined as the instantaneous power per unit mass of vehicle and can be calculated based on speed, acceleration, rolling resistance, aerodynamic drag, and roadway grade as shown in Equation (2.1).

$$VSP = \frac{A_r V + BV^2 + CV^3 + MV(a + gsin\theta)}{M} \tag{2.1}$$

where,

V= vehicle speed (m/s);
a= vehicle acceleration (m/s^2);
A_r= rolling resistance coefficient (kW/m/s);
B= speed correction to rolling resistance coefficient (kW/(m/s)^2);
C= air drag resistance coefficient (kW/(m/s)^3);
M= vehicle mass (ton);
g= gravitational constant (9.81 m/s^2); and,
θ= road grade (degree).

2.3 Key Highway Geometric Design Features

Several key highway geometric design criteria/features are reviewed in this section: design speed, sight distance, grades, vertical and horizontal curves. Current available highway design manuals and guidebooks provide dimensions and characteristics of the key geometric design criteria/features.

2.3.1 Design Speed

Design speed is an essential parameter in the highway geometric design, and affects other design features. The design speed is the maximum safe speed that can be maintained on a specified section of highway when conditions are so favorable that the design features dominate (AASHTO, 2004). It is important to note that any speed selected as the design speed for a project should reflect the speeds at which vehicles can be expected to operate, or are actually operated, on the highway. The GreenBook provides guidelines for setting design speed (AASHTO, 2004):

- It should be set with the consideration of topographical characteristics, anticipated operating speed, the adjacent land use, and the functional classification of highway.
- High design speed as practical to attain a desired degree of safety, mobility, and efficiency under the constraints of environmental quality, economics, aesthetics, and societal or political impacts.
- Selected design speed should be consistent with the speeds that drivers are likely to expect on a given highway facility, and should include nearly all of the desired speeds of drivers.
- A design speed of 110 km/h (or 70 mph) should be used for freeways, expressways, and other arterial highways in rural areas if the design features permit for high speed operation.
- Drivers do not adjust their speeds to the importance of the highway, but to their perception of the physical limitations of the highway and its traffic.

Table 2.1 presents the recommended minimum design speeds according to highway functional classification. Although the desirable design speeds are recommended, the selection of design speed is flexible and affected by safety, environmental, economic, or aesthetic considerations. For examples, one design speed can be selected for an entire highway design process, or a series of design speeds can also be applied. Average running speed, calculated by dividing the length of the highway section by the running time over the section, may be used as the design speed in determining lane and shoulder widths; operating speed, the 85th percentile in the distribution of observed speeds during free-flow conditions, may be used for horizontal and vertical curves (FHWA, 2010). This flexibility on the selection of design speed can minimize the disparity between design speeds and actual operating speeds. Some studies observed the operating speeds at horizontal curves and compared them with inferred design speeds (Chowdhury et al., 1991; Krammes, 2000). At those curves designed for speeds of less than 100 km/h, the observed operating speeds were greater than designed speeds. However, the operating speeds were less than designed speeds at the curves designed for greater than 100 km/h. The disparity between design and operating speeds, especially when the design speed is lower than the operating speed, may cause safety problems (Krammes, 2000; Misaghi & Hassan, 2005).

Table 2.1 Recommended design speeds (source: AASHTO, 2004)

Functional Classification	Rural			Urban
	Level	Rolling	Mountainous	
Freeway	110 (70)		80-100 (50-60)	more than 80 (50)
Arterial	100-120 (60-75)	80-100 (50-60)	60-80 (40-50)	50-100 (30-60)
Collector	60-100 (40-60)[1]	50-80 (30-50)[1]	30-60 (20-40)[1]	50 (30)
Local	50-80 (30-50)[1]	30-60 (20-40)[1]	30-50 (20-30)[1]	30-50 (20-30)

NOTE: unit is km/h (mph); [1] design speeds vary with design volume (veh./day).

2.3.2 Sight Distance

Sight distance is the length of the roadway ahead visible to the driver. A sufficient sight distance allows the driver to apply the brakes before reaching a stationary object in its path with the assumption that the vehicle travels at design speed. There are several sight distance factors that should be considered in the highway design process: 1) stopping sight distance, 2) decision sight distance, and 3) passing sight distance.

Stopping sight distance is the sum of 1) the distance traveled during brake reaction time and 2) braking distance. Braking reaction time is the time between a driver's perception of a stationary object in his/her path to the instant the brakes are applied. The reaction time depends on the driver's visual acuity and natural rapidity, the atmospheric visibility, the condition of roadway, vehicle speed, and nature of the object (AASHTO, 2004). Based on several studies, the GreenBook recommends 2.5 seconds for braking reaction time because it can accommodate the capabilities of most drivers. Braking distance is calculated from vehicle speed, deceleration rate, and grade (Equation (2.2)). The distance is highly dependent on vehicle speed; high vehicle speed requires a longer braking distance.

$$d = Vt + \frac{V^2}{3291.8\left[\left(\frac{a}{9.81}\right) \pm G\right]} \tag{2.2}$$

where,

t= braking reaction time (use 2.5 second);

a= deceleration rate (use 3.4 m/s^2); and,

G= roadway grade (percent).

If a roadway condition is more complex, or unusual maneuvers are required of the driver, the stopping sight distance may not be adequate for safe and efficient driving. In these cases, a longer sight distance should be provided. Decision sight distance adds the distance traveled during a driver's decision to the stopping sight distance. The GreenBook provides recommendations on decision sight distance according to avoidance maneuver types, roadway types, and design speed (AASHTO, 2004).

On two-lane highways, faster vehicles can only pass slower vehicles using the lane for opposing traffic. To accomplish the passing maneuver safely, a sufficient distance should be provided so that the passing driver can return to the appropriate lane before encountering an opposing vehicle. Passing sight distance is dependent on average speeds of passing and passed vehicles, time it takes to pass a vehicle in the same lane, and acceleration rate. The GreenBook provides recommended passing sight distance with consideration of design speed (AASHTO, 2004). In addition, the GreenBook recommends that the distance should consider the effect of roadway grades, because a downhill grade makes passing easier than on level roads, but an uphill grade requires a longer time and distance for passing.

2.3.3 Alignment

The roadway alignment is essential in the highway geometric design process unless the roadway is horizontally straight and vertically flat. At any given speed, a better roadway alignment can carry more traffic. The roadway alignment can be divided into horizontal and vertical alignments in the highway geometric design process.

2.3.3.1 Horizontal Alignment

The design of a horizontal alignment should be balanced between design speed and curvature with superelevation rate and side friction factor (AASHTO, 2004). Design speed increases with curve radius and superelevation rate. The GreenBook recommends a horizontal curve radius based on the design speed and superelevation rate. The selection of design speed on a horizontal curve should be based on the minimization of the difference in the operated speeds to ensure safe and efficient traffic operation on the curve (Krammes, 2000; Misaghi and Hassan; 2005). According to Krammes (2000), when the horizontal curve was designed at a lower design speed, the observed operating speeds were greater than the designed speeds. When the curve was designed for a higher design speed, the observed operating speeds were less than the design speed. Minimizing the difference between the design and operating speeds is related to the concept of “design consistency” in the highway design process. Lamm et al. (1999) quantified design consistency using speed difference; if the difference is less than or equal to 10 km/h, greater than 10 km/h and less than or equal to 20 km/h, or greater than 20 km/h, the horizontal curve can be considered as a good, fair, or poor design, respectively. In addition, they concluded that a good design means the horizontal curve is designed consistently; a fair design has some minor inconsistencies; and a poor design has inconsistencies causing speed differences in excess of 20 km/h.

Several studies have used the speed prediction model on horizontal curves to predict the observed the 85th percentile speeds (i.e., operating speed) and evaluate design consistency on the curves. Table 2.2 shows the speed prediction models for the operating speeds in the horizontal and vertical curves. The models for the horizontal curves are used for the prediction on the 85th percentile speeds at the middle of horizontal curves. The model by Islam and Seneviratne (1994) predicts the speeds at point of curve (PC), middle of curve (MC), and point of tangent (PT) on horizontal curves.

Table 2.2 Speed prediction models on horizontal and vertical curves for two-lane rural highways

Authors (Year)	Prediction Model	Type	Location
Islam and Seneviratne (1994)	$V_{85} = 95.41 - 1.48D - 0.012D^2$	Horizontal	PC
	$V_{85} = 103.03 - 2.41D - 0.029D^2$		MC
	$V_{85} = 96.11 - 1.07D$		PT
Abdul-Mawjoud and Sofia (2008)	$V_{85} = 17.749 + 0.5V + 0.05203R - 0.161I_c + 1.416e$	Horizontal	Middle of Curve
	$V_{85} = 0.790V_{app} + 0.0259R$	Horizontal & Vertical	Upgrade < 3percent
	$V_{85} = 17.519 + 0.432V_{app} + 0.0680R$	Horizontal & Vertical	3 ≤ upgrade < 9.3percent
	$V_{85} = 0.917V_{app} + 0.02431R - 0.300I_c$	Horizontal & Vertical	Downgrade < 3percent
	$V_{85} = 0.636V_{app} + 0.09481R$	Horizontal & Vertical	3 ≤ downgrade < 9.3percent
Bonneson and Pratt (2009)	$V_{85} = \left[\frac{49.21R_p(b_0 - b_1V_{t.85} + b_2V_{t.85}^2 - b_3I_{tk} + e/100)}{1 + 0.00358R_p}\right]^{\frac{1}{2}} \leq V_{t.85}$	Horizontal	Middle of Curve
Fitzpatrick and Collins (2000)	$V_{85} = 105.08 - \frac{149.69}{K}$ (K≤43)	Vertical Curve	Middle of Curve

where,

D= degree of curvature ($D = \frac{[222480(e+0.0000079V^2-0.0024V+0.28)]}{V^2}$);

V_{app}= approaching speed (km/h);

$V_{t.85}$= 85th percentile tangent speed (km/h);

V_{85}= 85th percentile curve speed (km/h);

R_p= travel path radius ($R_p = R + \frac{0.9144}{1-cosine(0.5I_c)}$);

I_{tk}= indicator variable for trucks (=1 if model is used to predict truck speed; 0 otherwise);

Coefficient: b_0=0.196, b_1=0.000659, b_2=0.00002189, and b_3=0.0150.

2.3.3.2 Vertical Alignment

In a terrain with elevation changes, the design of vertical alignment encourages uniform operation throughout a highway. Vertical alignment should be designed with appropriate grades, minimizing vehicle speed reduction, and vertical curves that satisfy stopping sight distance needs. Generally, all passenger cars can negotiate grades as steep as four to five percent without any significant speed reduction (AASHTO, 2004). However, the effect of grades on heavy truck speed is more pronounced. The highway facilities should accommodate these trucking movements without degradation of safety and traffic operations. Any speed reduction exceeding 15 km/h on grades can cause higher crash rates and traffic congestion (AASHTO, 2004; Lan and Menendez, 2003). The road grade is estimated by taking two neighboring points ((x_{i-1}, y_{i-1}) and (x_i, y_i)) and their elevations (e_{i-1} and e_i) as shown in Equation (2.3).

$$G(percent) = \frac{e_i - e_{i-1}}{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}} \times 100 \tag{2.3}$$

Since speed reduction is critical for truck operation on grades, the GreenBook provides guidance for the design of "critical length of grade." It is defined as the maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable speed reduction. Any vertical alignment design exceeding the guided critical length of grade will cause unreasonable speed reductions by trucks, which will adversely affect safety and traffic operations. To prevent an adverse effect on uphill traffic operations, the GreenBook justifies the installation of a climbing lane when meeting one of the following criteria:

- Upgrade traffic flow rate in excess of 200 vehicles per hour
- Upgrade truck flow rate in excess of 20 vehicles per hour
- One of the following conditions exists:
    - A 15 km/h or greater speed reduction is expected for a typical heavy truck.

- Level-of-service E or F exists on the grade.
- A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

- Safety considerations justifying a climbing lane regardless of grade or traffic volumes

Vertical curves should be designed with the consideration of stopping/passing sight distance. On two-lane highways, a crest vertical curve may be designed to provide adequate passing sight distance. In this case, the length of the crest vertical curve can be calculated using passing sight distance and the absolute difference in grades, as shown in Table 2.3. The design of a sag vertical curve differs from the crest vertical curve design because the sag curve is governed by stopping sight distance only in nighttime conditions. The length of sag vertical curve is calculated with stopping sight distance and the absolute difference in grades.

Table 2.3 Equations for length of vertical curve (source: AASHTO, 2004)

Condition	Crest Vertical Curve	Sag Vertical Curve
S is less than L	$L = \frac{AS^2}{658}$	$L = \frac{AS_l{}^2}{120 + 3.5S_l}$
S is greater than L	$L = 2S - \frac{658}{A}$A	$L = 2S_l - \left[\frac{120 + 3.5S_l}{A}\right]$
where, the height of eye =1080 X 10^{-3}m; the height of object = 600 X 10^{-3}m; A = algebraic difference in grades (percent); S= sight distance (m); and, S_l= light beam distance (m).		

A vertical curve is designed at the transition area to connect the graded tangent segments along a highway. The curve should be designed without consideration of any significant speed reduction from the tangent segment. A consistent design has less difference between operating speed and design speed and can promote safe driving on the curve. Table 2.2 provides the speed prediction model used for crest vertical curves by Fitzpatrick and Collins (2000). The operating speed at the midpoint of the crest vertical curve is a function of the rate of vertical curvature.

2.4 Impacts of Highway Geometric Design Features on Fuel Consumption and Emissions

Energy consumption and emissions can be influenced by the design of highway geometric features. Certain highway features that lessen vehicle engine loads and the frequency of acceleration reduce the amount of fuel consumed and emissions released by vehicles (Deakin, 2001).

VSP quantifies fuel consumption and emissions associated with vehicle characteristics and operating conditions. By using vehicle speed, acceleration rate, and roadway grade, VSP is capable of capturing the characteristics of a vehicle’s operating conditions, as shown in Equation (2.1). Among these operating conditions, vehicle speed is a key factor not only in highway geometric design, but also in the consideration of fuel consumption and emissions (Barth and Boriboonsomsin, 2008; Servin et al., 2006). Barth and Boriboonsomsin (2008) concluded that CO_2 emissions rates were highly dependent on speed and flow; traveling at a steady-state speed (around 72 to 80 km/h) resulted in much lower emissions and fuel consumption compared with stop-and-go driving patterns. But speeds exceeding 105 km/h, or speeds below 72 km/h due to severe congestion, can cause an adverse effect on fuel consumption and emissions. Existing research regarding the prediction of fuel consumption and emissions using operating conditions find that vehicle speed is expressed as a second-by-second variable, because average speed is not adequate for evaluation of the impacts of highway geometric design and traffic-signal control on emissions and fuel consumption. This is due to a lack of accounting for vehicle driving dynamics, such as acceleration or deceleration (Song and Yu, 2009; Qi et al., 2004).

Barth and Boriboonsomsin (2008) suggested that congestion mitigation strategies, speed management techniques, and traffic flow-smothering techniques were beneficial for reducing fuel consumption and emissions. Strategies regulating vehicle speeds are closely linked to acceleration because regulating speed variation can be achieved by reducing the frequencies of acceleration. Servin et al. (2006) analyzed how much fuel consumption and emissions could be reduced by intelligent speed adaptation (ISA) that regulates speed variation in driving, and found that ISA significantly saved fuel and reduced CO_2 by approximately 37 percent and 35 percent, respectively.

In addition, Ahn et al. (2002) and Qi et al. (2004) developed microscopic emission models that predict vehicle fuel consumption and emissions using instantaneous speed and acceleration/deceleration as explanatory variables. These models more accurately predict fuel consumption and emissions as compared to the measured data. El-Shawarby et al. (2005) studied the impact of vehicle acceleration level on vehicle fuel-consumption and emission rates. They found that an aggressive acceleration rate, using 100 percent of the maximum vehicle acceleration envelope, emitted more HC by a factor of six than did mild acceleration using 40 percent of the maximum vehicle acceleration. Also, a vehicle repeatedly stops, waits (or idles), and accelerates at intersections due to changing signals; these patterns of non-voluntary stop/idling/acceleration increase fuel consumption and emissions (El-Shawarby et al., 2005; Ericsson et al., 2006; Hallmark et al., 2002; Stevanovic et al., 2009). According to Stevanovic et al. (2009), about 1.5 percent fuel was saved due to signal timing optimization at a 14-intersection network.

Several studies concluded that roadway grade is one of the key variables affecting fuel consumption and emissions, as are vehicle speed and acceleration. Boriboonsomsin and Barth (2009), Kean et al. (2003), and Park and Rakha (2006) analyzed the impacts of roadway grades on fuel consumption and emissions. According to Boriboonsomsin and Barth (2009), a vehicle consumed 15 to 20 percent more fuel on an uphill route at a six-percent grade followed by downhill route at a six-percent grade than on flat route. The larger amount of fuel consumed going uphill was not fully compensated for by the smaller amount of fuel consumption going downhill. Boriboonsomsin and Barth (2009) concluded that speed and acceleration had a large impact on vehicle fuel consumption and tailpipe emissions, and found that roadway grade was one of the primary variables that determine the power requirements necessary for specific driving maneuvers. The aggregated emissions and fuel consumption based on the second-by-second speed profile, including acceleration and roadway grades, can be used to represent an inventory of emissions and fuel consumption related to the highway geometric design features.

2.5 Chapter Summary

This chapter reviewed current environmental evaluation in the highway development process, and the factors affecting vehicle fuel consumption and emissions. This chapter concluded with the review regarding the impacts of speed, acceleration, and roadway grades on fuel consumption and emissions.

There are several steps in environmental analyses and evaluation in highway development. However, these analyses and evaluations focus on the macroscopic prediction of overall mobile emissions inventory from general project, not microscopic prediction of emissions variation related to various geometric design features/conditions.

To conduct microscopic environmental analyses and evaluation, it is essential to understand the relationship between vehicle movement and fuel consumption and emissions. Several factors affect fuel consumption and emissions. These factors suggest that fuel consumption and emissions can be reduced with less vehicle traveling, friendly driving reducing the opportunity of speeding or aggressive acceleration, flatter roadway design, or vehicle engine technology improvement.

Among the factors affecting fuel consumption and emissions, speed is a primary factor in the analyses. However, the evaluation using constant speed without any consideration vehicle driving dynamic can result in inadequate results because of a lack of the consideration on vehicle dynamic movement. For example, intelligent speed adaptation, regulating high speed and reducing the frequency of acceleration, could save about one third of each fuel consumed and CO_2 produced from vehicle traveling. In addition, the roadway characteristics, such as grades, affect fuel consumption and emissions. A vehicle has more engine loads on steeper roadway segment; consequently grades increase fuel consumed and emissions produced than a level segment. Finally, highway features lessening vehicle engine loads by avoiding excessive speed, frequency of acceleration, and steep grades reduce the amount of fuel consumption and emissions. The next chapter presents the methods used for speed profiles and fuel consumption and emission rates.

CHAPTER III

METHODOLOGY

This chapter describes the speed prediction models for predicting the operating speeds on horizontal and vertical curves, and the truck dynamic model for roadway grades. The non-uniform acceleration models are used to get second-by-second speed profiles along various geometric design features. Finally, the emission rates from the mobile emission model are matched with the generated speed profiles, and the calculated emissions per second are aggregated along the traveled distance and time. Section 3.1 contains a description of the speed prediction models on the curves, and Section 3.2 is for the non-uniform acceleration/deceleration models. Section 3.3 covers a description of the vehicle emissions model for fuel consumption and emission rates.

3.1 Speed Prediction Models

Vehicle speed is a key variable in measuring a vehicle's operating conditions and predicting fuel consumption and emissions (Barth and Boriboonsomsin, 2008; Servin et al., 2006). The speed prediction models are used for the prediction of operating speeds at the middle of horizontal and vertical curves.

3.1.1 Operating Speeds on Horizontal Curves

For the operating speeds on horizontal curves on two-lane highways, this study used the model from the study by Bonneson and Pratt (2009) because the model reflects the key design factors in horizontal curve design such as the travel path radius (R_p), the 85th percentile tangent speed ($V_{t.85}$), a deflection angle (I_c), and superelevation (e) as shown in Equation (3.1).

$$V_{85} = \left[\frac{49.21R_p(b_0 - b_1V_{t.85} + + b_2V_{t.85}^2 - b_3I_{tk} + e/100)}{1 + 0.00358R_p}\right]^{\frac{1}{2}} \leq V_{t.85} \tag{3.1}$$

where,

R_p: travel path radius ($R_p = R + \frac{0.9144}{1 - cosine(0.5I_c)}$);

I_{tk}: indicator variable for trucks (=1 if model is used to predict truck speed; 0 otherwise); and,

Coefficients: b_0=0.196, b_1=0.000659, b_2=0.00002189, and b_3=0.0150.

In the speed prediction model, the variable of travel path radius is used, instead of curve radius. A travel path radius reflects driving behavior shifting laterally inward while cornering to track larger radius than a designed curve radius (Bonneson and Pratt, 2009). In addition, this prediction model is based on the condition that the operating speeds on the curves are less than or equal to approaching tangent speeds as shown in Equation (3.1).

3.1.2 Operating Speeds on Vertical Crest Curves

Fitzpatrick and Collins (2000) provided the speed prediction model on vertical curves, in which the predicted operating speed is dependent on the degree of curvature (K). This speed prediction model is available on the condition that K is less than or equal to 39 m/percent. In the study of Fitzpatrick and Collins (2000), the K was specified as 43 m/percent when the height of driver eye and object were 1070×10^{-3} and 150×10^{-3} m, respectively, based on the GreenBook (AASHTO, 1994). However, the height of driver eye and object changed to 1080×10^{-3} and 600×10^{-3} m, respectively, in the most recent edition of GreenBook (AASHTO, 2004). Thus, the K-value should be updated to 39 m/percent in the equation for speed prediction on vertical curve in Table 2.2, instead of 43 m/percent in the original model as shown in Equation (3.2).

$$V_{85} = 105.08 - \frac{149.69}{K} \quad (\mathrm{K} \leq 39) \tag{3.2}$$

The predicted operating speeds based on the models are spot speeds at the middle of both vertical and horizontal curves. However, vehicles do not move at constant speeds on vertical curves. For example, some studies pointed out that using average speed was not appropriate for the evaluation of the impacts of highway geometric design and traffic pattern on fuel consumption and emissions, due to a lack of accounting for acceleration or deceleration (Song and Yu, 2009; Qi et al., 2004). This study expresses vehicle speed as a second-by-second variable along the traveled distance/time, and the instantaneous speeds are calculated from acceleration/deceleration rates based on the non-uniform acceleration models.

3.2 Non-uniform Acceleration/Deceleration Models

There are several models that predict acceleration/deceleration profiles, and these predicted profiles, in turn, can permit the calculation for speeds and distance profiles. The non-uniform acceleration/deceleration models can be categorized into two types: 1) vehicle kinematics model and 2) vehicle dynamic model (Rakha et al., 2001). The vehicle kinematics model predicts vehicle acceleration resulted from simplified mathematical relationships with speed and distance; however, this model does not account for vehicle type and mass, roadway grades, and other factors affecting vehicle accelerating capacity (Rakha et al., 2001). However, the vehicle dynamic model predicts vehicle acceleration from the factors that are not accounted in the kinematics model, such as vehicle type and mass, engine generated force, external resistance forces, etc.

In this study, two vehicle kinematics models, the linear decreasing acceleration model and the polynomial model, were used for instantaneous acceleration/deceleration and speed profiles, and the vehicle dynamic model developed by Lan and Mendendez (2003) was used.

3.2.1 Linear Decreasing Acceleration Model

The linear decreasing acceleration model assumes that the maximum acceleration occurs at a speed of zero and then linearly decreases to zero at the maximum speed, and it can be formulated as (Rakha et al., 2004)

$$a(t) = \alpha - \beta V(t) \tag{3.3}$$

where,

a(t)= acceleration rate at time t;

V(t)= speed at time t; and,

α, β= coefficients.

Acceleration is the rate of change of speed over time and expressed as in Equation (3.4):

$$dt = \frac{dV}{a(t)} = \frac{dV}{(\alpha - \beta V(t))} = \int_{V_0}^{V} \frac{dV}{(\alpha - \beta V(t))} \tag{3.4}$$

Integrating Equation (3.4),

$$t = -\frac{1}{\beta} \ln\left[\frac{(\alpha - \beta V(t))}{(\alpha - \beta V_0)}\right] \tag{3.5}$$

Rewriting Equation (3.5) with speed,

$$V(t) = \frac{\alpha}{\beta}\left(1 - e^{-\beta t}\right) + V_0 e^{-\beta t} \tag{3.6}$$

When transforming Equation (3.4) into the change of distance,

$$dx = \frac{VdV}{a(t)} = \frac{VdV}{(\alpha - \beta V(t))} = \int_{V_0}^{V} \frac{VdV}{(\alpha - \beta V(t))} \tag{3.7}$$

Integrating Equation (3.7),

$$x(t) = \frac{\alpha}{\beta}\left[t - \frac{1}{\beta}\left(1 - e^{-\beta t}\right)\right] + \frac{V_0}{\beta}\left(1 - e^{-\beta t}\right) \quad (3.8)$$

The linear decreasing acceleration model is used for second-by-second speed profiles by trucks on vertical grades because highway design on grades and critical length of grades are based on the truck performance with maximum acceleration and crawl speeds (i.e., speed at zero acceleration rate on grades).

3.2.2 Polynomial Model

Akcelik and Biggs (1987) and Wang et al. (2005) demonstrated that the constant and uniform acceleration/deceleration models were not a realistic reflection of drivers' behavior. In real-life driving, the curve representing the relationship between acceleration and time typically has a bell-shape and S shape for speed and time curve (Akcelik and Biggs, 1987; Wang et al., 2005); these curve shapes describe that acceleration rates are zero at the start and end of acceleration and support the better fit to driving pattern of deceleration from cruise speed and acceleration to the cruise speed. According to Akcelik and Biggs (1987) and Akcelik and Besley (2001), this pattern of acceleration can be explained by the polynomial model that be expressed as Equation (3.9):

$$a(t) = r a_m \theta (1 - \theta^m)^2 \ \ (\mathrm{m} > -0.5) \quad (3.9)$$

where,

a_m= maximum acceleration;

θ= the ratio of time since the start of acceleration to the total acceleration time (t_a), t/t_a; and,

m, r= parameters.

The values for m, r, and a_m are determined with the equations following:

$$\frac{V_a - V_i}{V_f - V_i} = \frac{2m^2 + 15m + 19}{3[(m+3)(2m+3)]} \tag{3.10}$$

$$r = \frac{\left[(1+2m)^{2+\frac{1}{m}}\right]}{4m^2} \tag{3.11}$$

$$\mathrm{a_m} = \frac{\mathrm{V_f} - \mathrm{V_i}}{\mathrm{r t_a}} \frac{[(2\mathrm{m}+2)(\mathrm{m}+2)]}{\mathrm{m}^2} \tag{3.12}$$

In Equation (3.12), V_a, V_f, and V_i represent average speed, final speed, and initial speed during acceleration, respectively. Using Equations (3.10) to (3.12), acceleration rate at time t could be calculated, and also speed and distance at time t could be acquired with the equations following (Akcelik and Besley, 2001).

$$dV = a(t)dt = ra_m\theta(1-\theta^m)^2 dt = ra_m\left(\frac{t}{t_a}\right)\left[1-\left(\frac{t}{t_a}\right)^m\right]^2 dt \tag{3.13}$$

$$V(t) = \int_0^t ra_m\left(\frac{t}{t_a}\right)\left[1-\left(\frac{t}{t_a}\right)^m\right]^2 dt \tag{3.14}$$

$$dx = V(t)dt = \left\{\int_0^t ra_m\left(\frac{t}{t_a}\right)\left[1-\left(\frac{t}{t_a}\right)^m\right]^2 dt\right\}dt \tag{3.15}$$

$$x(t) = \int_0^t\left\{\int_0^t ra_m\left(\frac{t}{t_a}\right)\left[1-\left(\frac{t}{t_a}\right)^m\right]^2 dt\right\}dt \tag{3.16}$$

Integrating Equations (3.14) and (3.16), the equations for speed (Equation (3.17)) and distance (Equation (3.18)) at time t can be acquired:

$$V(t) = V_i + 3.6ra_m t_a\theta^2\left[0.5 - \frac{2\theta^m}{(m+2)} + \frac{\theta^{2m}}{(2m+2)}\right] \tag{3.17}$$

$$x(t) = \frac{V_i t}{3.6} + ra_m t_a^2\theta^3\left[\frac{1}{6} - \frac{2\theta^m}{(m+2)(m+3)} + \frac{\theta^{2m}}{(2m+2)(2m+3)}\right] \tag{3.18}$$

These equations are based on the known acceleration time (t_a). When the acceleration time and distance are unknown, the regression equation (Equation (3.19)), provided by Akcelik and Biggs (1987), for acceleration time can be used.

$$t_a = \frac{V_f - V_i}{2.08 + 0.127(V_f - V_i)^{1/2} - 0.0182V_i} \tag{3.19}$$

The polynomial model is used for generating second-by-second speed profiles on horizontal and vertical crest curves. From the speed prediction models, this study already had spot speeds at the middle of curves; however, there were no information on the speed variation per unit time while speed changing from the 85th percentile tangent speed to the reduced spot speed and vice versa. In this situation, the polynomial model provides the information on the speed variation on the curves.

3.2.3 Truck Dynamics Model

The truck dynamics model was used for second-by-second truck speed profile related to vertical grades and critical length of grades in highway design, as one of the non-uniform acceleration models. In addition, the calculated second-by-second speeds and accelerations were used for the estimation of vehicle fuel consumption and emissions at various grades and length of grades. The determination of roadway vertical grade design features is based on a typical heavy truck of 120 kg/kW because the effect of grades is more critical to truck movement than a passenger car (AASHTO, 2004). Generally, all passenger cars can negotiate grades as steep as four to five percent without any significant speed reduction (AASHTO, 2004). Truck performance may be subjected to the following forces: 1) tractive effort (F), 2) aerodynamic resistance (R_a), 3) rolling resistance (R_r), and 4) grade resistance (R_g) as shown in Equation (3.20):

$$ma = F - (R_a + R_r + R_g) \tag{3.20}$$

The tractive effort (F) generated by a truck's engine acts to overcome external resistance and/or to accelerate the truck (Mannering et al., 2009). The tractive effort can be degraded by two sources of power loss: 1) the operation of engine accessories, such as fan, generator, water/fuel pump, and compressor and 2) transmission system. According to Mannering et al. (2009), five to 25 percent of tractive effort is typically lost due to the transmission system. The tractive effort can be expressed as Equation (3.21):

$$F = \frac{1000rP}{V} \tag{3.21}$$

where,

r= engine efficiency factor;
P= engine generated power (kW); and,
V= vehicle speed (m/s).

Aerodynamic resistance is commonly called air drag and has a significant impact on truck performance. This resistance is a function of air density, the coefficient of drag, frontal area of the vehicle, and a square of vehicle speed (Equation (3.22)). At high speeds, aerodynamic resistance will overwhelm other resistance. Aerodynamical vehicle designs with smaller frontal area and reduced turbulent airflow around the vehicle may be essential for high performance vehicles at high speeds.

$$R_a = \frac{\rho}{2} C_D A_f V^2 \tag{3.22}$$

Rolling resistance is generated from the deformation of tires interacting with the roadway surface, and mostly depends on a vehicle's weight, a roadway surface condition, and a type of tire. A weighed vehicle increases tire deformation and affects a broader area of roadway surface, and increases the resistance on the vehicle operation. The rolling resistance is expressed with two coefficients (C_r and C_R) as Equation (3.23):

$$R_r = (C_r + C_R\, V\,)W \tag{3.23}$$

When vehicles are operated on paved roadway surfaces, the rolling coefficients, C_r and C_R, are approximately 0.01 and 1/4,473, respectively (Mannering et al., 2009).

Grade resistance is generated from the gravitational force caused by a graded roadway profile. This resistance increases with increased highway grades and can be expressed as Equation (3.24):

$$R_g = W \sin\theta \tag{3.24}$$

As highway grades are usually very small, sinθ can be replaced with tanθ. Equation (3.24) is therefore modified into Equation (3.25),

$$R_g \cong W \tan\theta = W\ G \tag{3.25}$$

where grades (G) are defined as the rate of vertical rise (ft or m) per 100 (ft or m) horizontal distance and expressed as percentages (percent).

Vehicle accelerating force is required for the static mass as well as the rotating mass due to the inertia of rotating parts and gear reduction ratio. When the rotating masses are added to the static mass, the result is the effective mass (M_e) (Lan and Menendez, 2003). The accelerating force is expressed with Equation (3.26):

$$F_a = M_e\ a \tag{3.26}$$

To calculate the acceleration rate, Equation (3.20) is rewritten with the tractive effort and resistances as shown in Equation (3.29):

$$a = \frac{1}{M_e}(F - \sum R) = \frac{1}{M_e}\{(F - (R_a + R_r + R_G)\} \tag{3.27}$$

$$= \frac{1}{M_e}\left\{\frac{1000rP}{V} - \left(\frac{\rho}{2}C_D A_f V^2 + C_r\ W + C_R\ V\ W + W\ G\right)\right\} \tag{3.28}$$

$$= \frac{M}{M_e}\left\{\frac{1000rP}{MV} - \left(\frac{\rho}{2M}C_D A_f V^2 + g(C_r + C_R\ V\ +\ G)\right)\right\} \tag{3.29}$$

The ratio M/M_e differs in trucks according to the size of the engine and number of gears. According to Bester (2000), the difference of the ratio M/M_e between trucks for speeds above 25 km/h is less than five percent. Therefore, the ratio can be divided and calculated below:

$$\frac{M}{M_e} = \begin{cases} 0.2 & \text{for } V \leq 1.8 \text{ m/s} \quad (3.30) \\ 1.02 - 1.45/V & \text{for } V > 1.8 \text{ m/s} \quad (3.31) \end{cases}$$

Rewriting Equation (3.29) with the ratio M/M_e,

$$a = \left(1.02 - \frac{1.45}{V}\right) \times \left\{\frac{101.97rP}{WV} - \left(\frac{\rho}{2W} C_D A_f V^2 + g(C_r + C_R V + G)\right)\right\} \quad (3.32)$$

$$(\text{V} > 1.8\, m/s)$$

Each of speed and distance by travel time can be obtained from the integration of Equations (3.4) and (3.7) with Equation (3.32). However, the numerical integration is intractable due to cubic speed function in denominator. Thus, Lan and Menendez (2003) provided an alternative method for practical design. In addition, their study used both the non-linear and linear acceleration and speed models to increase the accuracy of the estimation under the actual acceleration-speed functional relationship below:

1) Under all possible ranges of trucks' weight-to-power ratio, power, and grades, the relationship between acceleration and speed is linear above truck speed of 65km/h (Equation (3.33)); and
2) At a speed lower than 65 km/h, acceleration is a reciprocal function of speed due to lower resistance forces (Equation (3.34)).

This relationship between acceleration and speed can be expressed using Equations (3.33) and (3.34):

$$\text{a(t)} = \begin{cases} \alpha - \beta V(t) & \text{for } V \geq 65 \text{ km/h} \quad (3.33) \\ c + \frac{d}{V(t)} & \text{for } V \leq 65 \text{ km/h} \quad (3.34) \end{cases}$$

Based on the initial speed (V_i) and final speed (V_f), four possible cases can be considered whether these speeds are greater than V_0 (cut-off speed[1]: 65 km/h) or not, and then each case has its own equations for travel time and distance with V_i and V_f. Second-by-second speed profiles along roadway vertical grades can be calculated with Equations (3.35) to (3.42).

- Case I: $V_i \geq V_0$ and $V_f \geq V_0$

$$t = -\frac{1}{\beta} ln\left(\frac{\alpha-\beta V_f}{\alpha-\beta V_i}\right) \tag{3.35}$$

$$x = \frac{V_i-V_f}{\beta} - \frac{\alpha}{\beta^2}\ln\left(\frac{\alpha-\beta V_f}{\alpha-\beta V_i}\right) \tag{3.36}$$

- Case II: $V_i \leq V_0$ and $V_f \leq V_0$

$$t = \frac{V_i-V_f}{c} - \frac{d}{c^2} ln\left(\frac{cV_f+d}{cV_i+d}\right) \tag{3.37}$$

$$x = \frac{V_f^2-V_i^2}{2c} - \frac{d}{c^2}(\mathrm{V_f} - \mathrm{V_i}) + \frac{\mathrm{d}^2}{\mathrm{c}^3}\ln\left(\frac{cV_f+d}{cV_i+d}\right) \tag{3.38}$$

- Case III: $V_i \geq V_0$ and $V_f \leq V_0$

$$t = -\frac{1}{\beta} ln\left(\frac{\alpha-\beta V_o}{\alpha-\beta V_i}\right) + \frac{V_o-V_f}{c} - \frac{d}{c^2} ln\left(\frac{cV_f+d}{cV_o+d}\right) \tag{3.39}$$

$$x = \frac{V_i-V_o}{\beta} - \frac{\alpha}{\beta^2}\ln\left(\frac{\alpha-\beta V_o}{\alpha-\beta V_i}\right) + \frac{V_f^2-V_o^2}{2c} - \frac{d}{c^2}(\mathrm{V_f} - \mathrm{V_o}) + \frac{\mathrm{d}^2}{\mathrm{c}^3}\ln\left(\frac{cV_f+d}{cV_o+d}\right) \tag{3.40}$$

- Case IV: $V_i \leq V_0$ and $V_f \geq V_0$

$$t = -\frac{1}{\beta} ln\left(\frac{\alpha-\beta V_f}{\alpha-\beta V_o}\right) + \frac{V_i-V_o}{c} - \frac{d}{c^2} ln\left(\frac{cV_o+d}{cV_i+d}\right) \tag{3.41}$$

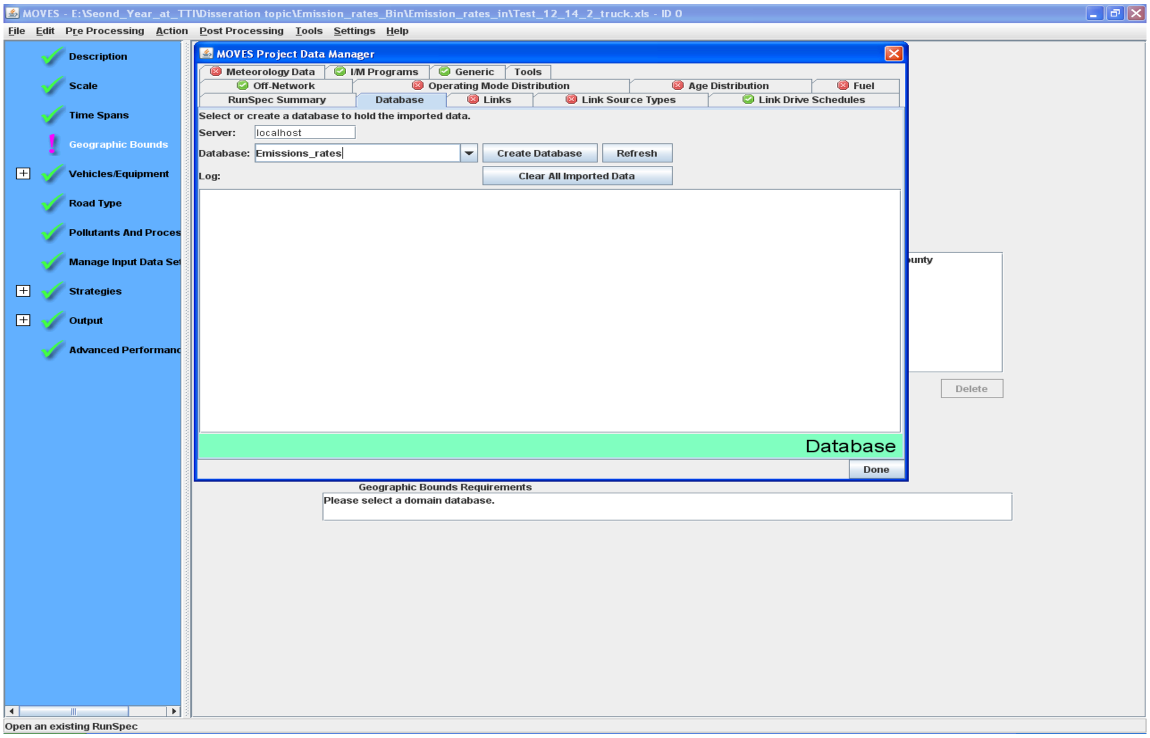
$$x = \frac{V_o^2-V_i^2}{2c} - \frac{d}{c^2}(\mathrm{V_o} - \mathrm{V_i}) + \frac{\mathrm{d}^2}{\mathrm{c}^3}\ln\left(\frac{cV_o+d}{cV_i+d}\right) + \frac{V_o-V_f}{\beta} - \frac{\alpha}{\beta^2}\ln\left(\frac{\alpha-\beta V_f}{\alpha-\beta V_o}\right) \tag{3.42}$$

---

[1] Both acceleration equations (3.33 and 3.34) have same slopes and acceleration at V_0.

3.3 Motor Vehicle Emission Simulator (MOVES)

MOVES is the U.S. EPA’s state-of-the-art tool for estimating fuel consumption and emissions from vehicle operations. It allows users to analyze motor vehicle emissions at the national, county, and project levels, using different levels of input data. MOVES is used for emission inventory development for SIPs and for regional emissions analysis of transportation conformity determinations in urban nonattainment areas. In recent years, the demand for the development of fine-scale emission modeling has expanded in response to statutory requirements for localized emission assessments (EPA, 2010), i.e. hot-spot analyses for transportation conformity and evaluation of the impacts of specific changes, such as signalization and lane additions, on emissions. Figure 3.1 shows the screen-capture of MOVES that includes many input categories for area, vehicle type, road type, operating mode distribution, age distribution, and others.



MOVES - E:\Seond_Year_at_TTI\Disseration topic\Emission_rates_Bin\Emission_rates_in\Test_12_14_2_truck.xls - ID 0

MOVES Project Data Manager

Select or create a database to hold the imported data.

Server: localhost

Database: Emissions_rates

Log:

Geographic Bounds Requirements

Please select a domain database.

Open an existing RunSpec

Figure 3.1 Screen capture of MOVES

MOVES incorporates large amounts of in-use data from a variety of sources based on the analyses of emission test results, and generates emission rates based on operating modes with instantaneous vehicle speeds and VSPs. The operating modes account for different patterns of acceleration, cruising, and deceleration as well as vehicle speed (Koupal et al., 2002). In addition, the VSP used in the operating modes characterizes emission rates of the running exhaust emission process, and accounts for vehicle speed, acceleration, roadway grade, and resistance forces such as rolling resistance and aerodynamic drag. Based on instantaneous vehicle speeds and VSPs, MOVES categorizes operating modes for predicting running exhaust emissions into 23 bins as shown in Table 3.1.

Table 3.1 MOVES operating mode bins

Braking (if $a_t \le -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$): Bin 0			
Idle (if $-1.0 \le v_t < 1.0$): Bin 1			
	Instantaneous Speed (mph)		
Instantaneous VSP (kW/tonne)	**0-25**	**25-50**	**> 50**
< 0	Bin 11	Bin 21	
0 to 3	Bin 12	Bin 22	
3 to 6	Bin 13	Bin 23	
6 to 9	Bin 14	Bin 24	
9 to 12	Bin 15	Bin 25	
12 and greater	Bin 16		
12 to 18		Bin 27	Bin 37
18 to 24		Bin 28	Bin 38
24 to 30		Bin 29	Bin 39
30 and greater		Bin 30	Bin 40
6 to 12			Bin 35
< 6			Bin 33

This study acquired second-by-second emission rates for each operating mode bin from MOVES. Since MOVES does not directly report the emissions rates for each bin, this study used a project-level analysis, a single model year, and a single operating mode distribution (i.e., 1 for the target bin and 0 for the rest). The repetitive processing with changing the target bin generated the emission rates for each of the 23 operating mode bins. The detailed procedures to extract fuel consumption and emissions rates using MOVES are provided in Appendix C. Table 3.2 and Figure 3.2 show the basic condition and diagram for the MOVES processing, respectively. The researcher extracted fuel consumption and emission rates on the 23 operating modes from two types of a vehicle, a passenger car and heavy duty truck, in Dallas County, Texas. The rate of fuel consumption is represented by gallon per second (i.e., gal/s), and the rate for emissions, regarding CO_2, NO_x, CO, HC, and $PM_{2.5}$, is gram per second (i.e., g/s).

Table 3.2 Basic condition in MOVES processing

Variable			Specification	
Input	Vehicle	Type	A Single Passenger Car	
			A Single Heavy Duty Diesel Truck	
		Mass (ton)	Passenger Car	1.478
			Heavy Duty Truck	31.404
		Model Year	Passenger Car	4 yrs old
			Heavy Duty Truck	4 yrs old
		Fuel	Passenger Car	Reformulated Gasoline (RFG) (Market share: 25 percent)
				Gasohol (E10) (Market share: 75 percent)
			Heavy Duty Truck	Conventional Diesel Fuel
	Roadway	Type	Rural Unrestricted Access	
		Grade	Level	
	Area		Dallas County, TX	
	Year		2010	
	month		May	
	Temperature (℉)		79.4	
	Relative Humidity (percent)		56.3	
Output	Fuel Consumption		Rate (gal/s) on each operating mode by each vehicle type	
	Emissions		Rates (g/s) of CO_2, NO_x, HC, CO, and $PM_{2.5}$ on each operating mode by each vehicle type	

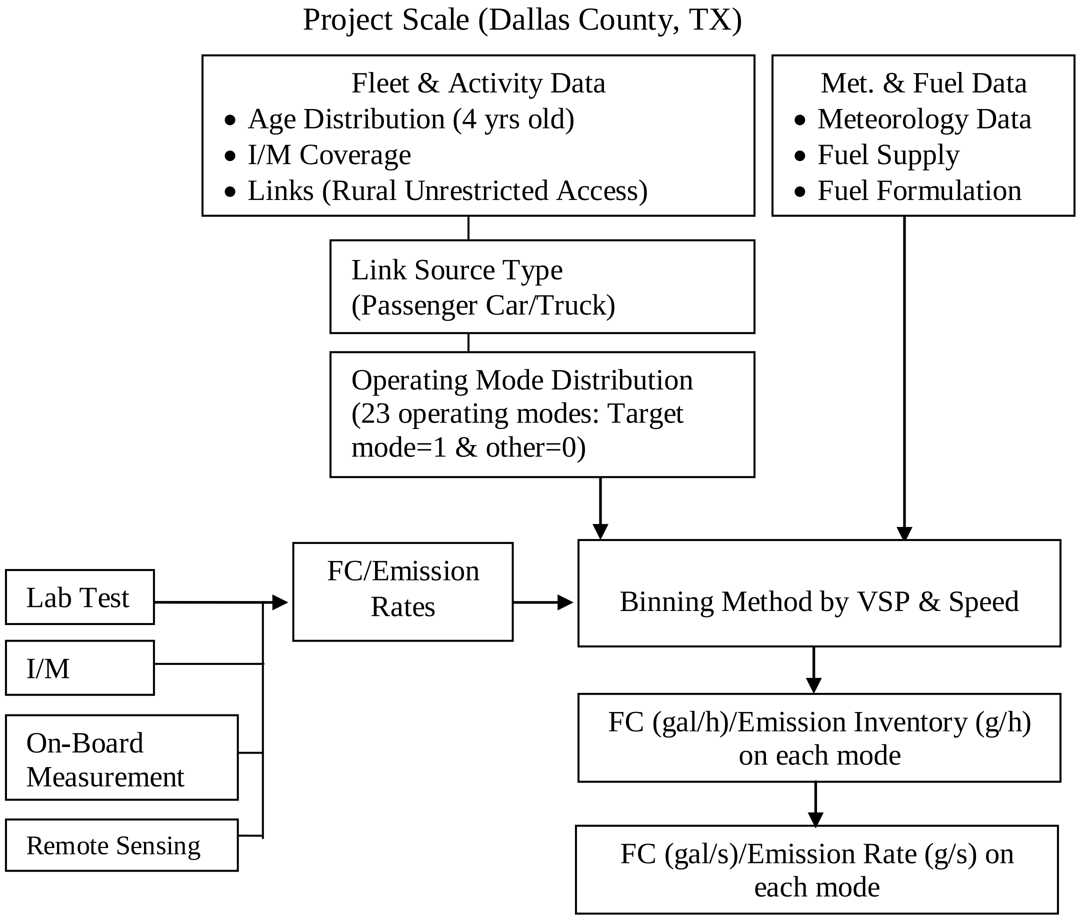


Figure 3.2 MOVES procedure diagram in this study (source: Koupal, 2003)

Fuel consumption and emissions are aggregated during a travel time based on second-by-second operating mode bins from speed profiles and emission rates for each operating mode bin, and this process can be expressed as following:

$$E_{type} = \sum_{t=1}^{n} e_{type,bin,t} \tag{3.43}$$

where,

E_{type}= total emission for each of CO_2, NO_x, CO, HC, $PM_{2.5}$ or total fuel consumption; and

$e_{type,\ bin,\ t}$= fuel consumption or emission rate for type (i.e., passenger car and heavy duty truck) and operating bin at time t.

3.4 Chapter Summary

This chapter provides the methodology used for generating speed profiles on roadway vertical grades and horizontal and vertical crest curves and estimating emission rates for each of the 23 operating mode bins that are categorized by instantaneous vehicle speed and VSP. The speed prediction models were used for predicting operating speeds at the middle of horizontal and vertical crest curves. Drivers can have lower operating speeds on the curves than approaching tangent speeds due to safety and comfort reasons, and the reduction in the operating speeds is dependent on geometric design features, such as smaller radius or rate of vertical curvature than recommended ones. These predicted operating speeds are not constant on the curves. To reflect the variation of the operating speeds, this study used the polynomial model as one of the non-uniform acceleration/deceleration models. The polynomial model can predict operating speeds between approaching tangent speeds and reduced operating speeds at the middle of the curves from calculated acceleration/deceleration rates.

The truck dynamic model provides truck acceleration/deceleration rates under the consideration of vehicle type and mass, engine generated force, external resistance forces including the resistance from roadway grades. However, truck speed and distance by travel time can be hardly predicted because of intractable numerical integration on the equation for acceleration. Thus, the non-linear and linear acceleration and speed models proposed by Lan and Menendez (2003) were used for second-by-second speed profiles related to various roadway grades and critical length of grades in highway design.

This study used MOVES for acquiring the rates of fuel consumption and emissions on each of the operating modes during a vehicle running exhaust process. These rates were matched with the operating modes calculated from second-by-second speed profiles on highway vertical grades and horizontal and vertical crest curves. Then, the fuel consumption and emissions per second were accumulated during vehicle traveling. The next chapter describes the hypothetical conditions for the quantitative evaluation of fuel consumption and emissions on the grades and curves.

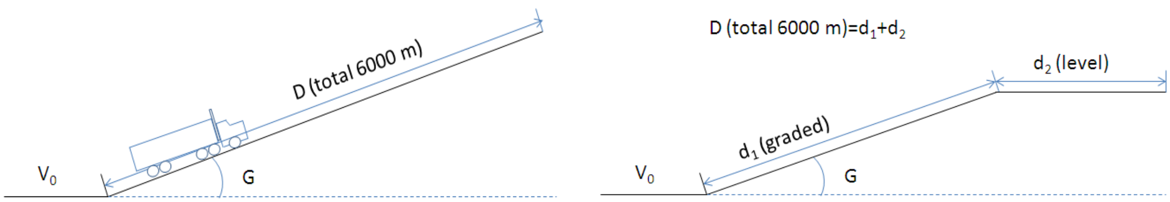
CHAPTER IV

DATA SIMULATION

This chapter provides simulated data for the analyses of the link between various highway geometric features and fuel consumption and emissions. The data were simulated for the speed profiles on: 1) roadway vertical grades, 2) crest vertical curves considering the degree of curvatures, and 3) horizontal curves using a radius, the 85th percentile approaching tangent speed, a deflection angle, and superelevation.

4.1 Simulation for Grades

The second-by-second truck (a typical heavy truck of 120 kg/kW) speed profiles of grades (zero ~ nine percent) were generated under the same conditions provided in the GreenBook using the truck dynamic model and linear and non-linear acceleration-speed models. Figure 4.1 and Table 4.1 describe the base conditions for the simulation.



(a) Initial speeds (V_0) and grades (G)

(b) Critical length of grades (d_1)

Figure 4.1 Description of simulation on highway vertical grades by initial speeds, grades, and critical length of grades

There are three key factors, grades, initial speeds, and critical length of grades, in the design of roadway vertical grades. First, fuel consumption and emissions are aggregated from the trips reflecting various grades of zero[2] to nine percent and initial speeds of 10 to 110 km/h while traveling from 6,000 m (Figure 4.1 (a) and Table 4.1). In terms of critical length of grades, the length is divided into two segments: vertical grade (d_1) and leveled (d_2). The length of vertical grade segment is dependent on speed reductions of 10 or 20 km/h. The length of leveled segment is decided from the subtraction of the graded length from the distance of 6,000 m (Figure 4.1 (b) and Table 4.1).

Table 4.1 Conditions in the simulation for vertical grades

Variable	Condition
Initial Speed (km/h)	$V_i = 10i$ $(i=1, \ldots, 11^1)$
Grade (percent)	$G_j = j$ $(j=0^1, \ldots, 9)$
Travel Distance (m)	$6{,}000 = d_1+d_2$
Design Vehicle	A Typical Heavy Truck of 120 kg/kW
Driver	Normal
Roadway Type	Two-Lane Rural Highways

NOTE: ^{1}base condition for initial speed and grade are 110 km/h and a flat (0 percent); d_1 stands for length of vertical grade segment; d_2 stands for length of leveled segment.

4.1.1 Process for Second-by-second Speed Profiles on Vertical Grades

Although it is more precise to get second-by-second speed profiles using Equation (3.32) in the truck dynamic model, the numerical integration is intractable and impractical for

---

[2] For the vertical grades in the highway geometric design, the minimum grade should be 0.5 percent for drainage purposes. However, a 0 percent grade is considered as a leveled segment in this research.

highway designer/engineers. Therefore, this study used the methods provided by Lan and Menendez (2003) as follows:

1. Assume that W/P= 120 kg/kW where P= 261.7 kW and W= 31403.8 kg; $C_d = \frac{\rho}{2} C_a A = 3.71$ where ρ= 1.2256 kg/m3 at sea level, Ca= 0.8, and A= 0.9x 2.4 x 3.5 m2= 7.56 m2 ; Cr = 0.01, Cs = 1/4470, r =0.92, and G= 6 percent.
2. Solve the acceleration rates, a0 and ah at 65 km/h (18.06 m/s) as V0 (cut-off speed) and 105 km/h (29.17 m/s) as Vh (higher speed), respectively, using Equation (3.32).

$$a_0 = \left(1.02 - \frac{1.45}{18.06}\right) \times \left\{\frac{101.97rP}{W * 18.06} - \left(\frac{0.3997}{W} * (18.06)^2 + g\left(0.01 + \frac{1}{4470} 18.06 + 0.06\right)\right)\right\}$$

= -0.3195

$$a_h = \left(1.02 - \frac{1.45}{29.17}\right) \times \left\{\frac{101.97rP}{W * 29.17} - \left(\frac{0.3997}{W} * (29.17)^2 + g\left(0.01 + \frac{1}{4470} 18.06 + 0.06\right)\right)\right\}$$

= -0.5707

The coefficients, α, β, c, and d, for linear and non-linear acceleration-speed models (Equations (3.33) and (3.34)) that were defined in the study by Lan and Menendez (2003) were calculated from the below:

$$\alpha = \frac{a_0 V_h - a_h V_o}{V_h - V_0} = 0.0886$$

$$\beta = \frac{a_0 - a_h}{V_h - V_0} = 0.0226$$

$$c = \alpha - 2\beta V_0 = -0.7277$$

$$d = \beta V_0^2 = 7.3692$$

3. Apply the values of α, β, c, and d into Equations (3.33) and (3.34).

$$a(t) = \begin{cases} 0.0886 - 0.0226V(t) & \text{for } V \geq 65 \text{ km/h} \\ -0.7277 + \frac{7.3692}{V(t)} & \text{for } V \leq 65 \text{ km/h} \end{cases}$$

4. Acquire speed values on each travel time using Equations (3.35) to (3.42) dependent on whether the speed is greater than or equal to 65 km/h or not. Figure 4.2 shows the example of speed profiles of a 110 km/h initial speed for various grades (i.e., zero to nine percent)[3]. On a six percent of grade, the initial speed of 110 km/h decreased to 36.5 km/h[4] and maintained this speed until the end of the trip. Design vehicle's speed can be dropped to a maximum 36.5 km/h from 110 km/h depending on the length of the graded segment.

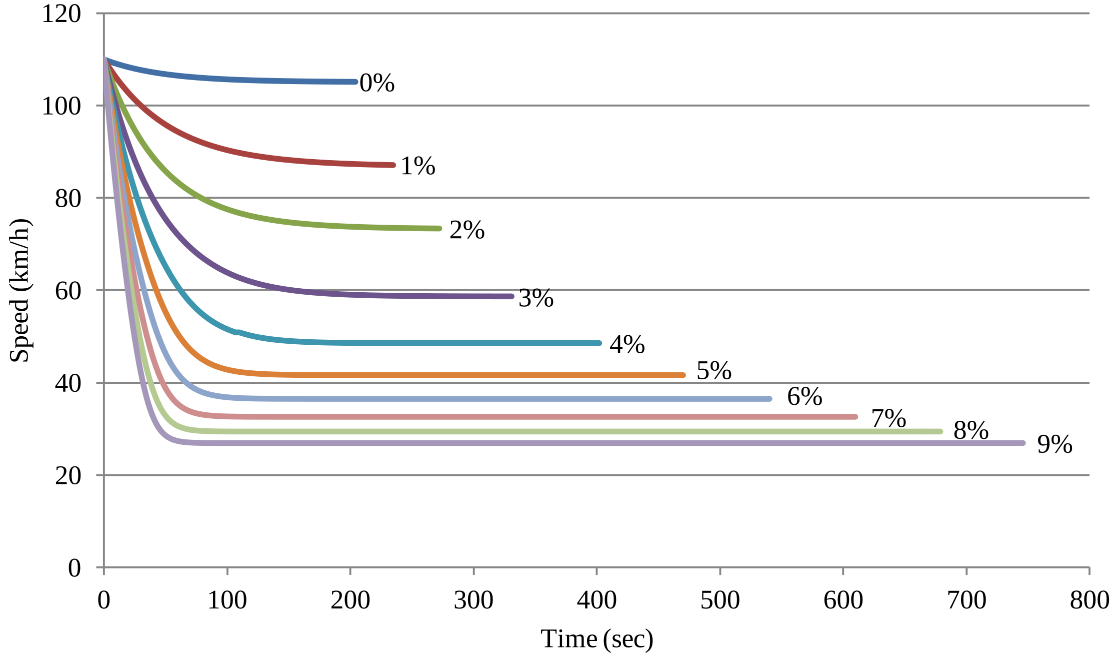


Figure 4.2 Example of second-by-second speed profiles of initial speed of 110 km/h

---

[3] Speed profiles for other initial speeds (i.e., 10 to 100 km/h) are shown in Appendix B.

[4] It is called a crawl speed which is maximum sustained speed of truck on the 6 percent grade.

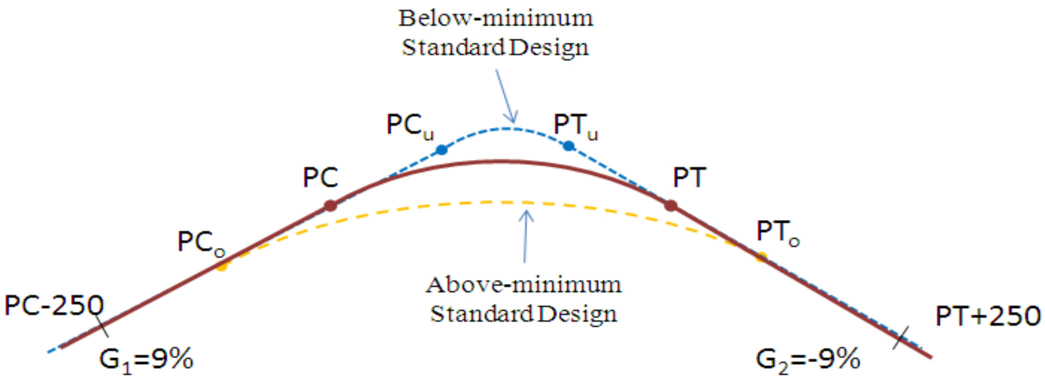
4.2 Simulation for Vertical Crest Curves

The second-by-second speed profiles on vertical crest curves with various rates of vertical curvature (K) were generated with the speed prediction model and polynomial model. The GreenBook recommends the minimum K of 39 m/percent for the design speed of 90 km/h (AASHTO, 2004). Although vertical crest curves should be designed with greater values than the recommended minimum standard in the GreenBook, highway might be constructed with the values less than the recommended ones in the design guide book. Additional explanations on this issue will be discussed with actual highway geometric data in a later chapter. The researcher considered the cases of the below-minimum standard design using the less K and the above-minimum standard design using the greater K than the recommended minimum value in the GreenBook (AASHTO, 2004). Table 4.2 and Figure 4.3 show the base conditions and assumption for the speed profiles on vertical crest curves in a two-lane highway.

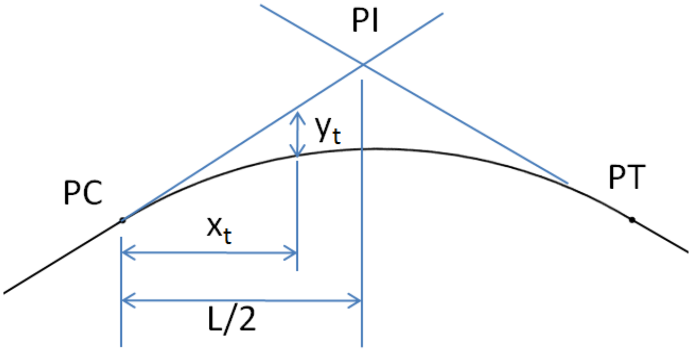
Table 4.2 Conditions in the simulation for vertical curve

Variable		Condition
Rate of Vertical Curvature, K (m/percent)		K_m= 39(0.5+0.1m) (m=0, …, 10)
85th Percentile Tangent Speed (km/h)		100
Grades (percent)	Uphill Tangent	9
	PC to PT	G(x)^1
	Downhill Tangent	-9
Design Vehicle		A Passenger Car
Driver		Normal
Roadway Type		Two-Lane Highways

NOTE: K_5 = 39 (Base condition); the below-minimum standard design when K < 39; the above-minimum standard design when K > 39; ^{1} Grade on vertical curve changes by x.



(a) Overall vertical crest curve profile



(b) Grade changes on the curve

Figure 4.3 Description of simulation scenarios on vertical curves

The base condition in the simulation of vertical curve was set when K was 39 m/percent, and the curve profile was illustrated with the point of curve (PC) and the point of tangent (PT) in Figure 4.3 (a). In addition, fuel consumption and emissions were aggregated during the trip from 250 m before PC (PC-250) and 250 m after PT (PT+250) because the length of 250 m was sufficient for covering the possible the above-design conditions simulated in this study. When vertical curve was designed with the smaller K than the minimum standard (i.e., below-minimum standard design), the curve was connected with two tangent segments at points of PC_u and PT_u. For the below-minimum standard design conditions, speed profiles were respectively generated for 50 percent, 40 percent, 30 percent, 20 percent, and 10 percent reductions rather than the recommended minimum K-value (39 m/percent), and fuel consumption and emissions would be aggregated during the trip from PC-250 to PT+250. For the above-minimum standard design scenario, the curve was profiled with two connecting points of PC_o and PT_o as shown in Figure 4.3 (a), and speed profiles were respectively generated for 50 percent, 40 percent, 30 percent, 20 percent, and 10 percent increases rather than the recommended. The aggregation of fuel consumed and emissions would be performed during the trip from PC-250 to PT+250. Basically, the predicted operating speed on the curve should be less or equal to the 85th percentile tangent speed (100 km/h). A grade changes on a vertical curve with vehicle traveling, as shown in Figure 4.3 (b). Using the elevation at the travel distance (i.e., x_t: travel distance at time t) from PC, grades on the curve can be calculated from Equation (4.1):

$$G_t(percent) = \left(\frac{E_t - E_{t-1}}{x_t - x_{t-1}}\right) \times 100 = G_0 + \frac{100A(x_t - x_{t-1})}{60.96L} \tag{4.1}$$

where G_0 is nine percent and E_t is the elevation at the distance of x_t from the point of PC.

4.2.1 Process for Second-by-second Speed Profiles on Vertical Curves

Based on the equations that predict the operating speed at the middle of vertical crest curve, acceleration rates, and acceleration time, this study could obtain speed profiles related with various K-values with the following procedure:

1. Predict the operating speed at vertical crest curve and calculate the length of vertical curvature ($L = KA=K|G_2-G_1|$). For examples,

$$V_{85} = 105.08 - \frac{149.69}{20} \cong 97km/h$$

$$L = KA = 20 * |-9 - 9| = 351\, m$$

2. Determine the acceleration time (Equation (3.21)) with the predicted operating speed (V_f) at the middle of curve and approaching tangent speed (V_i).

$$t_a = \frac{V_f - V_i}{2.08 + 0.127(V_f - V_i)^{1/2} - 0.0182V_i} \cong 6 \text{ second}$$

3. Based on the calculations above, a vehicle would decelerate from 100 km/h (V_i) to 97 km/h (V_f) while six second.
4. Calculate the speeds and travel distance every second using the following equations; for example, acceleration rate, speed, and distance at three second after starting a deceleration on the curve:

$$a(3) = ra_m\theta(1-\theta^m)^2 = -0.2185\ m/s^2$$

$$V(3) = V_i + 3.6ra_m t_a\theta^2\left[0.5 - \frac{2\theta^m}{(m+2)} + \frac{\theta^{2m}}{(2m+2)}\right]\text{=98.7 km/h}$$

$$x(3) = \frac{V_i t}{3.6} + ra_m t_a^2\theta^3\left[\frac{1}{6} - \frac{2\theta^m}{(m+2)(m+3)} + \frac{\theta^{2m}}{(2m+2)(2m+3)}\right]\text{=81.8 m}$$

   where m (= 3.2122), a_m (= -0.2203) and r (= 2.4929) would be calculated from the Equations (3.10), (3.11), and (3.12).
5. Grade per second would be calculated using Equation (4.1). Figure 4.4 describes the changes of grades on vertical crest curves.

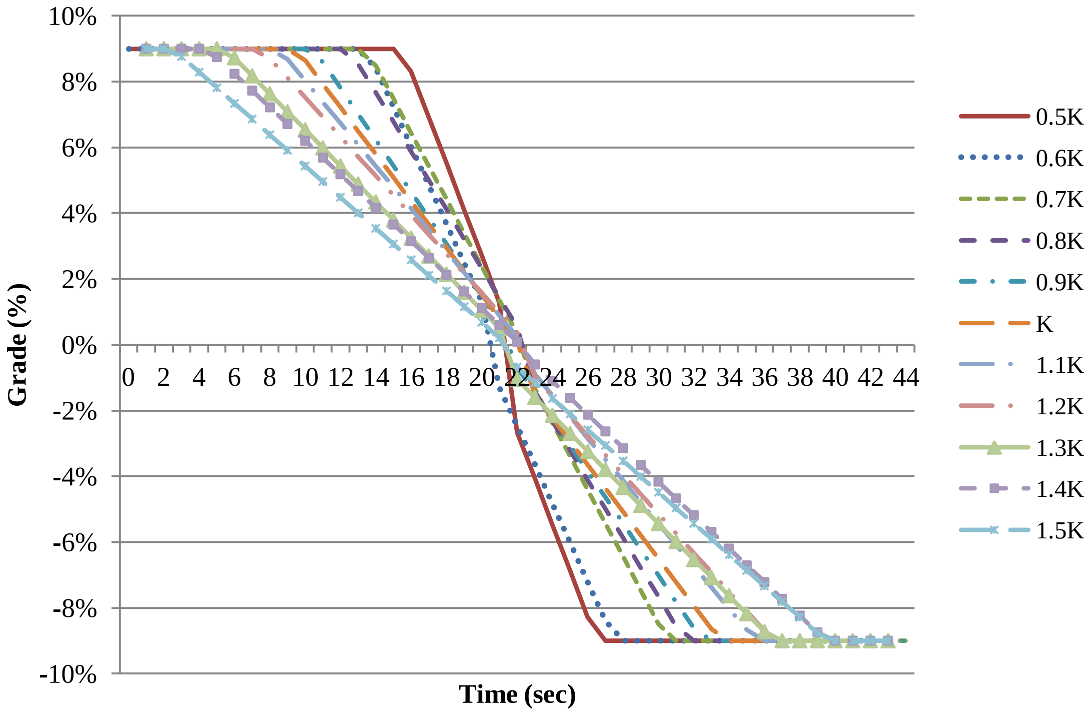
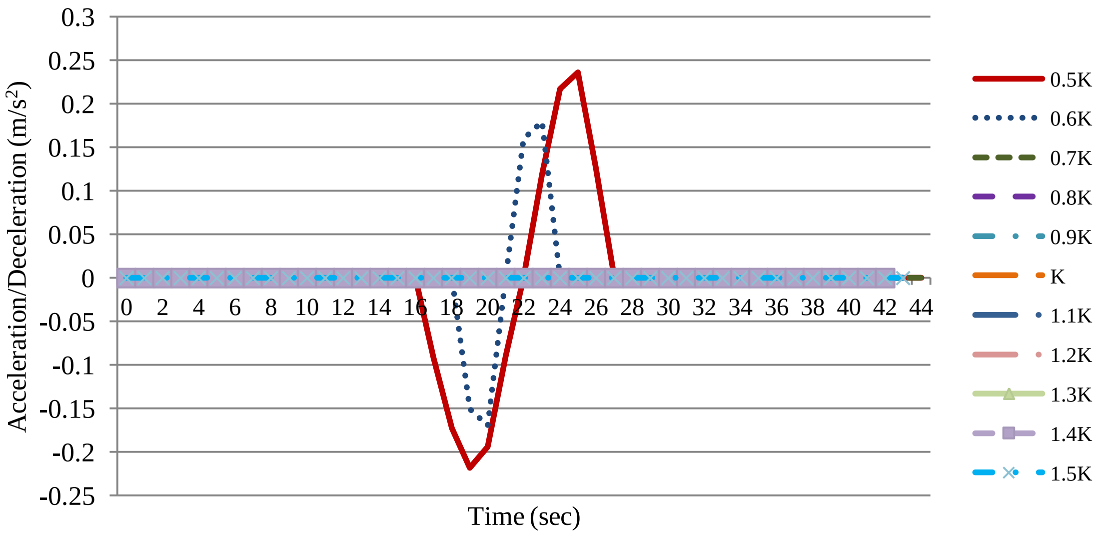
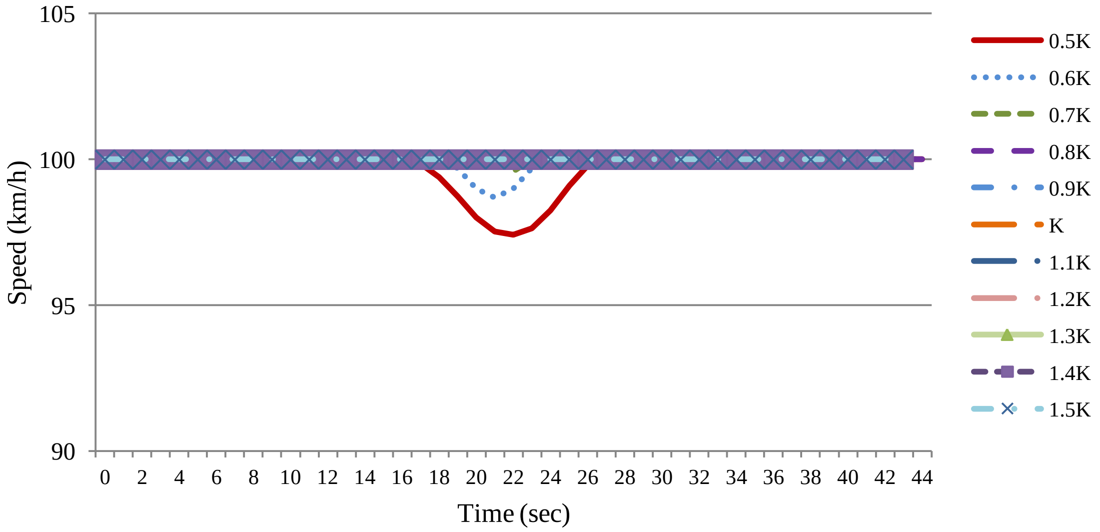


Figure 4.4 Grade changes by travel time on vertical curve

From the procedures above, the researcher could have generated the second-by-second speed and acceleration profiles on the vertical curves (Figure 4.5). However, there were speed reductions on only 50 percent and 40 percent reduced K scenarios; thus, acceleration/deceleration could be calculated from the speed changing for only two scenarios. On the vertical curves designed with other K-values, operating speeds were same with the approaching tangent speed. In other words, the design vehicle kept the 85th percentile tangent speed throughout the curve.



(a) Acceleration profiles with travel time



(b) Speed profiles with travel time

Figure 4.5 Speed and acceleration profiles on vertical crest curves

4.3 Simulation for Horizontal Curves

Figure 4.6 describes horizontal alignments considered in the simulation. At each tangent speed, the base condition was set when curve was designed with the recommended minimum radius. The curve was connected with two tangent segments at the points of PC and PT, as shown in Figure 4.6. Fuel consumption and emissions per second would be aggregated during the trip from the point of PC-250 (i.e., 250 m before PC) to the point of PT+250 (i.e., 250 m after PT). Under the same tangent speed, it was categorized as the above-minimum standard design (curve connecting by points of PC_o and PT_o) when the curve radius was greater than the recommended minimum standard. When the radius was less than the recommended, the curve was categorized as the below-minimum standard design (curve connecting by points of PC_u and PT_u). For both the above- and below-minimum standards, fuel consumption and emissions would be aggregated during the trips starting at the point of PC-250 and ending at the point of PT+250.

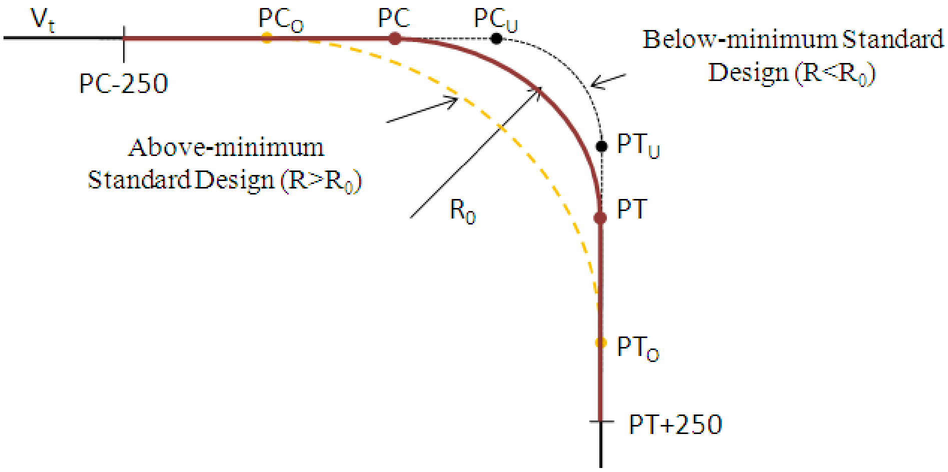


Figure 4.6 Description of simulation scenarios on horizontal curve

The second-by-second speed profiles related to various horizontal curve radiuses and the 85th percentile tangent speeds were generated with the speed prediction model and polynomial model under the conditions specified in Table 4.3. The speed profiles were, respectively, generated for 50 percent, 40 percent, 30 percent, 20 percent, and 10 percent reductions and increases of the minimum standard horizontal curve radius related to given design speed in the GreenBook, as well as including the case for the recommended minimum radius, within each scenario.

Table 4.3 Conditions in the simulation on horizontal curve

	Scenario 4-3-1	Scenario 4-3-2	Scenario 4-3-3
85th Percentile Tangent Speed (km/h)	70	90	110
Recommended Horizontal Curve Radius (GreenBook)	168 (R_1^1)	304 (R_2^1)	501 (R_3^1)
Designed Horizontal Curve Radius (m)	R_n=R_1 (0.5+0.1n) (n=0, …, 10)	R_n =R_2(0.5+0.1n) (n=0, …, 10)	R_n =R_3(0.5+0.1n) (n=0, …, 10)
Deflection Angle (degree)	90		
Superelevation (percent)	8		
Grade (percent)	Level (0)		
Design Vehicle	Passenger Car		
Driver	Normal		
Roadway Type	Two-Lane Highways		

NOTE: [1] base condition; the above-minimum standard design when R > recommended minimum radius; the below-minimum standard design when R < recommended minimum radius.

4.3.1 Process for Second-by-second Speed Profiles on Horizontal Curves

Based on the equations that predict operating speed at the middle of horizontal curve, acceleration rates, and an acceleration time, this study could only obtain speed profiles related to different initial speeds and curve radius values with the following procedure:

1. Calculate the radius of travel path at horizontal curves (Equation (3.1)) and predict the operating speeds in the middle of the curves. For examples, where R=251 m, $V_{t.85}$ = 110 km/h, superelevation (e) = 8 percent, I_c = 90 degree, and I_{tk}= 0 (for a passenger car).

$$R_p = R + \frac{0.9144}{1 - cosine(0.5I_c)} = 251 + \frac{0.9144}{1 - cosine\ (0.5 * 90)} = 252.4\ \text{m}$$

$$V_{85} = \left[\frac{49.21R_p(b_0 - b_1V_{t.85} + +b_2V_{t.85}^2 - b_3I_{tk} + e/100)}{1 + 0.00358R_p}\right]^{\frac{1}{2}} \leq V_{t.85}$$

$$= \left[\frac{49.21R_p(0.196 - 6.59\times10^4V_{t.85} + 2.189\times10^5\ V_{t.85}^2 + 8/100)}{1 + 0.00358R_p}\right]^{\frac{1}{2}} = 95.95\ km/h \leq V_{t.85}$$

2. Determine the deceleration time (Equation (3.19)) from the 85th percentile tangent speed (V_i =110 km/h) to the predicted operating speed (V_f = 95.95 km/h).

$$t_{a1} = \frac{|95.95 - 110|}{2.08 + 0.127|95.95 - 110|^{1/2} - 0.0182\times110} = 25.35\ \text{second}$$

Based on the result, vehicle would decelerate from 110 km/h to 96 km/h while 25 second to the middle of horizontal curve. In addition, the acceleration time for recovering to the initial speed (i.e., 110 km/h) from the reduced speed after passing the middle of the curve is

$$t_{a2} = \frac{|110-95.95|}{2.08+0.127|110-95.95|^{1/2}-0.0182\times 95.95}\text{=17.34 second}$$

It takes 17 second to accelerate from 96 km/h to 110 km/h.

3. Calculate the speeds and travel distance every second using Equations (3.17) and (3.18). For example, the acceleration rate, speed, and traveled distance at 15 second since starting a deceleration:

$$a(15) = ra_m\theta(1-\theta^m)^2 = -0.2554\, m/s^2$$

$$V(15) = V_i + 3.6ra_mt_a\theta^2\left[0.5 - \frac{2\theta^m}{(m+2)} + \frac{\theta^{2m}}{(2m+2)}\right]\text{=100.75 km/h}$$

$$x(15) = \frac{V_it}{3.6} + ra_mt_a^2\theta^3\left[\frac{1}{6} - \frac{2\theta^m}{(m+2)(m+3)} + \frac{\theta^{2m}}{(2m+2)(2m+3)}\right]\text{=420.2 m}$$

where m (= 3.2122), a_m (= -0.2627) and r (= 2.4929) would be calculated from Equations (3.10), (3.11), and (3.12).

With the process above, this study could have acceleration and speed profiles as shown in Figure 4.7.

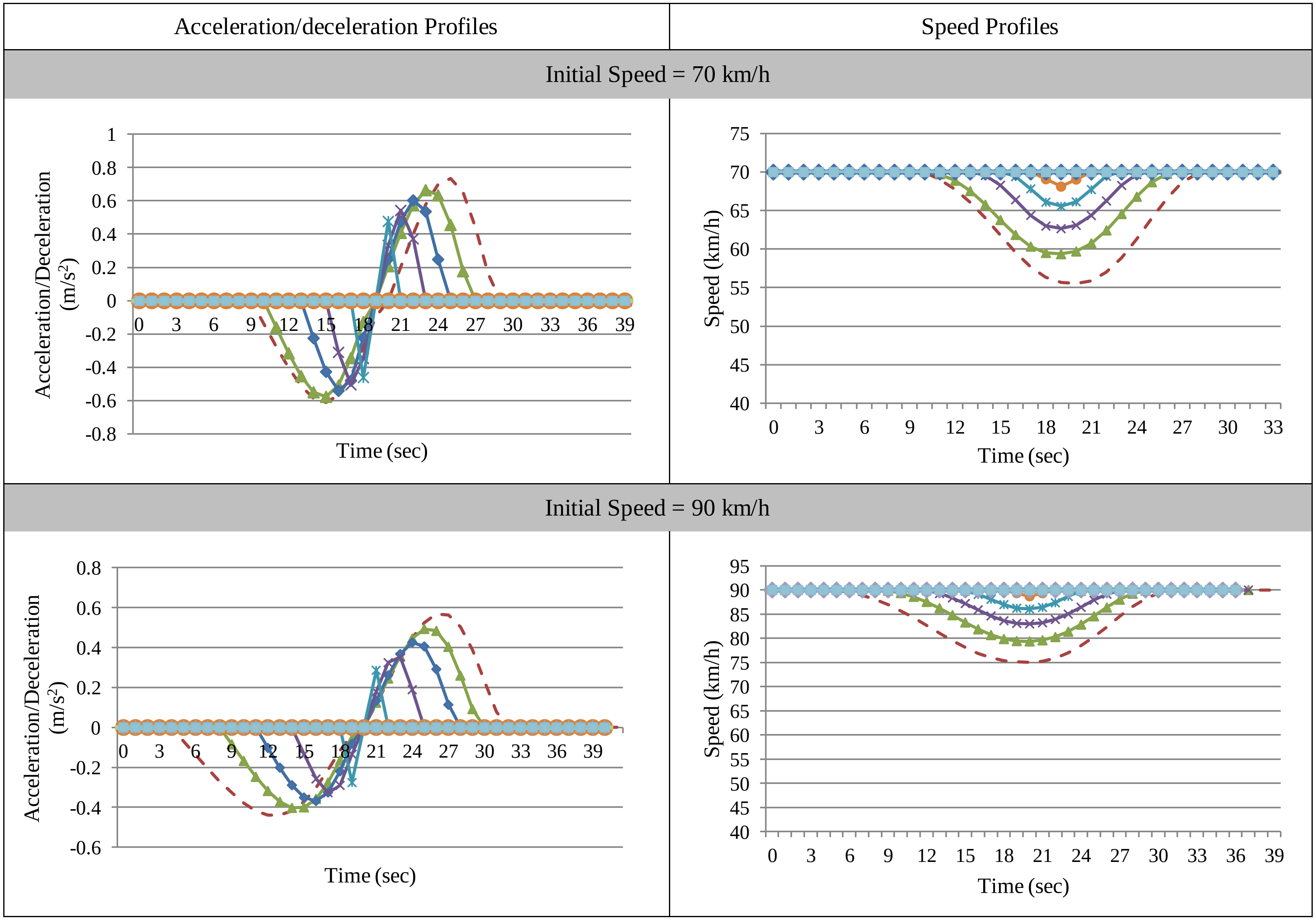


Figure 4.7 Acceleration/deceleration and speed profiles on horizontal curves

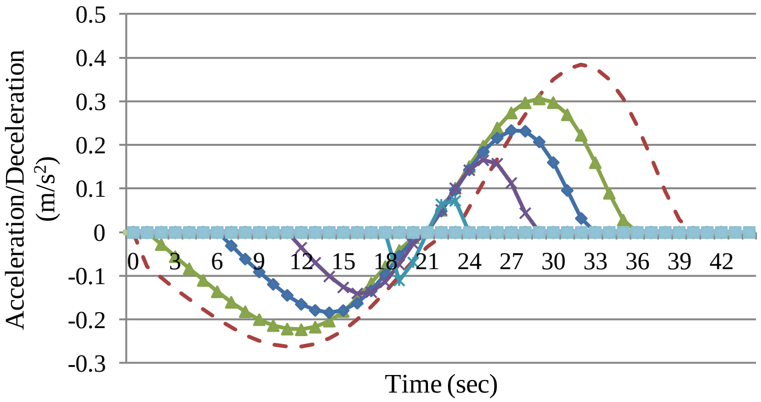
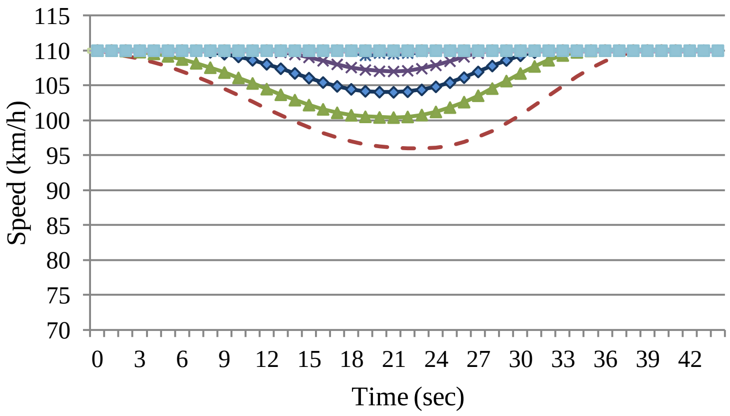
<table>
<tr><th>Acceleration/deceleration Profiles</th><th>Speed Profiles</th></tr>
<tr><td colspan="2">Initial Speed = 110 km/h</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">NOTE: Legend
- - - 0.5R
▲ 0.6R
◆ 0.7R
× 0.8R
✳ 0.9R
● R
+ 1.1R
– 1.2R
— 1.3R
◆ 1.4R
■ 1.5R</td></tr>
</table>

Figure 4.7 continued

4.4 Chapter Summary

In this chapter, the research described the data simulation procedures for generating speed profiles at the design of highway vertical grades and horizontal and vertical curves, and specified the base conditions as well as other conditions related to key design variables (e.g., grades, initial speeds, critical length of grades, curve radius, rate of vertical curvature, and tangent speeds).

On highway vertical grades, there were three variables: initial speeds, grades, and critical length of grades. Speed profiles were generated at the intertwined conditions between initial speeds of 10 km/h to 110 km/h and grades of zero to nine percent. In terms of critical length of grades, speed profiles were generated on the grades designed not only with the consideration of speed reduction of less than 10 and 20 km/h, but also without any consideration of speed reduction, such as vertical grade design causing greater than a 20 km/h speed reduction.

At horizontal and vertical curves, the speed profiles were generated under the consideration of various design conditions. The base conditions were related to the minimum standards as documented in the GreenBook (e.g., R = 304 m or K = 39 m/percent at a 90 km/h design speed). When the design value was greater or less than the recommended minimum, the design was categorized as the above- or below-minimum standard design, respectively. This chapter also provided the processes for predicting acceleration rate, speed, and travel distance by travel time based on the application of the equations provided in the methodology chapter. Finally, the speed profiles were generated at each of the simulated conditions. The next chapter presents the results for aggregated fuel consumption and emissions during trips on the grades and curves based on the simulated conditions.

CHAPTER V

SIMULATION RESULTS

This chapter provides the results for the fuel consumption and emission rates related to the 23 operating mode bins from the MOVES processing. Later, these rates are matched with operating modes from the speed profiles on vertical grades and vertical and horizontal curves, and aggregated fuel consumption and emissions during each trip related with various design conditions could be compared with base design conditions.

5.1 Fuel Consumption and Emissions Rates from MOVES

This section provides the rates of fuel consumption and emissions on the 23 operating mode bins that are categorized by VSP and vehicle speed from the MOVES_2010a that is the most recent vehicle emissions simulator provided by EPA. The rates of fuel consumption and emissions are originated from two vehicle types: 1) passenger car and 2) heavy duty diesel truck. In addition, vehicle emissions are based on CO_2, NO_x, CO, HC, and $PM_{2.5}$.

Figure 5.1 shows the rates of fuel consumption and emissions for each of the 23 operating mode bins from a typical passenger car and heavy duty diesel truck in Dallas County, Texas. Generally, the truck consumed more fuel and produced more emissions than the passenger car. The rates of fuel consumption and emissions linearly or exponentially increased with their VSPs within each speed category. Higher engine load that can be represented by higher VSP directly resulted in the higher rates through the combustion process. Especially, CO_2 is the principal production from the fuel combustion process and mainly proportional to the rates of combusted fuel. Therefore, the rates from CO_2 and fuel consumption have almost same pattern on the 23 operating mode bins as shown in Figure 5.1.

In terms of rates by speed category, the pattern of the rates within the speed category having greater than 50 mph (80 km/h) was similar with the pattern from the speed category of greater than 25 mph (40 km/h) and lower than 50 mph (80 km/h). However, the pattern of the rates from the speed category of lower than 25 mph (40 km/h) was different with other speed categories of greater than 25 mph (40 km/h); the rates were lower than ones from higher speed categories.

The vehicle type affected the pattern in some emissions. In terms of the rates of fuel consumption, CO_2, and NO_x, it shows similar pattern of the rates on the 23 operating mode bins between two vehicle types. However, for CO, HC, and $PM_{2.5}$, the simulation results show different emission patterns between two vehicles. The emission rates for the passenger car varied greatly among the 23 operating mode bins; the rates for the #30 operating mode bin were more peaked than other modes. For the truck, the rates from CO and HC were relatively uniform on the entire operating mode bins than for the passenger car.

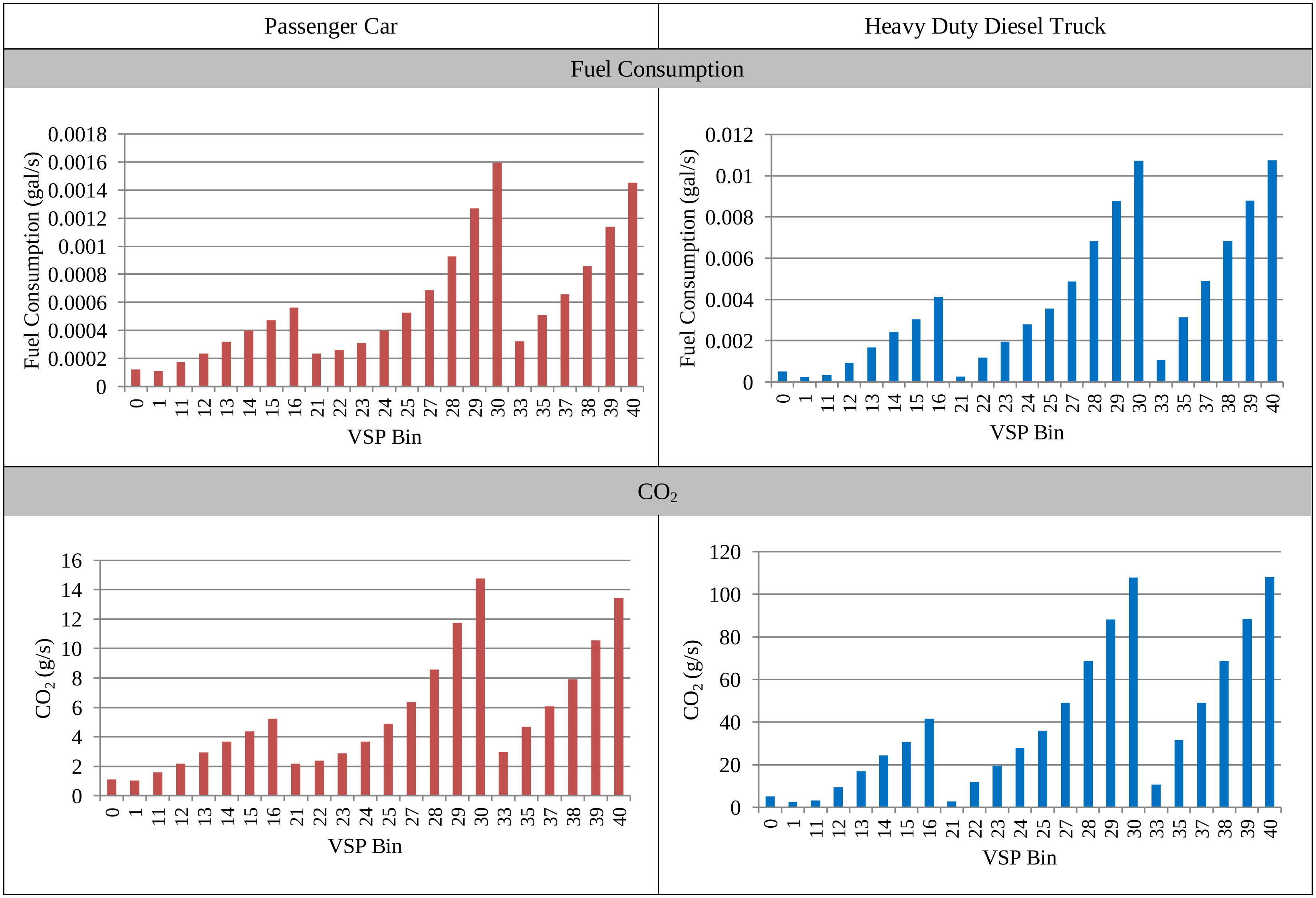


Figure 5.1 Running exhaust emission rates on 23 operating mode bins from MOVES

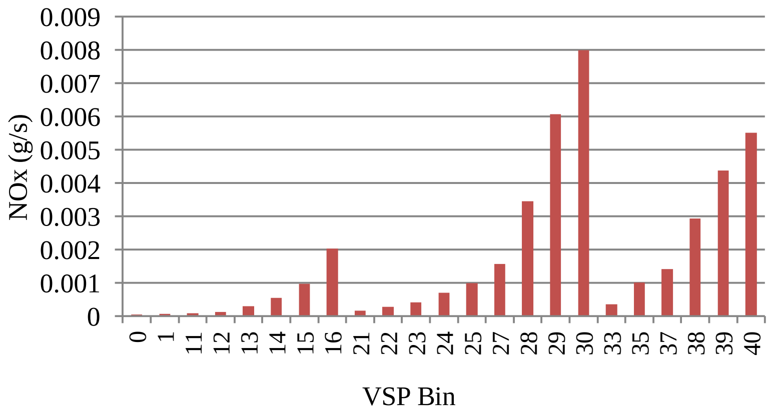
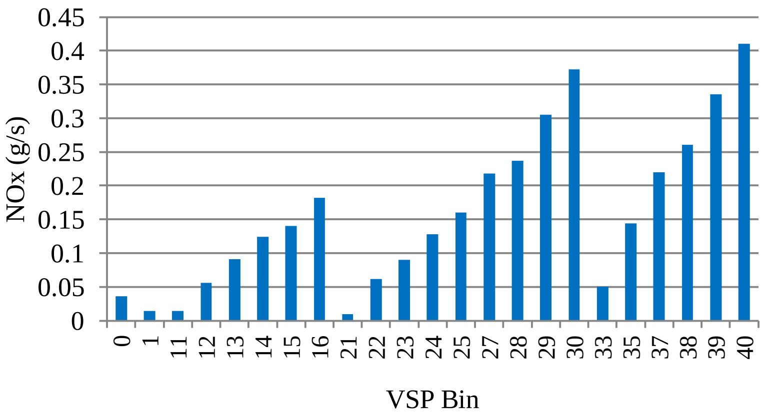
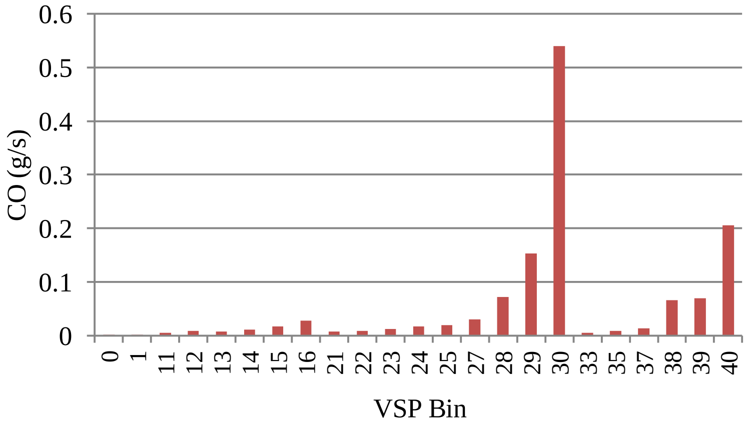
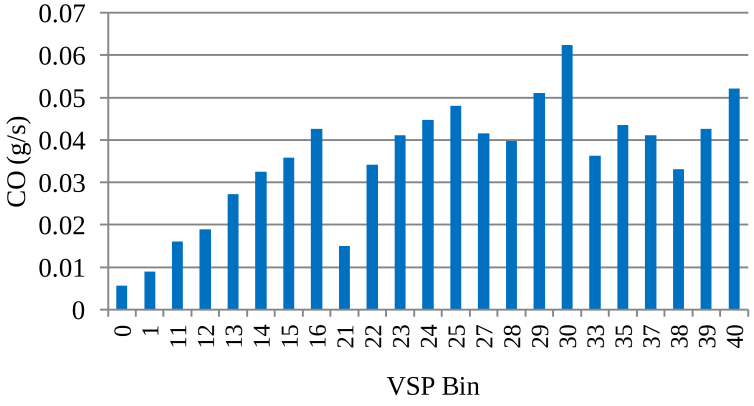
<table>
<tr><td>Passenger Car</td><td>Heavy Duty Diesel Truck</td></tr>
<tr><td colspan="2">NO_x</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">CO</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Figure 5.1 continued

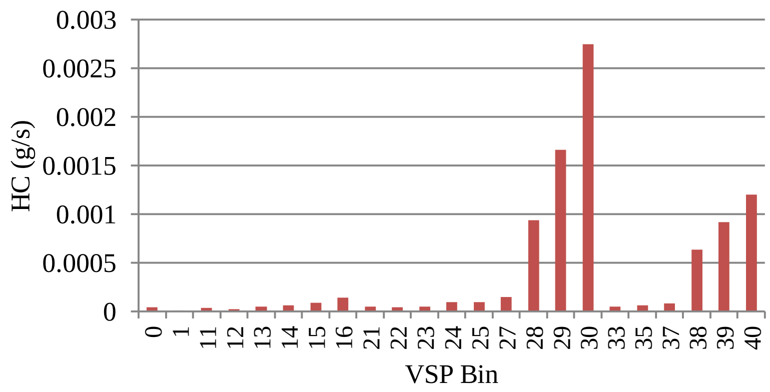
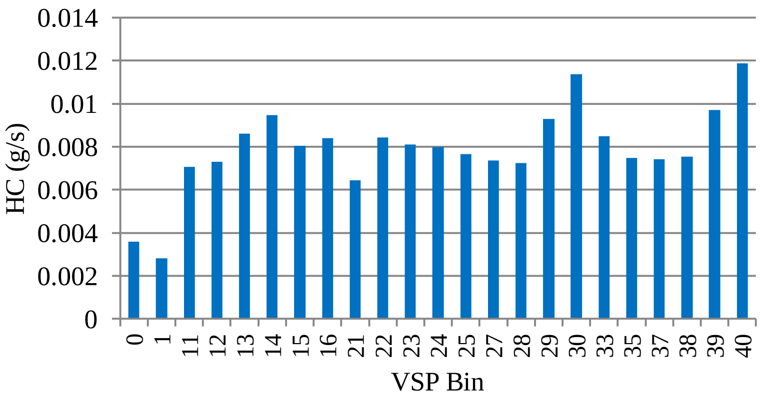
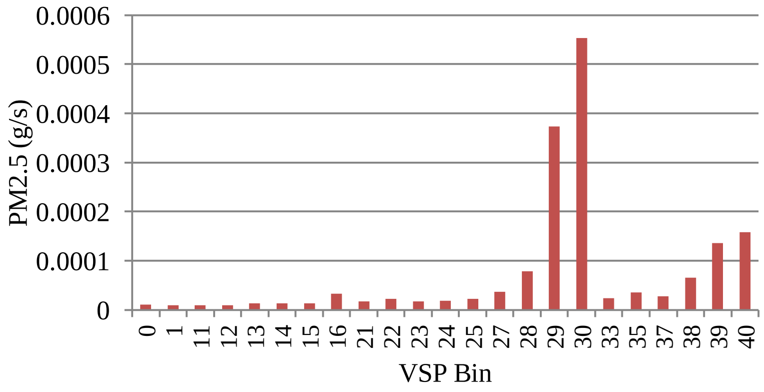
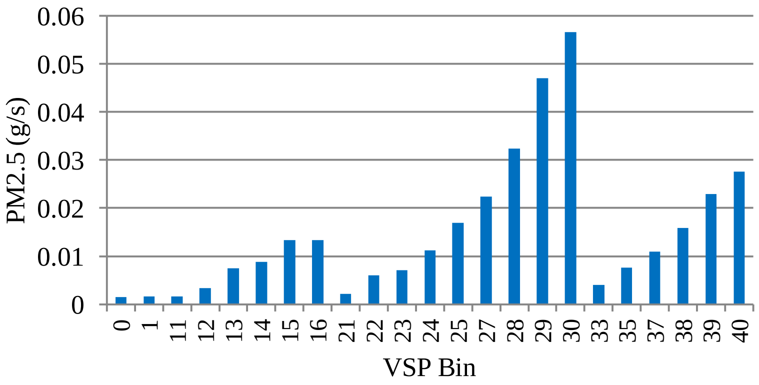
<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">HC</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">$PM_{2.5}$</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Figure 5.1 continued

5.2 Application of MOVES into Highway Geometric Design

This section provides the predicted fuel consumption and emissions related to highway geometric design features that are 1) vertical grades, 2) vertical crest curves, and 3) horizontal curves. From the previous sections, the rates of fuel consumption and emissions on the 23 operating mode bins were resulted from MOVES and the speed profiles including information of acceleration/deceleration and grades related to the design features were generated from the truck dynamic model, the linear and non-linear acceleration/deceleration models, the speed prediction models, and the polynomial model. Finally, the researcher aggregated fuel consumption and emissions from the combination of the rates (gal/s and g/s) with the second-by-second speed profiles, and then compared the aggregated results with environmental modification factors (EMFs). These EMFs represent the ratio between the changed geometric design features and the base conditions. For examples, an EMF equal to 1.0 means that there is no impact on the design change on fuel consumption or emissions. EMFs less than 1.0 indicate that the design change would consume less fuel or emissions relative to the base design feature, while EMFs greater than 1.0 would show more fuel consumption or emissions.

Table 5.1 shows how to match the speed profiles and the emission rates from MOVES with an example of the data from the initial speed of 110 km/h (30.6 m/s) and six percent grade. At 10th second, the instantaneous speed dropped to 90.6 km/h (25.2 m/s) from the initial speed and the calculated VSP from Equation (2.1) was 6.49 kW/ton. Based on VSP and speed (mph), the accounted operating mode bin number was 35, and the CO_2 emission rate for the bin number 35 was 31.64 g/s. Total CO_2 emission along with a travel time could be accumulated from each CO_2 emission at each second. Other types of emissions and fuel consumption from the trip were also calculated with the same process.

Table 5.1 Example of matching between speed profile and emission rates

Time (s)	Dist (m)	V (m/s)	a (m/s^2)	Grade (%)	VSP	V(mph)	OP Bin	Fuel Consumption	CO_2
0	0	30.6	-0.602	6	5.38	68.4	33	0.0010	10.5348
1	30	30.0	-0.589	6	5.54	67.1	33	0.0010	10.5348
2	60	29.4	-0.575	6	5.68	65.8	33	0.0010	10.5348
3	89	28.8	-0.563	6	5.82	64.5	33	0.0010	10.5348
4	118	28.3	-0.550	6	5.94	63.3	33	0.0010	10.5348
5	146	27.7	-0.538	6	6.05	62.1	35	0.0031	31.6353
6	173	27.2	-0.526	6	6.16	60.9	35	0.0031	31.6353
7	200	26.7	-0.514	6	6.25	59.7	35	0.0031	31.6353
8	226	26.1	-0.503	6	6.34	58.6	35	0.0031	31.6353
9	252	25.7	-0.491	6	6.42	57.5	35	0.0031	31.6353
10	278	25.2	-0.480	6	6.49	56.4	35	0.0031	31.6353
11	303	24.7	-0.470	6	6.56	55.3	35	0.0031	31.6353
12	327	24.2	-0.459	6	6.62	54.3	35	0.0031	31.6353
13	351	23.8	-0.449	6	6.67	53.3	35	0.0031	31.6353
14	375	23.3	-0.439	6	6.71	52.3	35	0.0031	31.6353
15	398	22.9	-0.429	6	6.75	51.3	35	0.0031	31.6353
16	420	22.5	-0.419	6	6.78	50.3	35	0.0031	31.6353
17	443	22.1	-0.410	6	6.81	49.4	24	0.0028	28.0325
18	464	21.7	-0.401	6	6.83	48.5	24	0.0028	28.0325
19	486	21.3	-0.392	6	6.85	47.6	24	0.0028	28.0325
20	507	20.9	-0.383	6	6.86	46.7	24	0.0028	28.0325
21	528	20.5	-0.375	6	6.87	45.9	24	0.0028	28.0325
22	548	20.1	-0.366	6	6.87	45.1	24	0.0028	28.0325
23	568	19.8	-0.358	6	6.87	44.3	24	0.0028	28.0325
24	587	19.4	-0.350	6	6.87	43.5	24	0.0028	28.0325
25	607	19.1	-0.342	6	6.86	42.7	24	0.0028	28.0325
26	626	18.7	-0.335	6	6.85	41.9	24	0.0028	28.0325
27	644	18.4	-0.327	6	6.84	41.2	24	0.0028	28.0325

5.2.1 Vertical Grades

In the vertical grade design, the researcher set initial speeds, grades, and critical length of grades as the key variables. Initial speeds changed from 10 km/h to 110 km/h, and grades inclined up to nine percent from a flat (i.e., zero-percent grade). The critical length of graded segment is dependent on speed reduction on grades. If the speed reduction is less than 10 km/h, the grade design would be categorized as a good design. When the speed reduction is greater or equal to 10 km/h and less than 20 km/h, the grade design is considered as a fair design. In addition, the design is classified as poor that causes the reduction of greater than 20 km/h. The results based on three key variables are provided in the following sections.

5.2.1.1 Initial Speeds

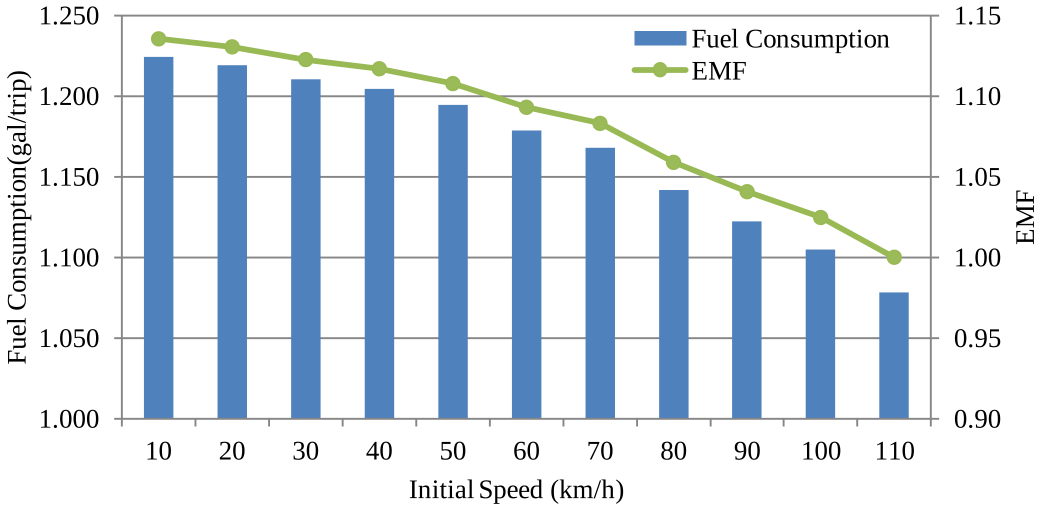
Figure 5.2 shows the aggregated fuel consumption and emissions and EMFs by initial speeds, from 10 to 110 km/h.[5] To provide these aggregated results by initial speeds, the researcher averaged the fuel consumption and emissions by different grades within the same initial speed. Based on the trip of a 6,000 m graded segment, the amount of fuel consumed and emissions produced decreased with increasing initial speeds. In terms of fuel, the trip starting with the initial speed of 10 km/h consumed about 1.2 gallon; however, the trip from 110 km/h consumed less than 1.1 gallons of diesel. EMF indicates that the 10 km/h initial speed consumed 14 percent more fuel than 110 km/h. In addition, emissions, CO_2, NO_x, CO, HC, and $PM_{2.5}$, have a similar trend with the fuel consumption. Higher initial speeds emitted less emission than lower speeds for a trip on the graded segment. For the comparison between 10 km/h and 110 km/h, the trip starting with the initial speed of 10 km/h produced:

- 14 percent more each of CO_2 and NO_x;
- 11 percent more CO;
- 13 percent more HC; and,
- 15 percent more $PM_{2.5}$ than the trip with 110 km/h of initial speed.

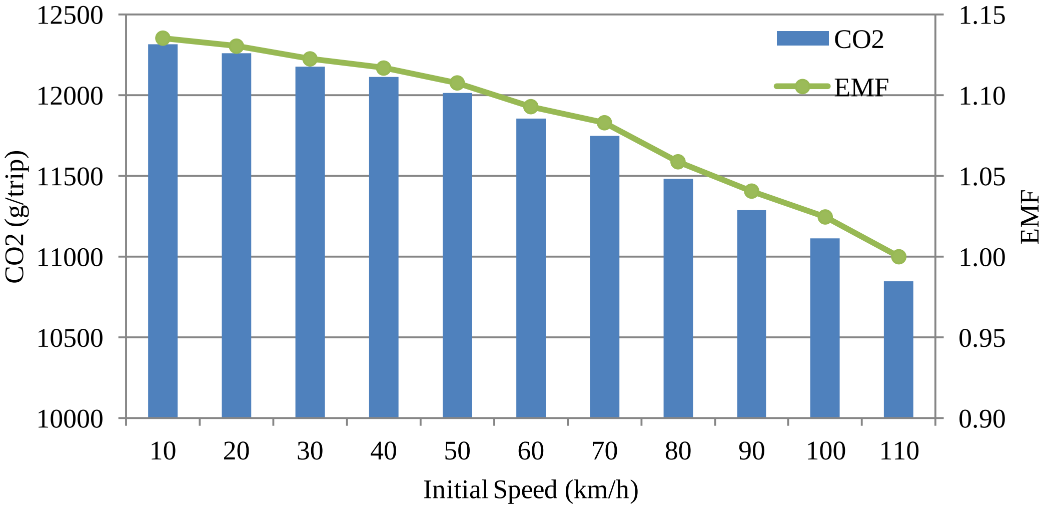
Based on the results on fuel consumption and emissions by the initial speeds, higher speeds consumed less fuel and produced lower emissions than the cases having lower speeds. As results, the reduction effects of the initial speed on fuel and emissions accounted for 11 to 15 percent.

---

[5] The amount of fuel consumption and emissions and values of EMF are shown in Appendix D and F, respectively.

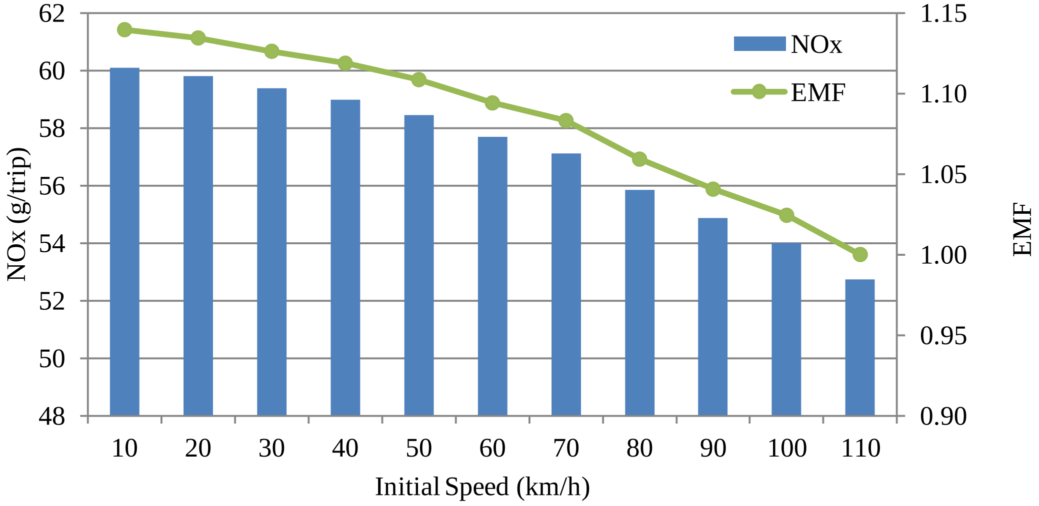


(a) Fuel Consumption

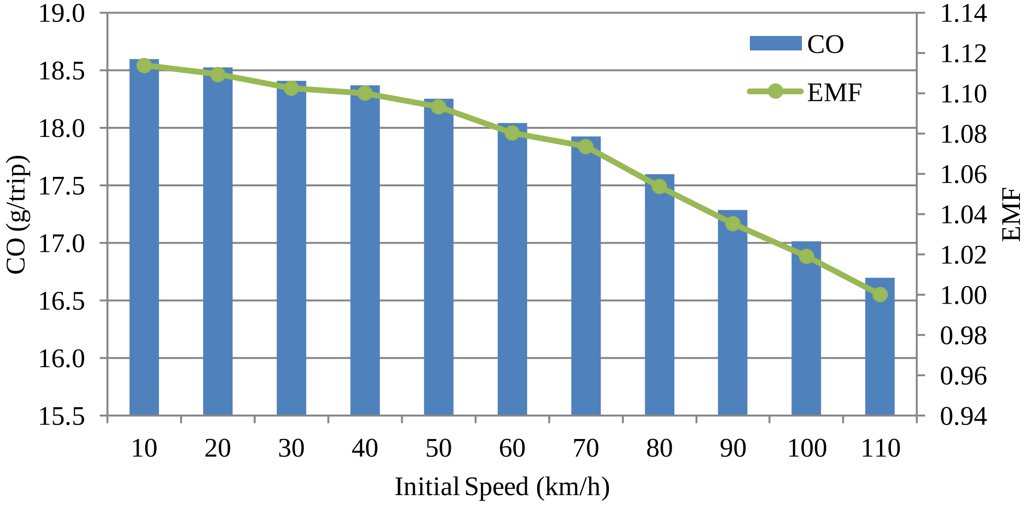


(b) CO_2

Figure 5.2 Fuel consumption and emissions by initial speeds

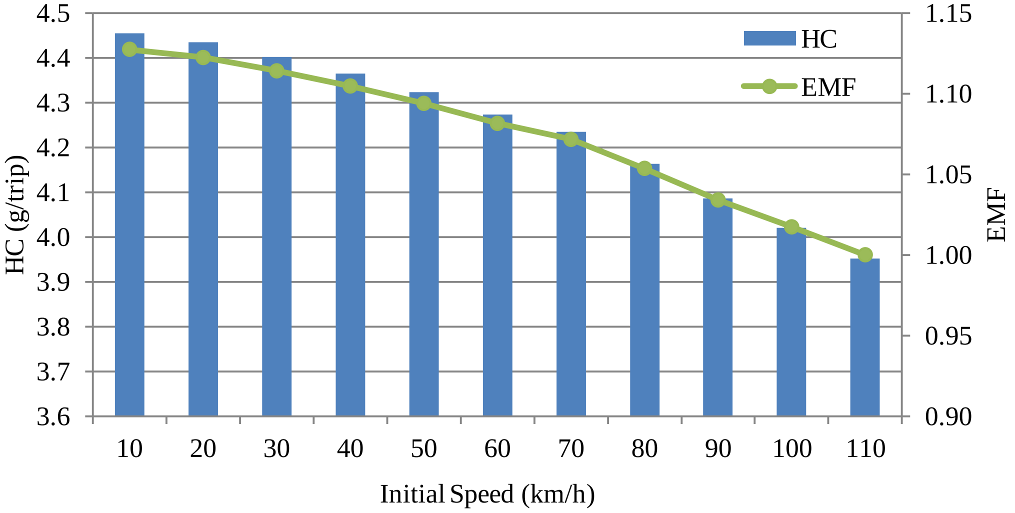


(c) NO_x

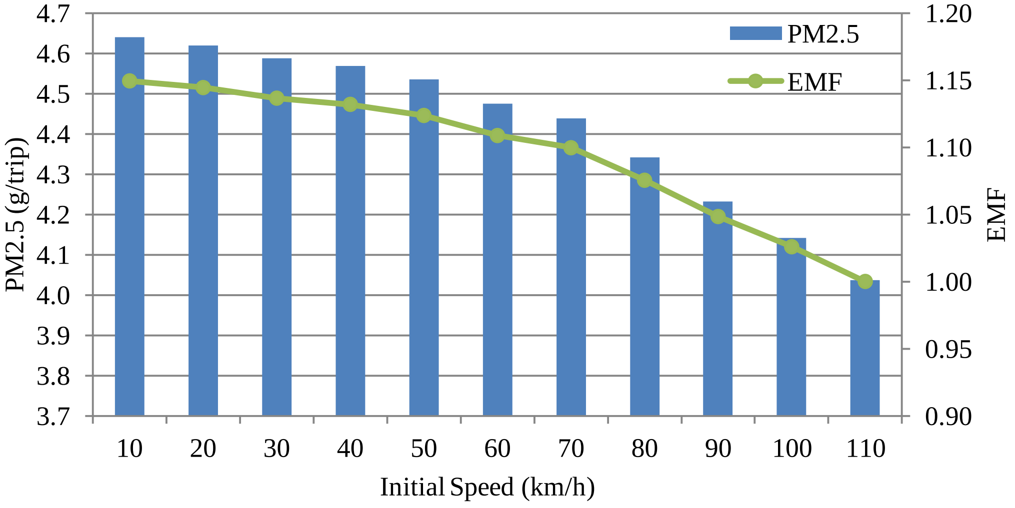


(d) CO

Figure 5.2 continued



(e) HC



(f) $PM_{2.5}$

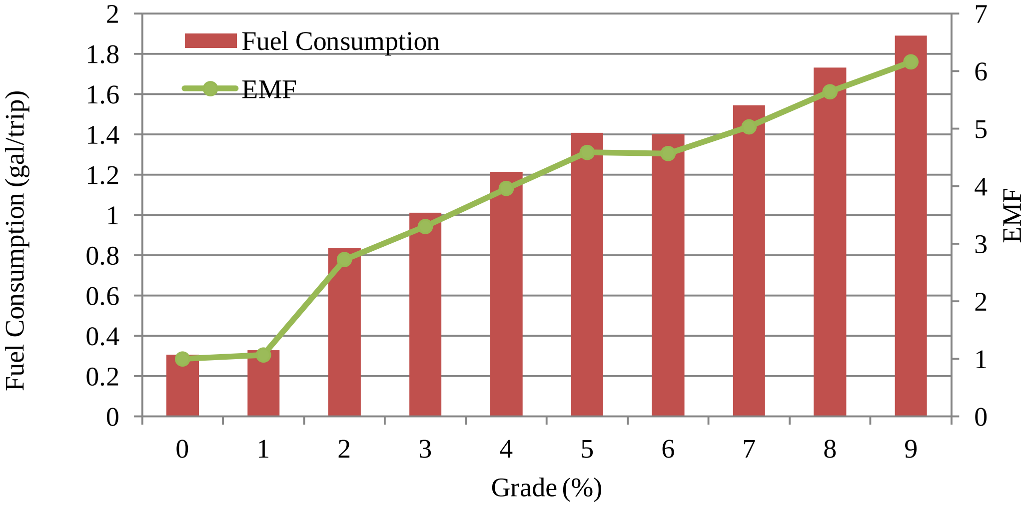
Figure 5.2 continued

5.2.1.2 Grades

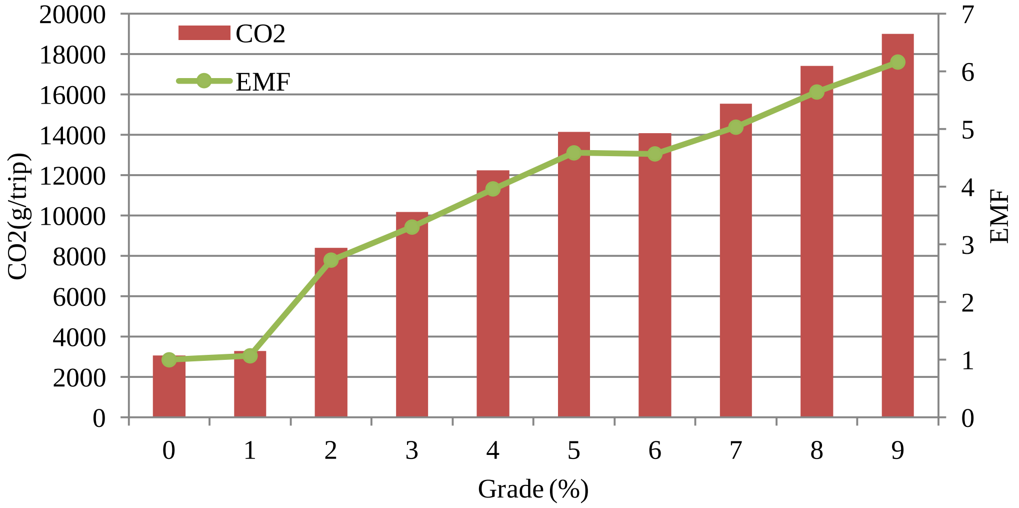
This section provides the aggregated fuel consumption and emissions by grades, from zero to nine percent. For reference, the minimum grade should be 0.5 percent for drainage purposes in the highway design, but a zero-percent grade is represented by a level in this research. These aggregated values are based on the average of fuel consumption and emissions from different initial speeds (10 to 110 km/h) within one category of grades. EMFs describe how much fuel consumption and emissions would be increased or decreased as a function of the vertical grade, relative to the level (base condition).

The results for the impact of grades on fuel consumption and emissions are provided in Figure 5.3. Overall, grades showed more distinctive results than those produced by the initial speeds. The truck consumed 0.31 gallon of diesel on a flat segment with the 6,000 m travel length, but the fuel consumption linearly increased with highway grades. On a nine-percent grade, the truck consumed 1.89 gallons. According to the EMF, more than six times the amount of fuel was consumed on a nine-percent grade than on the flat grade. Similarly, this inclination trend also occurred for the emissions of CO_2, NO_x, and $PM_{2.5}$. In the comparison between zero- and nine-percent of grades, the truck produced more than six times each of CO_2, NO_x, and $PM_{2.5}$. For other emissions, CO and HC, a nine-percent grade increased three times of CO and almost four times of HC than on the flat grade. Finally, grades strongly affected fuel consumption and emissions as expected. Under the other conditions being fixed except for highway grades, the more required engine loads with steeper grades increased the fuel consumption and emissions from the trip.

The design vehicle consumed more fuel consumption and produced more emissions with increasing grades (Figure 5.3). However, $PM_{2.5}$ and CO emissions decreased on a six-percent grade, relative to a five-percent grade. Appendix E shows the values for the vehicle speed and the calculated operating mode bin for each travel second during the trips on the five- and six-percent grades when the initial speed was 110 km/h. On the five-percent grade, the most frequent calculated operating bins were #24 (450 of total 470 seconds).

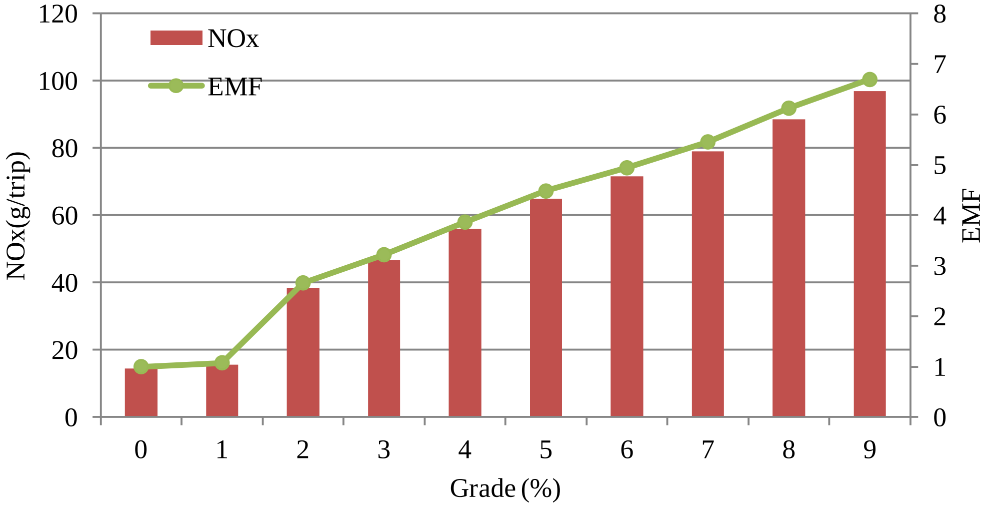


(a) Fuel Consumption

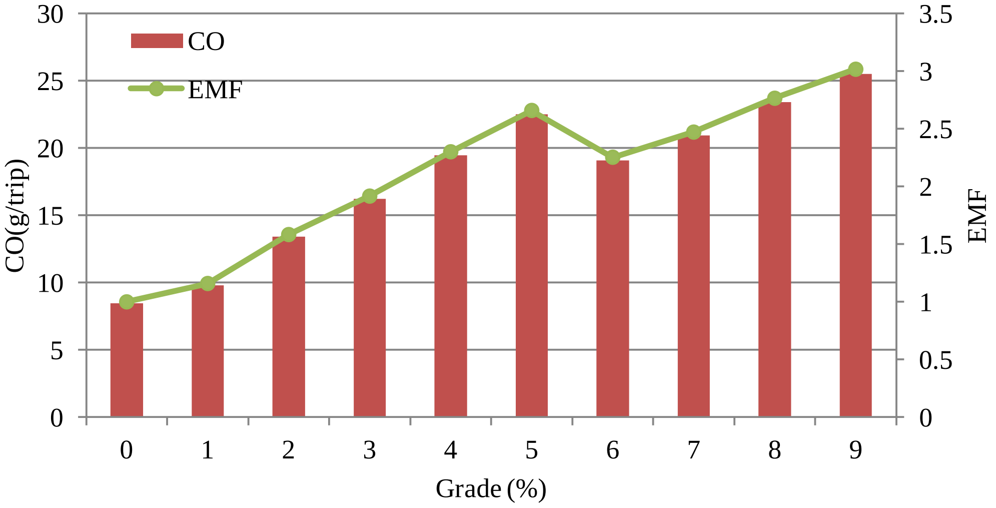


(b) CO_2

Figure 5.3 Fuel consumption and emissions by grades

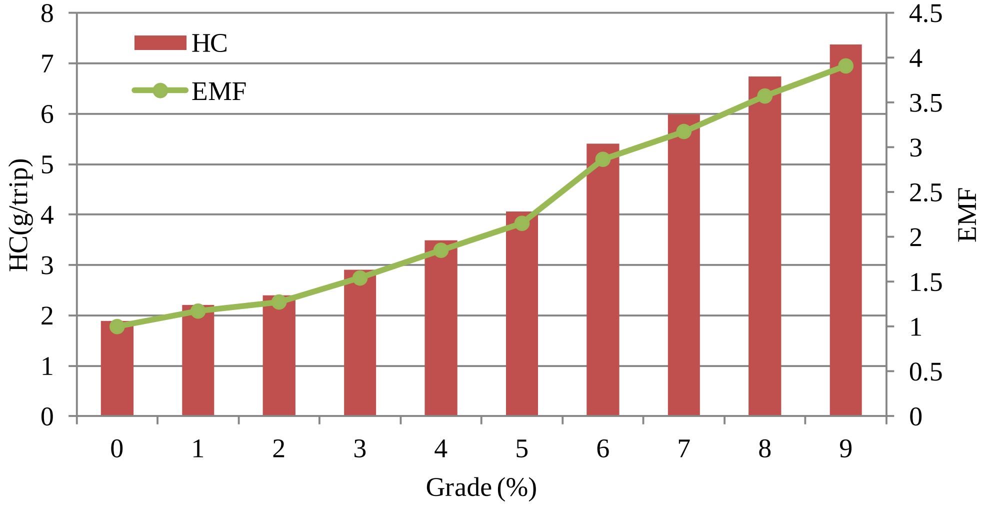


(c) NO_x

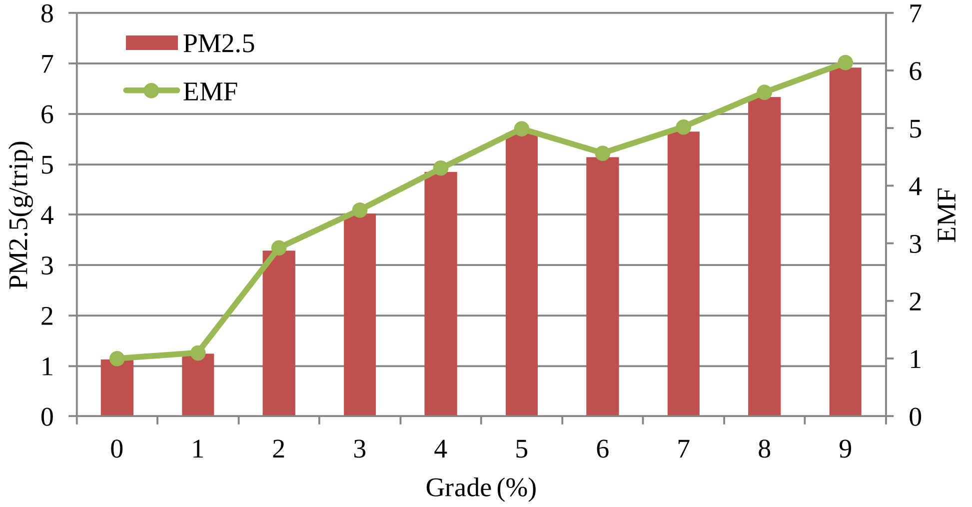


(d) CO

Figure 5.3 continued



(e) HC



(f) $PM_{2.5}$

Figure 5.3 continued

However, on the six-percent grade, the most frequent calculated operating mode bin was #14 (475 of total 540 seconds). When the operating mode bins changed from #24 to #14, the rates for fuel consumption and emissions decreased (Figure 5.1). Especially, the decreased amount of the rates of $PM_{2.5}$ and CO was greater than other emissions. When the bins moved from #24 to #14, the emissions rates for CO_2, NO_x, HC decreased by 13 percent, three percent, and 18 percent, respectively. In terms of $PM_{2.5}$ and CO, the emissions rates decreased by 21 percent and 27 percent, respectively.

The results on the accumulated fuel consumption and emissions are dependent on the rates for each second and total travel time. The vehicle consumed less fuel and produced lower emissions with the operating mode bin #14, relative to #24. However, longer travel time (540 vs. 470 seconds) on the six-percent grade increased the accumulated fuel consumption and emissions, except for $PM_{2.5}$ and CO, during the trip. In conclusion, the vehicle produced less $PM_{2.5}$ and CO on the six-percent grade because the amount of reduced rates of $PM_{2.5}$ and CO from #24 to #14 offset the amount of increased emissions due to the longer travel time.

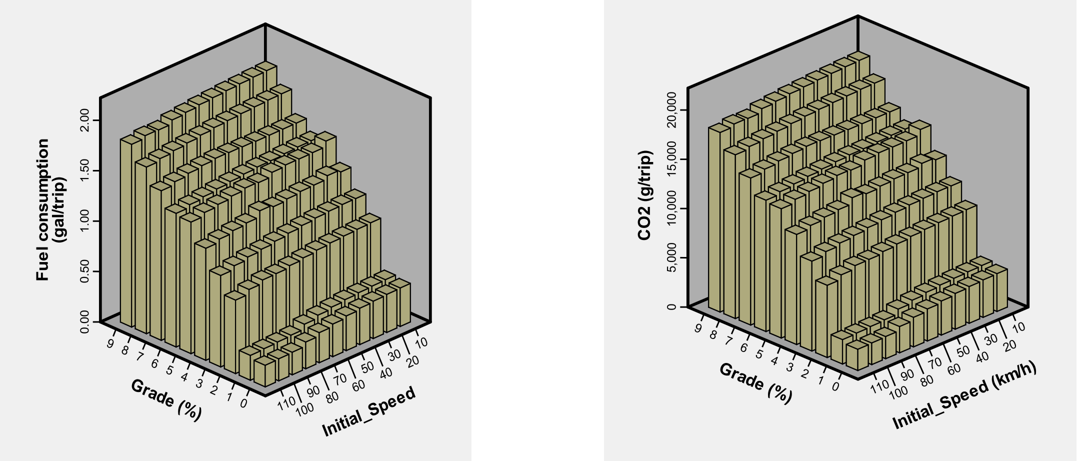
5.2.1.3 Impact of Grade and Initial Speed on Fuel Consumption and Emissions

In the previous sections, this study separately reported the results of the effect of each initial speed and grade on fuel consumption and emissions. A grade was assumed to be fixed when the impact of initial speeds was analyzed, and vice versa.

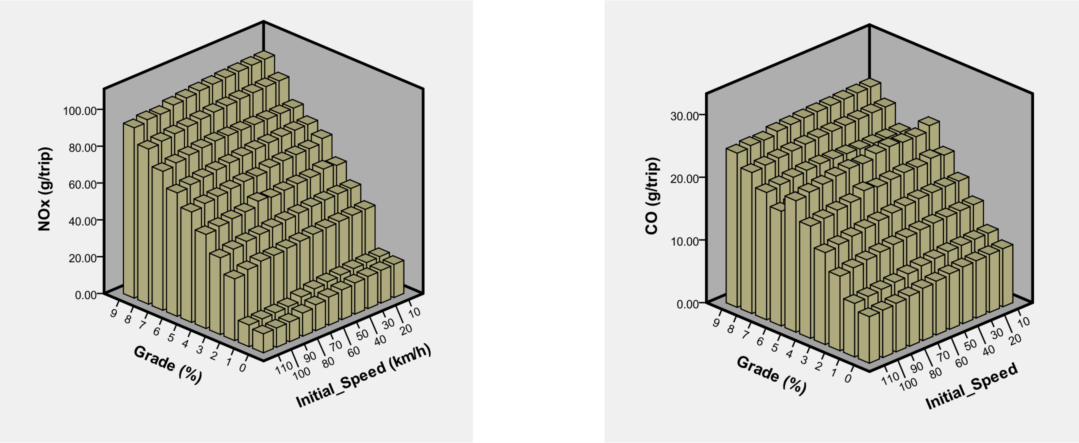
This section provided the results for simultaneously considering the impact of the initial speeds and grades on fuel consumption and emissions throughout three-dimensional bar graphs (Figure 5.4). Fuel consumption gradually increased with decreasing initial speeds. On the leveled grade, the design vehicle consumed 0.38 gallon and 0.21 gallon of fuel during the trips with the initial speeds of 10 and 110 km/h, respectively. The design vehicle consumed 78 percent more fuel when starting a trip with the speed of 10 km/h compared to 110 km/h. On the nine-percent grade, the vehicle consumed 1.94 gallons of fuel with an initial speed of 10 km/h and 1.82 gallons for 110 km/h, about seven-percent increase in fuel consumption. The ratio of the difference in fuel consumption between initial speeds was getting less with increasing roadway grades. In addition, there were similar changes in emissions with the case of fuel consumption. For examples, on the level grade, the vehicle emitted 1.38 g and 0.82 g of $PM_{2.5}$ for trips starting at 10 and 110 km/h, respectively. On the nine-percent grade, the $PM_{2.5}$ was 7.1 g for 10 km/h and 6.6 g for 110 km/h. The vehicle emitted 71 percent more $PM_{2.5}$ at 10 km/h than at 110 km/h on the level grade and about seven percent more $PM_{2.5}$ on the nine-percent grade.

Grades had a distinctive impact on the output. Above all, there was an abrupt change between one- and two-percent grades; the design vehicle consumed about three times more fuel on a two-percent graded segment than on a leveled or one-percent grade. Fuel consumption kept increasing with grades; steeper grades at higher initial speed had much increases in fuel consumption. At the initial speed of 10 km/h, the vehicle consumed about five times more fuel on the nine-percent grade than on the level. At 110 km/h, about eight times more fuel consumed on the nine-percent grade than on the level condition.

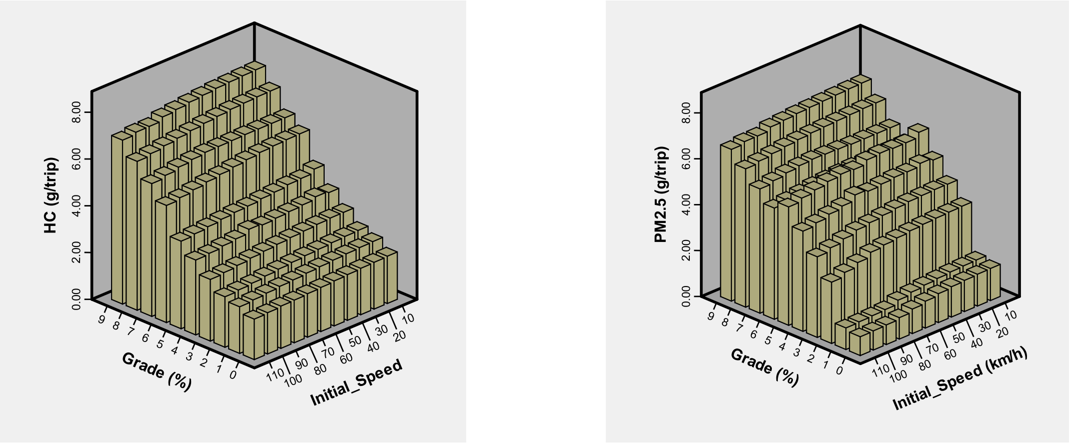
In terms of emissions, CO_2, NO_x, and $PM_{2.5}$ had similar results with ones found for the fuel consumption; the trip on the nine-percent grade increased those emissions by least five and eight times more than on the leveled grade with 10 and 110 km/h, respectively. Under the same conditions, both CO and HC had less difference in the ratios than the previous emissions. The trip on the nine-percent grade increased CO and HC about three and four times more than on the level with 10 and 110 km/h, respectively.



(a) Fuel Consumption (b) CO_2



(c) NO_x (d) CO



(e) HC (f) $PM_{2.5}$

Figure 5.4 Impact of grades and initial speeds on fuel consumption and emissions

There was a relationship between grades and initial speeds on fuel consumption and emissions. On lower grades, there were strong reduction impacts on fuel consumption and emissions by increasing initial speeds. In addition, at higher initial speeds, lower grades had much reduced fuel consumption and emissions than higher grades. As a result, fuel consumption and emissions by the design vehicle on highway grades increased with steep grades and lower initial speeds.

5.2.1.4 Critical Length of Grade

A common basis for critical length of grade design is determined by speed reduction. According to the GreenBook (AASHTO, 2004), highway grades should be designed with the consideration of speed reduction that is less than 15 km/h because crash rates could significantly increase when the reduction of truck speed by grades is greater than 15 km/h. This study used 10 and 20 km/h basis in highway grade design, instead of 15 km/h. The grade design was categorized as: 1) a good design by speed reduction of less than 10 km/h, 2) a fair design by speed reduction of greater or equal to 10 km/h and less than 20 km/h, and 3) a poor design by speed reduction of greater or equal to 20 km/h.

The process of decision on the critical length of grade and grade design categorization by speed reduction can be explained from Figure 5.5. For the case of a truck traveling on an one-percent graded segment with the initial speed of 110 km/h, the truck speed reduced to 100 km/h and 90 km/h at the travel distance of 871 m and 3,720 m, respectively, based on the speed-distance profile shown in Figure 5.5. When the length of one-percent graded segment is designed with less than 871 m, the design is considered as a good design. When the length is between 871 and 3,720 m, the design is classified as a fair design. Otherwise, the design is considered as poor when the length exceeds 3,720 m. Through this process using speed-distance profiles, the critical length of grades and design categorization are determined for each initial speed and grade. Table 5.2 provides the critical length of grades for initial speeds, design categorization, and grades.

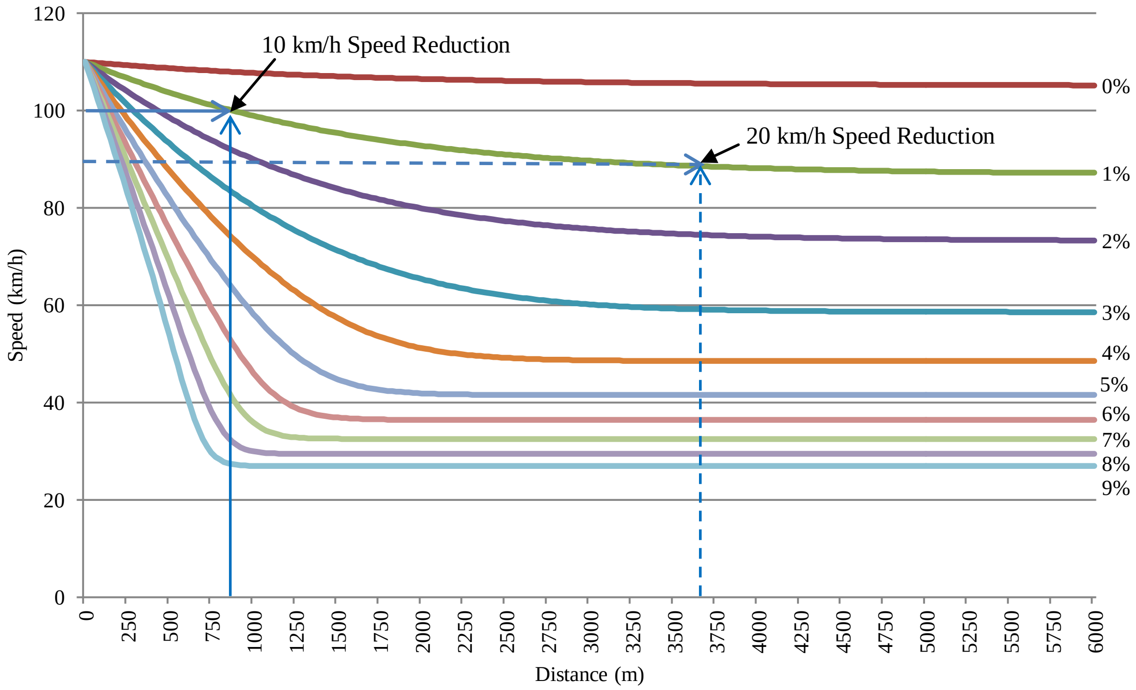


Figure 5.5 Example for critical length of graded segment on speed-distance profiles

As an initial speed or grade is getting lower, the highway grade design is less restricted by the length of graded segment because the design vehicle can have more available engine generated power to keep current speed on lower grades/initial speeds (Table 5.2). Below initial speeds of 30 km/h, the vehicle did not have any speed reduction greater than 10 km/h within 6,000 m of segment length.

This study focused on the difference in fuel consumption and emissions among three grade design categories based on the critical lengths by initial speeds and grades in Table 5.2, and the difference was described with EMFs. They represented the ratio of fair design and poor design to the base condition (i.e., good design). With EMFs, this study can provide the information on environmental impacts of grade design when the design has the speed reduction of more than 10 km/h relative to less than 10 km/h.

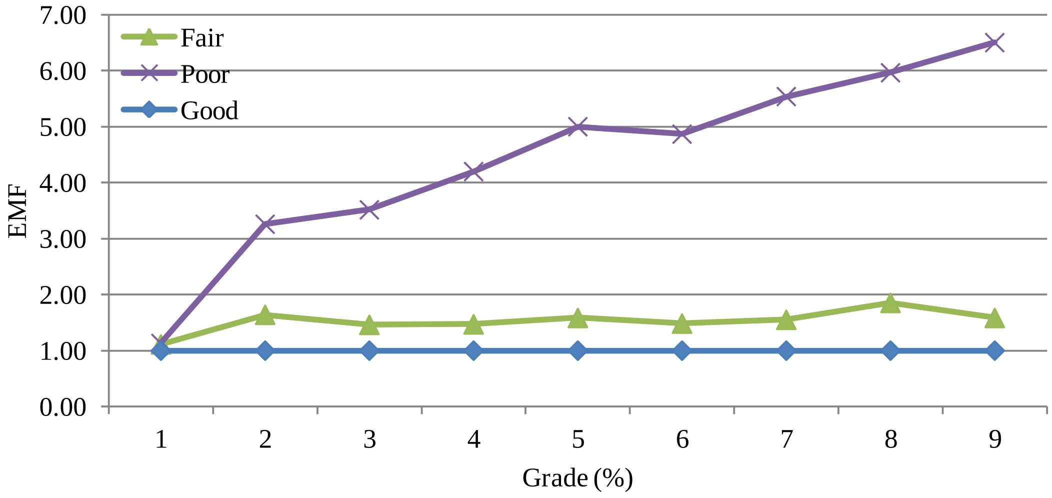
Table 5.2 Critical length of grade by speed and design categories

		Critical Length of Grade									
		Grade									
Speed	Category	0	1	2	3	4	5	6	7	8	9
110	Good		871	408	263	204	147	118	117	88	88
	Fair		3,720	988	607	442	333	278	223	195	168
	Poor						6,000	6,000	6,000	6,000	6,000
100	Good		2,848	553	316	212	159	132	106	80	80
	Fair			1,538	718	473	350	275	226	200	175
	Poor						6,000	6,000	6,000	6,000	6,000
90	Good			983	400	237	166	142	118	95	72
	Fair				960	549	376	288	243	200	177
	Poor						6,000	6,000	6,000	6,000	6,000
80	Good				560	291	188	146	105	84	84
	Fair				1,975	669	406	308	233	194	157
	Poor						6,000	6,000	6,000	6,000	6,000
70	Good				1481	377	216	145	109	91	73
	Fair				6,000	1,225	505	329	247	198	165
	Poor						6,000	6,000	6,000	6,000	6,000
60	Good					1,072	273	143	122	92	77
	Fair							439	283	205	165
	Poor										
50	Good						6,000	253	149	100	76
	Fair									378	210
	Poor										
40	Good									267	124
	Fair										
	Poor										

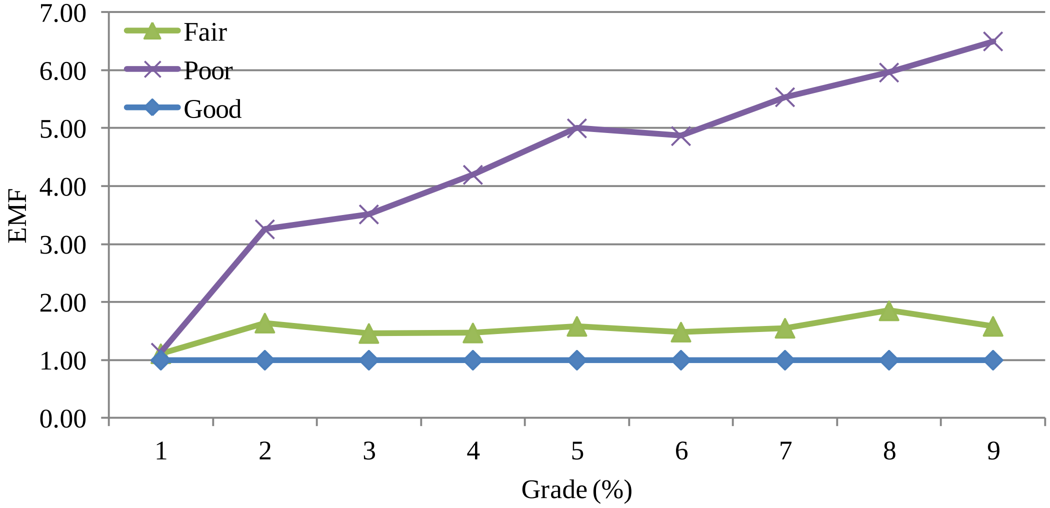
With an example of one-percent grade and initial speed of 110 km/h, the design was categorized as the good design when the length of graded segment was 871 m and the length of flat segment was 5,129 m (=6,000-871). When the length of the graded segment was 3,720 m and the length of the leveled segment was 2,280 m (=6,000-3,720), the grade design was categorized as the fair design. Finally, when the length of the graded segment was 6,000 m and simultaneously there was a speed reduction greater than 20 km/h, the design was classified as the poor design.

In terms of fuel consumption, the design vehicle consumed up to 85 percent more fuel on a fairly-designed graded highway than a good designed highway. The degree of fuel consumption and emissions more significantly increased on a poorly-designed highway. When the highway had a nine-percent grade, the design truck consumed 6.5 times more fuel on a poorly-designed highway than for a well-designed highway. In terms of emissions, the inclination on fairly or poorly designed highway was similar with the fuel consumption. For the comparison between the fair and good designs, the fair design had more emissions by a factor of about two over the good design. Compared with the poor design, it produced more by a factor of seven on CO_2, NO_x, and $PM_{2.5}$ than the good design, and three times more for CO and HC.

Finally, the amount of fuel consumption and emissions can be minimized when highway designers/engineers keep speed reductions less than 10 km/h for vertical grades. Of importance, the design condition for speed reductions of more than 20 km/h on steep grades should be avoided because of significantly adverse impacts. EMFs for the poor design linearly increased with grades, but EMFs for the fair design did not show any specific relationship with increasing grades as shown in Figure 5.6. The adverse impacts for the fair design seem to be less affected by the steepness of grades.

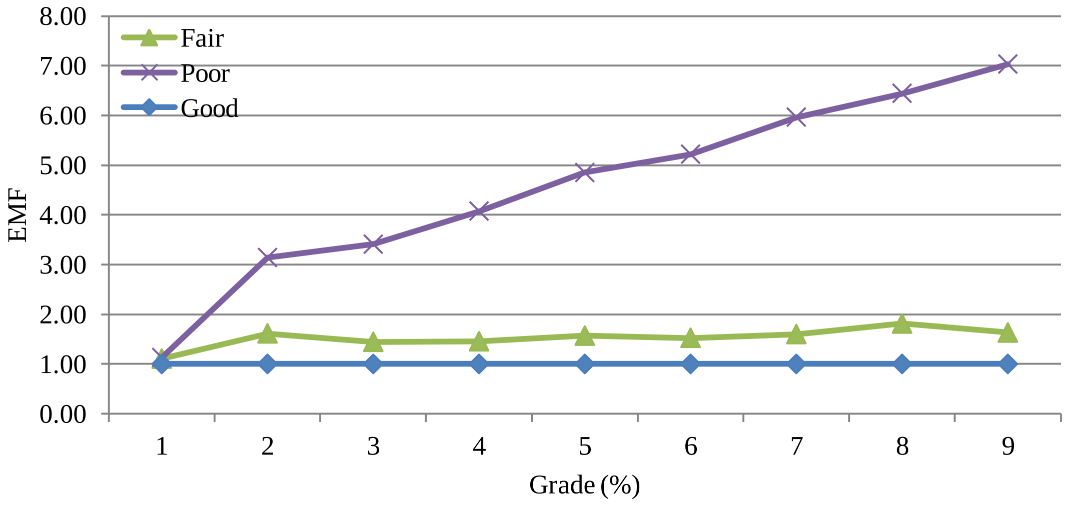


(a) Fuel Consumption

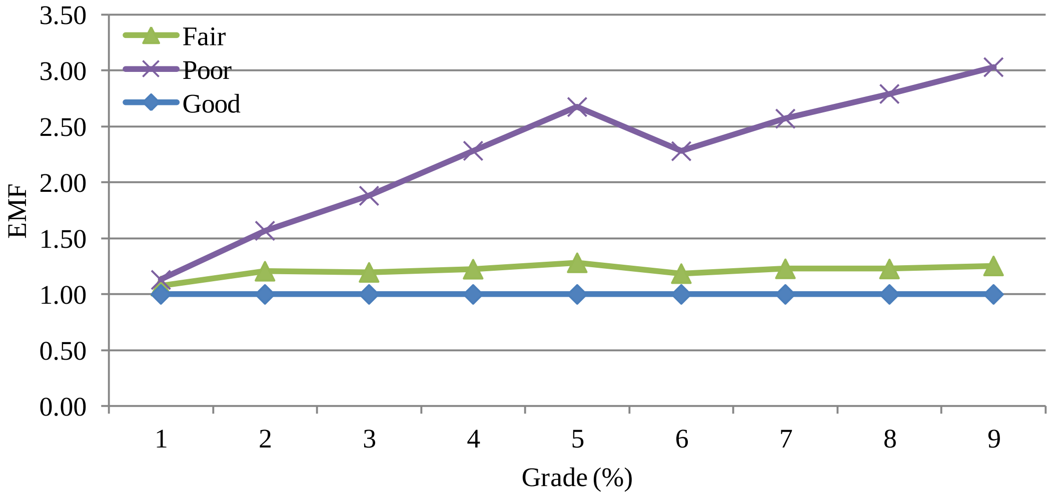


(b) CO_2

Figure 5.6 EMFs of fuel consumption and emissions by design categories

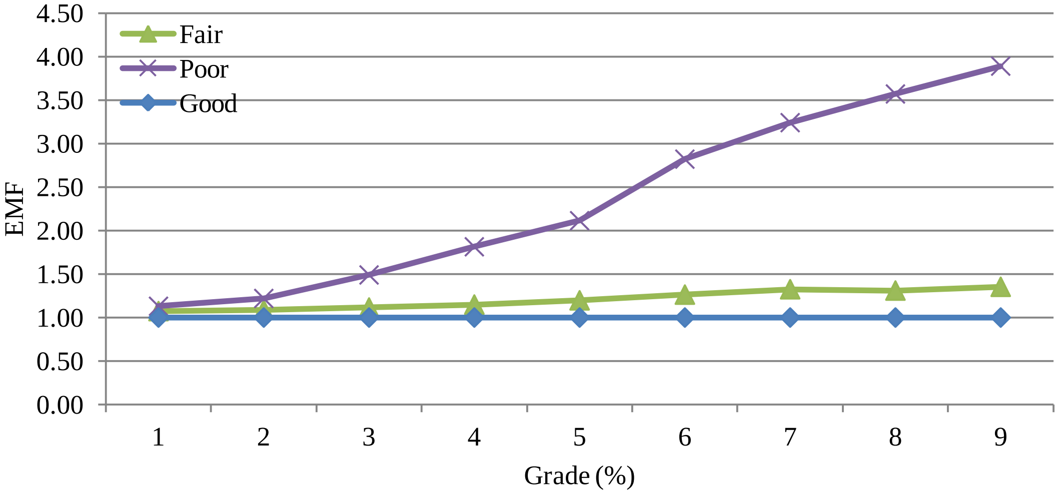


(c) NO_x

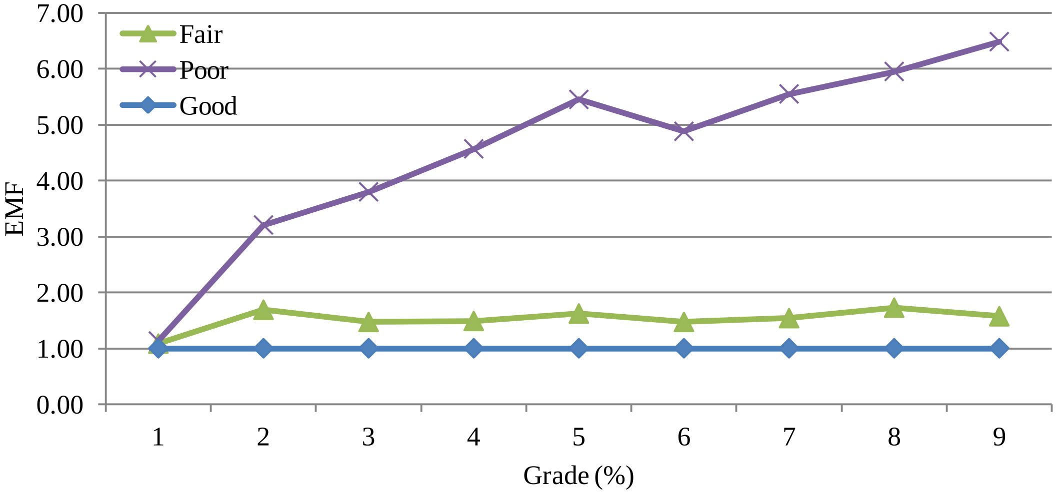


(d) CO

Figure 5.6 continued



(e) HC



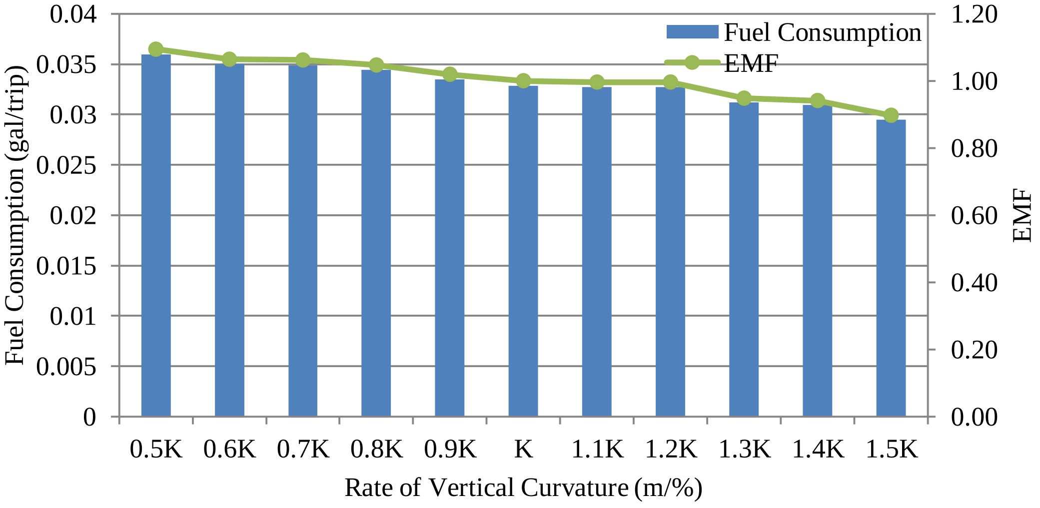
(f) $PM_{2.5}$

Figure 5.6 continued

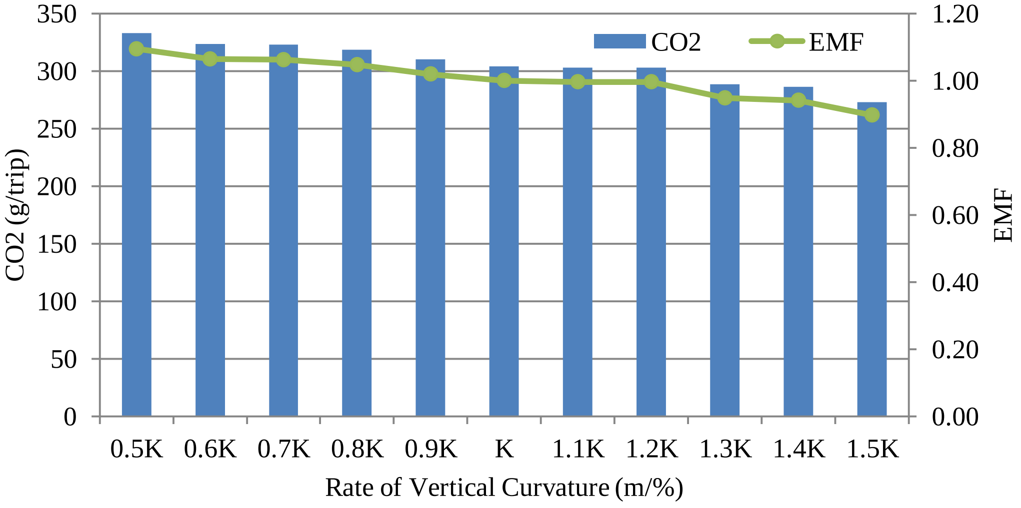
5.2.2 Vertical Crest Curves

In the analysis of fuel consumption and emissions on vertical crest curves, there was one key variable affecting the analysis: the rate of vertical curvature (K). K affected not only operating speeds on the curves, but also the curvature linked to the curve. The profile of vertical curve changed from the arc connecting PC and PT to the arc of PC_o and PT_o, when the curve was designed with greater K (i.e., the above-minimum standard design) than the recommended minimum standard (Figure 4.3 (a)). According to Figure 4.4, the amount of grade change per second depends on K; as K increased, there were more gradual flattening changes on the curve between two tangent grades (i.e., uphill and downhill grades). In fact, the impact levels of acceleration/deceleration and operating speeds related to the change of K-values on fuel consumption and emissions was not stronger than the degree of impact due to grade changes on the curve.

Figure 5.7 shows the amount of fuel consumption and emissions related to various Ks on the vertical crest curve. The comparisons were made between increased/decreased K-values and the recommended minimum K in the GreenBook (AASHTO, 2004) as a base condition. The vertical curve analyzed in this study was designed with design speed of 90 km/h, and the minimum recommended K for the speed was 39 m/percent in the most recent GreenBook (AASHTO, 2004). As K increased, the fuel consumption decreased while traveling on the vertical curve. The design vehicle (i.e., passenger car) consumed about 10 percent more fuel on the curve that is designed with a 50-percent reduced K (i.e., 20 m/percent) than the recommended minimum K (i.e., 39 m/percent). However, 10 percent less fuel was consumed on a 50-percent increased K (i.e., 59 m/percent), as shown in Figure 5.7. In addition, the design vehicle produced 10 percent more CO_2 on the curve with a 50-percent reduced K, and 10 percent less CO_2 on a 50-percent increased K, rather than the recommended minimum K. For other emissions (NO_x, CO, HC, and $PM_{2.5}$), the impact on the changes in K-values was greater than on CO_2. For the CO, approximately 25 percent more CO was produced for a 50-percent reduced K and 30 percent less CO for a 50-percent increased K were produced as shown in Figure 5.7.

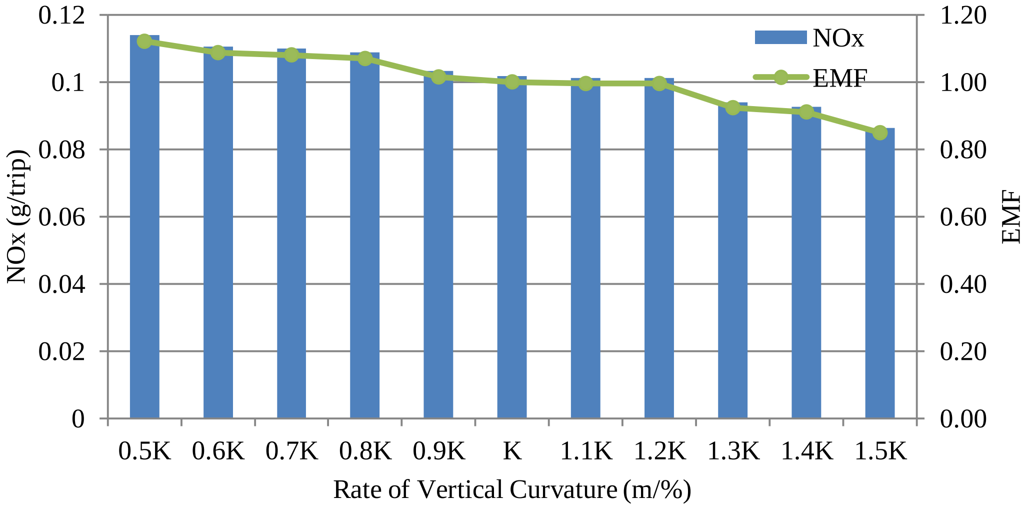


(a) Fuel Consumption

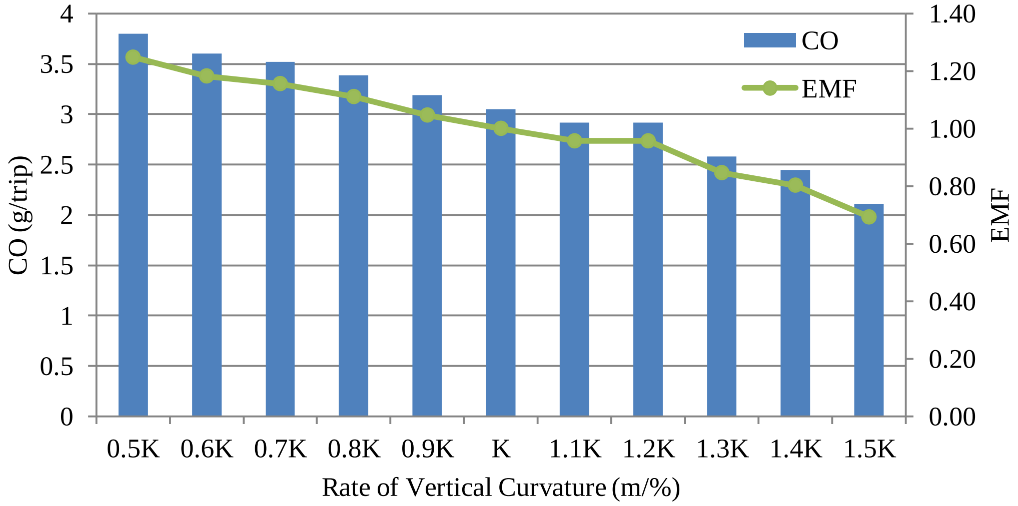


(b) CO_2

Figure 5.7 Fuel consumption and emissions by K on vertical curves

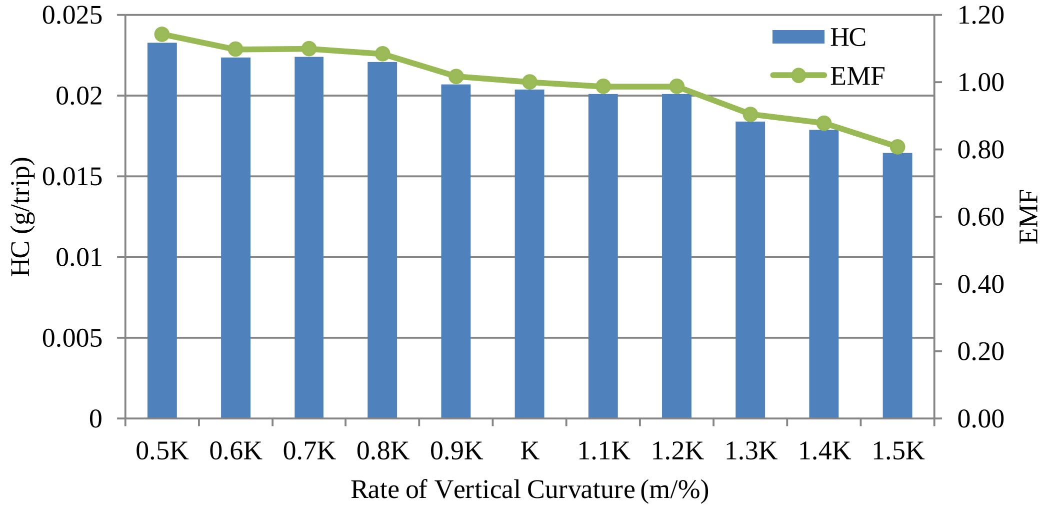


(c) NO_x

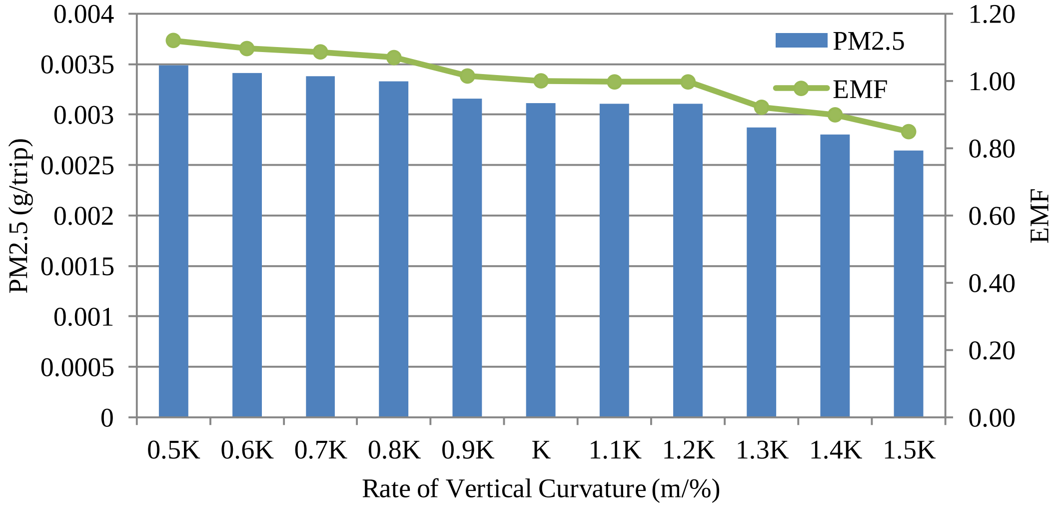


(d) CO

Figure 5.7 continued



(e) HC



(f) $PM_{2.5}$

Figure 5.7 continued

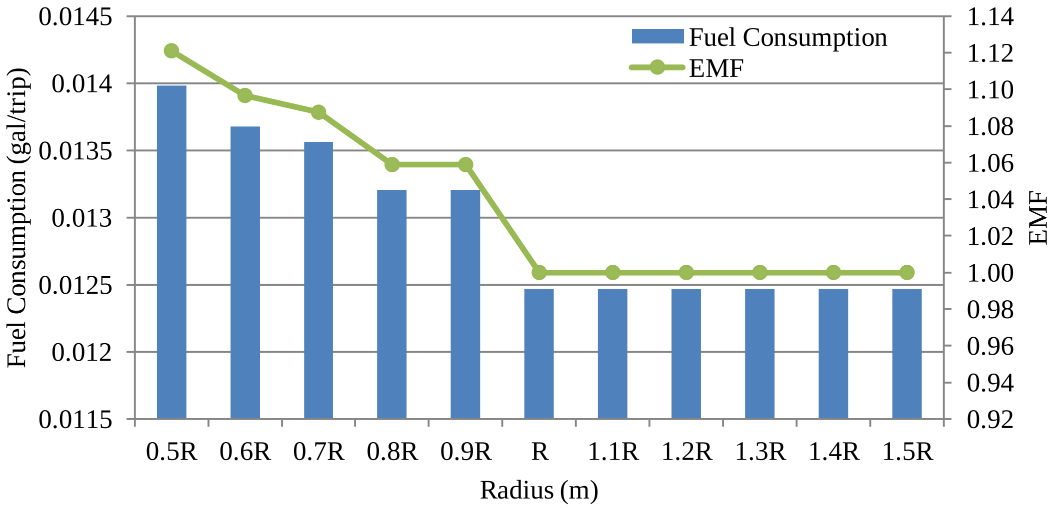
5.2.3 Horizontal Curves

This section provides the fuel consumption and emissions with various curve radiuses on horizontal curves. A curve radius changed while other design features, the 85th percentile tangent speed ($V_{t.85}$), a deflection angle (I_c), and superelevation (e), were fixed. As discussed above, the design vehicle (i.e., passenger car) is assumed to reduce its operating speed to the middle of horizontal curve, and the amount of speed reduction depends on the curve radius. On the curve with a smaller radius than the recommended minimum standard[6], a driver reduced the vehicle speed while cornering due to safety reason to the middle of the curve. Then, the driver was assumed to accelerate to the original speed after passing the middle of the curve. These vehicle movements on the curve affected fuel consumption and emissions due to speed reduction and acceleration/deceleration.

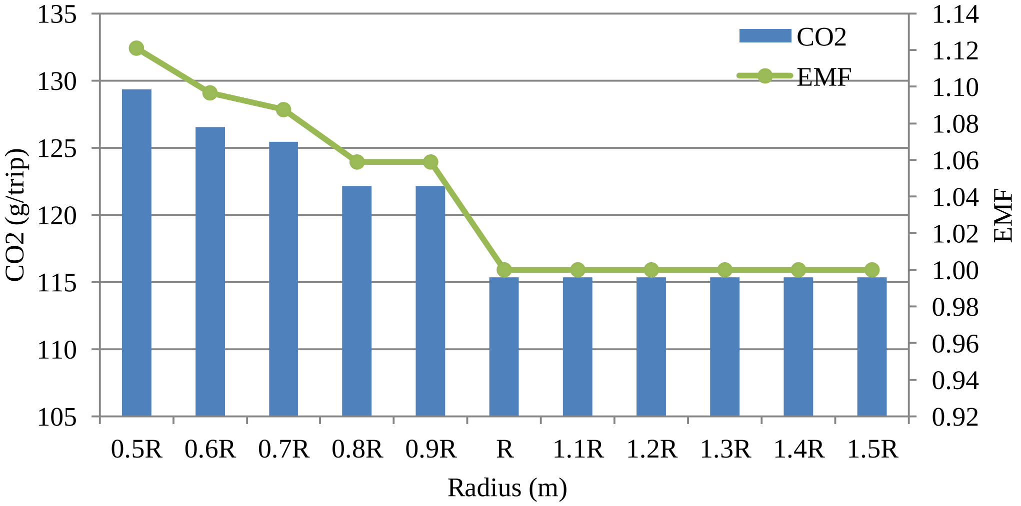
Figure 5.8 shows the comparison of fuel consumption and emissions with changes in horizontal curve radiuses when the 85th percentile operating speed was 70 km/h. The design vehicle consumed 12 percent of more fuel on the curve with a 50-percent reduced radius (i.e., 84 m) than the minimum standard (i.e., 168 m), but greater radiuses did not make any change in fuel consumption and emissions because speed did not change on the larger radius curve according to the speed prediction model.

---

[6] A design exception is required if the curve radius is less than the recommended minimum standard in the guidebook.

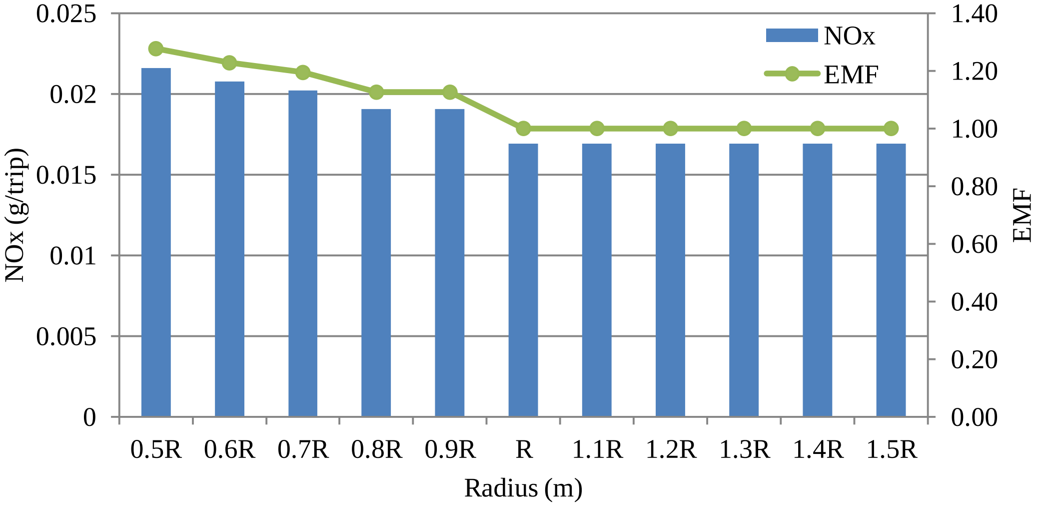


(a) Fuel Consumption

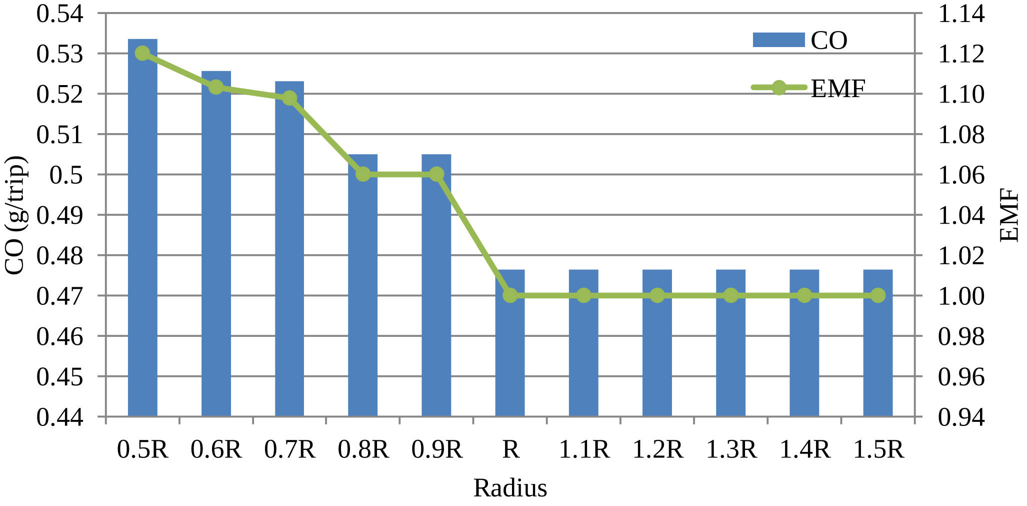


(b) CO_2

Figure 5.8 Fuel consumption and emission on horizontal curves with tangent speed of 70 km/h

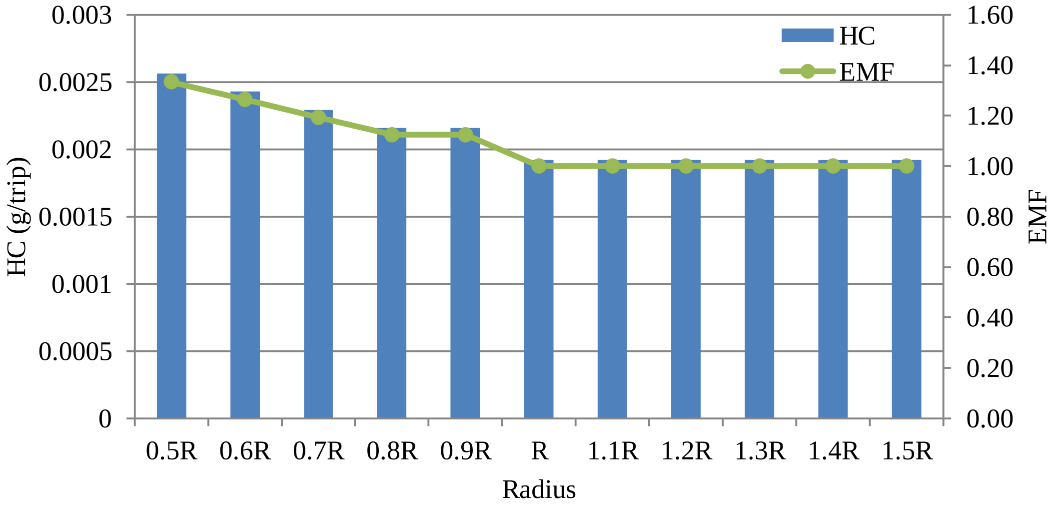


(c) NO_x

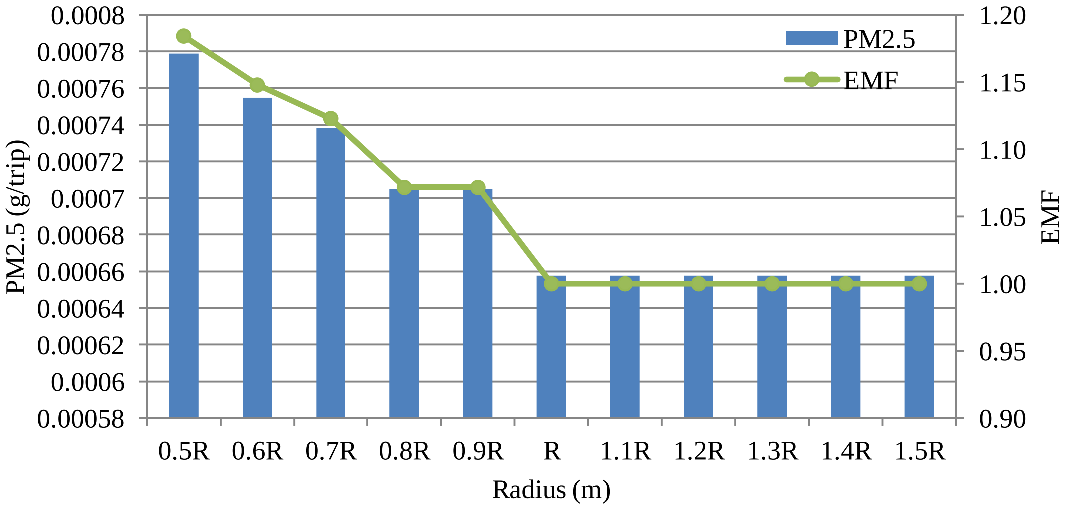


(d) CO

Figure 5.8 continued



(e) HC



(f) $PM_{2.5}$

Figure 5.8 continued

When the 85th percentile tangent speed was 90 km/h, the results on the comparison of fuel consumption and emissions resulted from radius changing were different from the previous analysis on the case of a 70 km/h tangent speed. Fuel consumption, CO_2, and $PM_{2.5}$ were smallest on the curve of a 50-percent reduced radius (Figure 5.9). However, HC and CO were more produced on the reduced radius curve. For the case of a 110 km/h tangent speed, the results were similar with the case of 90 km/h, except for $PM_{2.5}$. It had more $PM_{2.5}$ on the reduced radius than the increased radius. The reason for these heterogeneous results among different initial tangent speeds will be discussed in Chapter VIII.

5.3 Chapter Summary

In this chapter, we provided the rates of fuel consumption and emissions for each of the 23 operating mode bins from the process with MOVES, recently developed vehicle emission simulator, and also these rates have been matched with operating modes from the speed profiles on vertical grades and vertical crest and horizontal curves. The aggregated fuel consumption and emissions associated with various geometric design features have been compared with EMFs.

The emission rates presented in this research pertained to CO_2, NO_x, CO, HC, and $PM_{2.5}$ from the passenger car and the typical heavy-duty diesel truck. For the individual comparison, the rates of fuel consumption and emissions were relatively high at the operating mode bins that have high VSPs and speed category for the truck rather than the passenger car. In general, the fuel consumption and emissions rates increased linearly or exponentially with their VSPs within each speed category. Furthermore, this inclination pattern of the rates was similar with other speed categories.

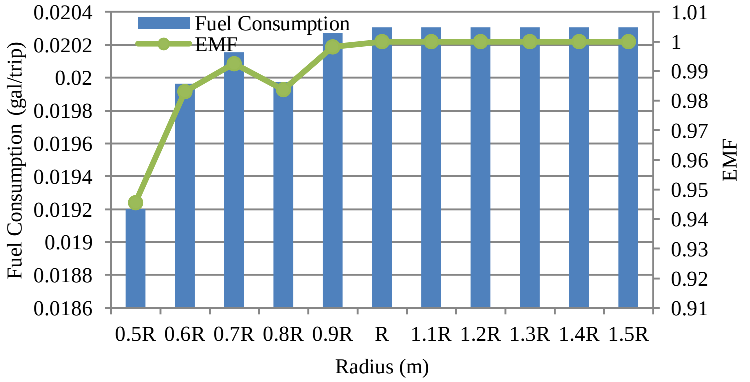
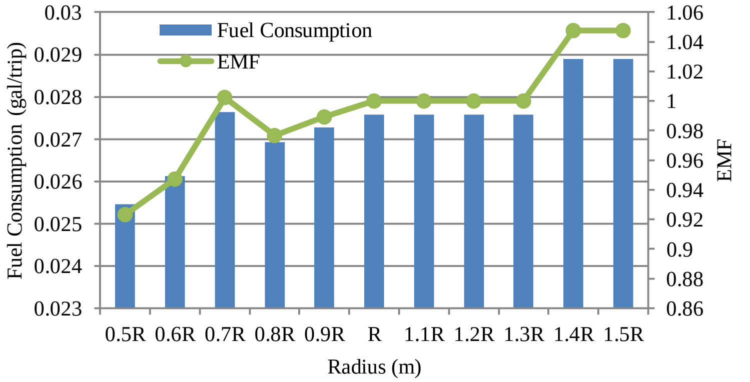
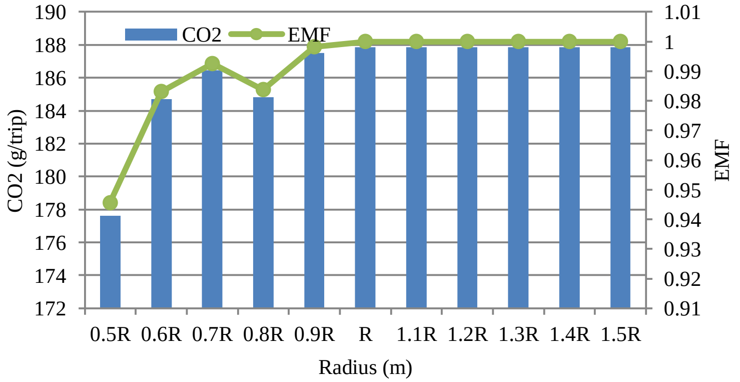
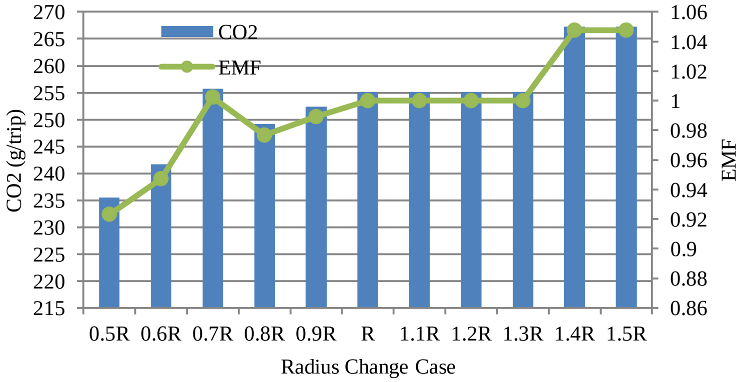
<table>
<tr><th>90 km/h Tangent Speed</th><th>110 km/h Tangent Speed</th></tr>
<tr><td colspan="2">Fuel Consumption</td></tr>
<tr><td>
</td>
<td>
</td></tr>
<tr><td colspan="2">CO$_2$</td></tr>
<tr><td>
</td>
<td>
</td></tr>
</table>

Figure 5.9 Fuel consumption and emissions on horizontal curves for tangent speeds of 90 km/h and 110 km/h

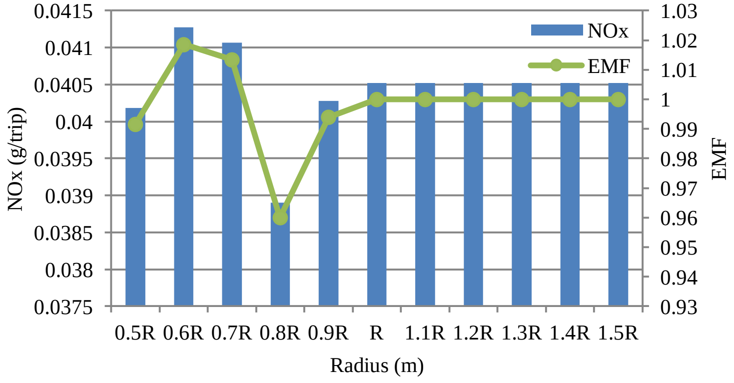
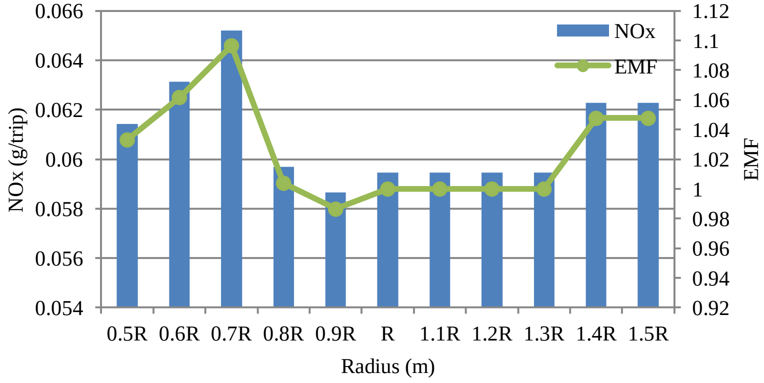
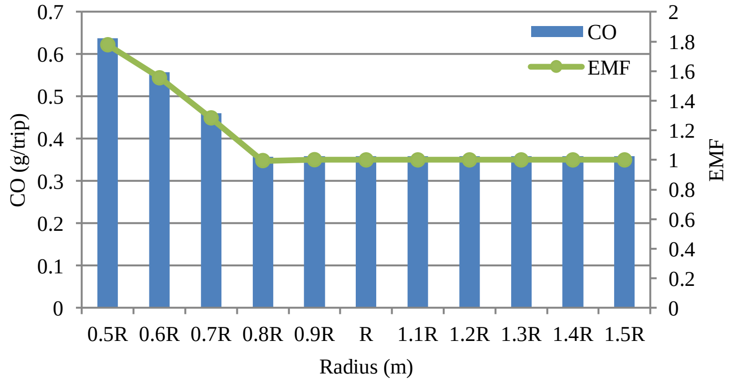
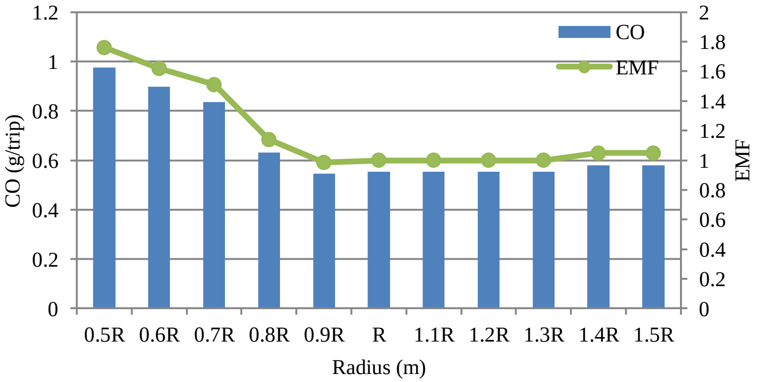
90 km/h Tangent Speed	110 km/h Tangent Speed
NO$_x$	
	
CO	
	

Figure 5.9 continued

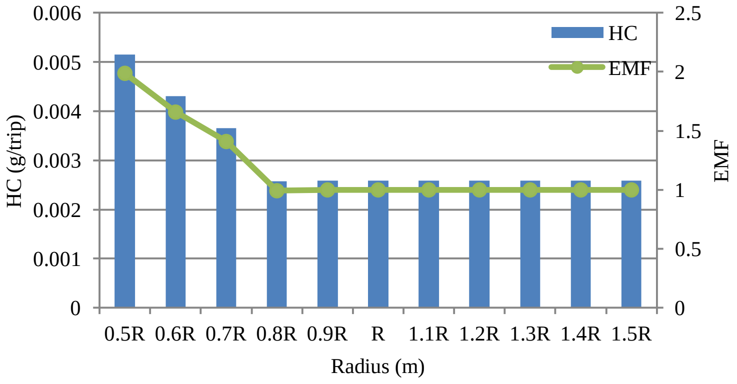
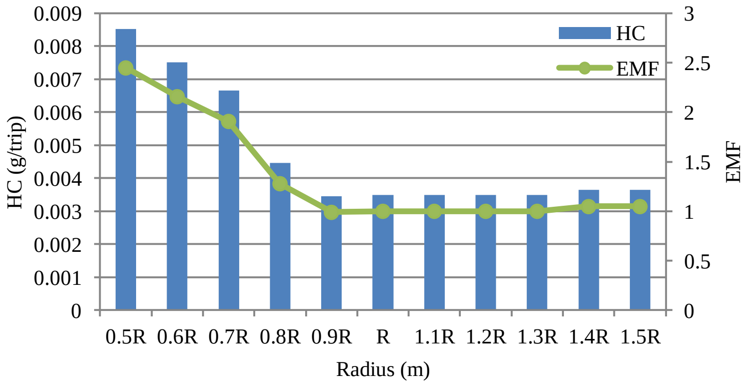
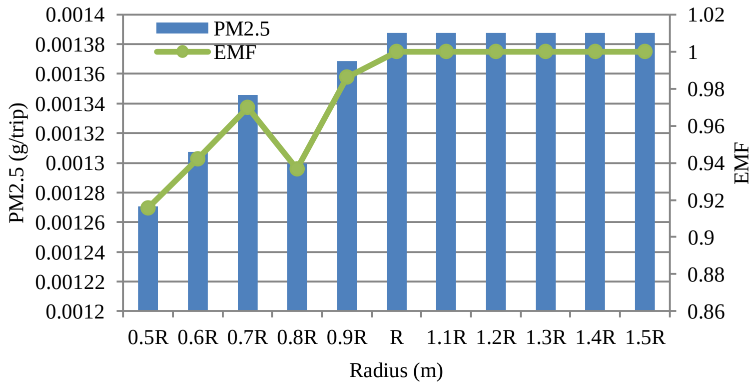
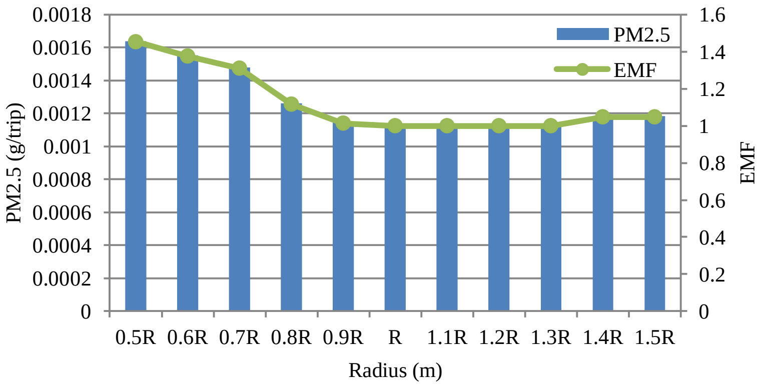
<table>
<tr><th>90 km/h Tangent Speed</th><th>110 km/h Tangent Speed</th></tr>
<tr><td colspan="2">HC</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">$PM_{2.5}$</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Figure 5.9 continued

For highway vertical grade design, the researcher set initial speeds, grades, and critical length of grades as key variables. The emissions and fuel consumption of the design vehicle on the trip of 6,000 m graded segment were predicted under the same conditions provided in the GreenBook (AASHTO, 2004), such as a typical duty truck of 120 kg/kW and the truck uses maximum power for the trip on grades. In the results by initial speeds, the truck consumed less fuel and produced less pollution with higher initial speeds; about 14 percent more fuel consumed at the initial speed of 10 km/h than 110 km/h. The effect of grade on fuel consumption and emissions were more significant; more than six times of fuel was consumed at the nine-percent grade relative to the flat. In addition, the truck produced four to six times emissions at steep grade. In terms of critical length of grade design, the researcher used the concept of 10 and 20 km/h speed reductions, and the grade design was categorized into three types: 1) the good design, 2) the fair design, and 3) the poor design. The truck consumed up to 85 percent more fuel on the fairly-designed graded segment than the good designed. The results with the poor design showed more fuel consumption than the other design types; the truck consumed 6.5 times more fuel on the poorly-designed segment than for the good design case. In terms of emissions, the results were similar with those from fuel consumption.

For the vertical crest curve design, the rate of vertical curvature (K) affected the predicted operating speeds at the middle of curves and grade changing within the curve. Dependent on increasing K, there were less or no speed reductions but gradual grade changes that made the curve flatter. The design vehicle consumed more fuel on the curve that was designed with lower K-values than the minimum standards as documented in the GreenBook (AASHTO, 2004). In addition, fuel consumption was getting lower with increasing K.

For the horizontal curve design, several factors affected environmental analyses: the curve radius, the 85th percentile tangent speed, the operating speed at the middle of curve, and the acceleration/deceleration between the tangent speed and the operating speed.

Among the tangent speeds of 70, 90, and 110 km/h, the design vehicle consumed the least fuel at 70 km/h, and then the fuel consumption increased with tangent speeds. For the curve radiuses less than the recommended minimum values in the design guidebook, there were speed reductions in the middle of curves and then the reduced speeds recovered to the original tangent speeds after passing the middle of the curves. Therefore, these travel patterns of speed reductions and recover caused acceleration/deceleration in the traveling on the curves, and this caused more fuel consumption from the trip on the curves. For the case of the 70 km/h tangent speed, the design vehicle consumed more fuel at the 50-percent reduced radius due to deceleration and acceleration. However, at higher tangent speeds, such as 90 and 100 km/h, the vehicle consumed less fuel on the 50 percent reduced radius due to speed control allowing lower speeds on the curve, despite of increased fuel consumption due to acceleration and deceleration. Higher tangent speeds and operating speeds, that were faster than the optimum speed minimizing fuel consumption, offset the fuel saving from the no acceleration/deceleration movement. The next chapter presents the results on fuel consumption and emissions in relation to highway geometric field data.

CHAPTER VI

APPLICATION OF THE QUANTITATIVE EVALUATION TO THE DESIGN PROCESS

The previous chapters (Chapters III and IV) provided the methods and processes for the quantitative evaluations on the vertical grades as well as horizontal and vertical crest curves. In addition, the results on the simulated design conditions were presented in Chapter V. This chapter illustrates how the provided tools and guidelines for quantitative environmental evaluation can be incorporated into the highway development process.

6.1 Environmental Evaluation in the TxDOT Design Process

For this chapter, the TxDOT highway development process is used for illustration. The TxDOT highway development process consists of six stages: planning and programming, preliminary design, environmental, right-of-way and utilities, PS&E development, and lettings (TxDOT Highway Development Process, 2009). Among the six stages, there are some tasks related to environmental impact analyses and documentation in four project stages: planning and programming, preliminary design, environmental, and PS&E development. The task description on the environmental impact analyses and evaluations at the four stages was presented in Figure 1.1 in Chapter I. However, it should be pointed out that these environmental evaluations focus on mobile emissions inventory prediction in the general project airshed not the quantitative evaluation with various geometric design criteria and features.

Figure 6.1 shows the detail design procedures at the preliminary design stage. During this stage, the basic features and preliminary design criteria are established. Based on the design features and criteria including traffic data and accident data, a project is evaluated in terms of safety, cost, operational and environmental impacts of the proposed and alternative designs. In addition, the need for a design exception on any design criteria that do not meet the established design standard may be identified during this stage.

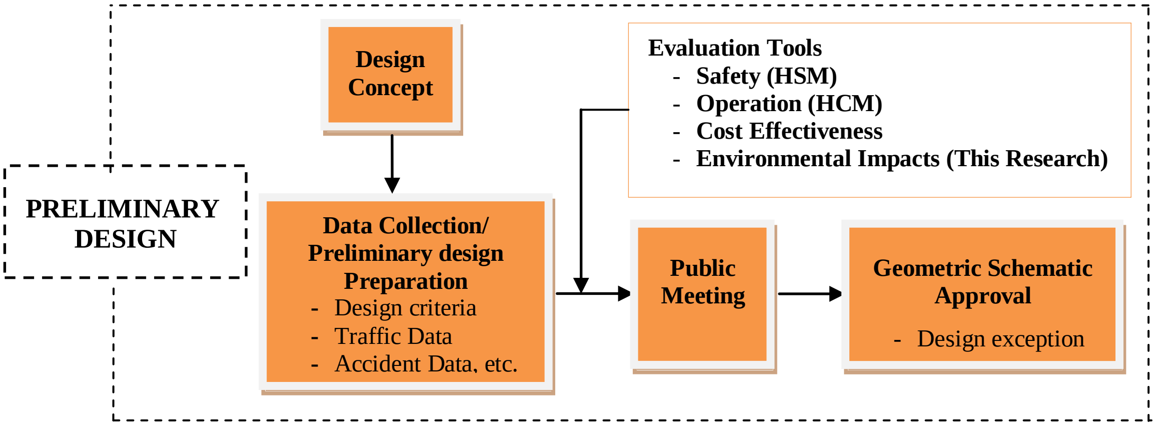
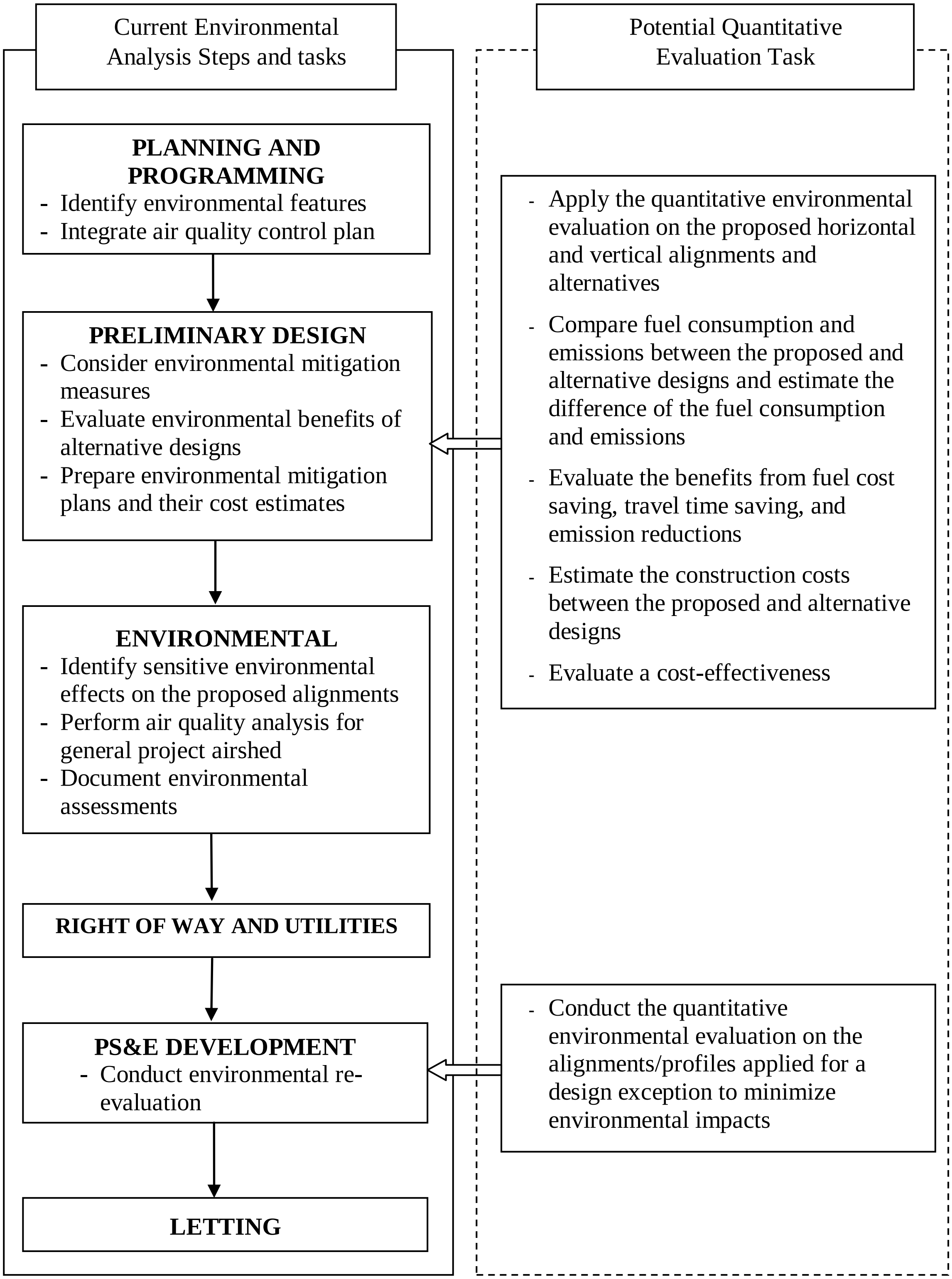


Figure 6.1 Detail design procedures at the preliminary design stage

During the preliminary design, if quantitative evaluations provide environmental impacts related to the selected highway geometric design features, the evaluations will provide the basic guideline necessary for making engineering and environmental decisions related to the design features. Figure 6.2 describes how to connect potential quantitative evaluation tasks that are proposed in this research into current environmental tasks of the highway development process.



PLANNING AND PROGRAMMING
- Identify environmental features
- Integrate air quality control plan

PRELIMINARY DESIGN
- Consider environmental mitigation measures
- Evaluate environmental benefits of alternative designs
- Prepare environmental mitigation plans and their cost estimates

ENVIRONMENTAL
- Identify sensitive environmental effects on the proposed alignments
- Perform air quality analysis for general project airshed
- Document environmental assessments

RIGHT OF WAY AND UTILITIES

PS&E DEVELOPMENT
- Conduct environmental re-evaluation

LETTING

- Apply the quantitative environmental evaluation on the proposed horizontal and vertical alignments and alternatives
- Compare fuel consumption and emissions between the proposed and alternative designs and estimate the difference of the fuel consumption and emissions
- Evaluate the benefits from fuel cost saving, travel time saving, and emission reductions
- Estimate the construction costs between the proposed and alternative designs
- Evaluate a cost-effectiveness

- Conduct the quantitative environmental evaluation on the alignments/profiles applied for a design exception to minimize environmental impacts

Figure 6.2 Potential quantitative evaluation tasks in the design process

The evaluation tools and guidelines proposed in this research can be incorporated to the tasks in the preliminary design and PS&E development stages, as shown in Figure 6.2. During the preliminary design stage, highway designers and engineers should consider countermeasures to mitigate environmental impacts related to a project design, and evaluate environmental benefits of alternative designs and their cost estimates. The evaluations are usually based on predicted traffic volume and design speeds, not highway geometric design features. Using microscopic simulations on the selected geometric design features, the quantitative evaluation will provide reasonable and accurate results in terms of environmental impacts. For quantitative environmental evaluation, the tools and guidelines provided in this research should be applied for the proposed horizontal and vertical alignments and alternative designs. The results should be monetized for fuel, travel time, emissions, construction costs, crash costs and any other costs that DOTs believe they need to be incorporated into the design process for a cost-effectiveness analysis.

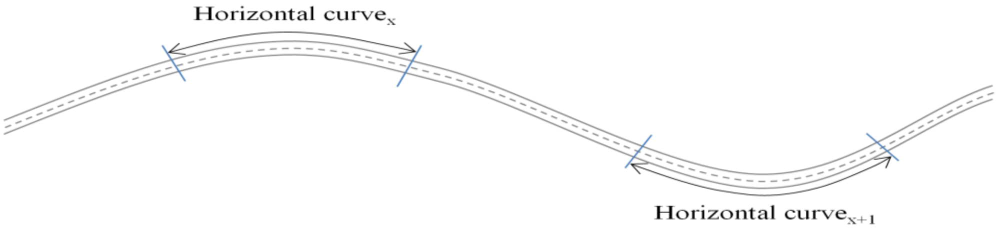
In the PS&E development stage, the design process requires environmental re-evaluation for final alignments/profiles. The re-evaluation includes design features that do not meet the minimum standard (i.e., design exception) to determine whether an environmental approval on project design is still valid. The quantitative evaluation proposed in this research can be used for the analysis to the alignments/profiles applied for a design exception to minimize environmental impacts (Figure 6.2).

Until now, the researcher described how to connect the proposed evaluation tools and guidelines from this research into the highway development process. The description provides the basic structure of environmental evaluation related to the design stages. Figure 6.3 provides a step-by-step procedure for quantitative evaluations used in this research. The procedure is useful to apply for the evaluation of design features that are not analyzed in this research.

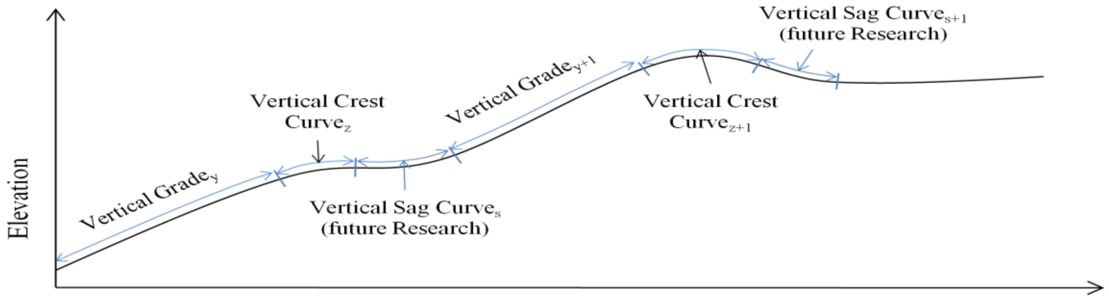
6.2 Step-by-step Procedure for Application

The quantitative environmental evaluation can be conducted with the following procedures (Figure 6.4):

- Step 1: Determine the highway geometric design features on the proposed alignment/profile.
- Step 2: Divide the alignment/profile into individual highway geometric design features (i.e., vertical grades, horizontal and vertical curves). Figure 6.3 illustrates how to divide a project design into the design features. Each horizontal curve can be identified from the highway alignment (Figure 6.3 (a)). Each vertical grade and vertical crest/sag curves on the project design can be identified from the proposed profile (Figure 6.3 (b)). The following steps should be applied for each of vertical grades, horizontal and vertical curves. Note that sag curves are not addressed in this research.



(a) Highway alignment



(b) Highway profile

Figure 6.3 Identification of highway design features

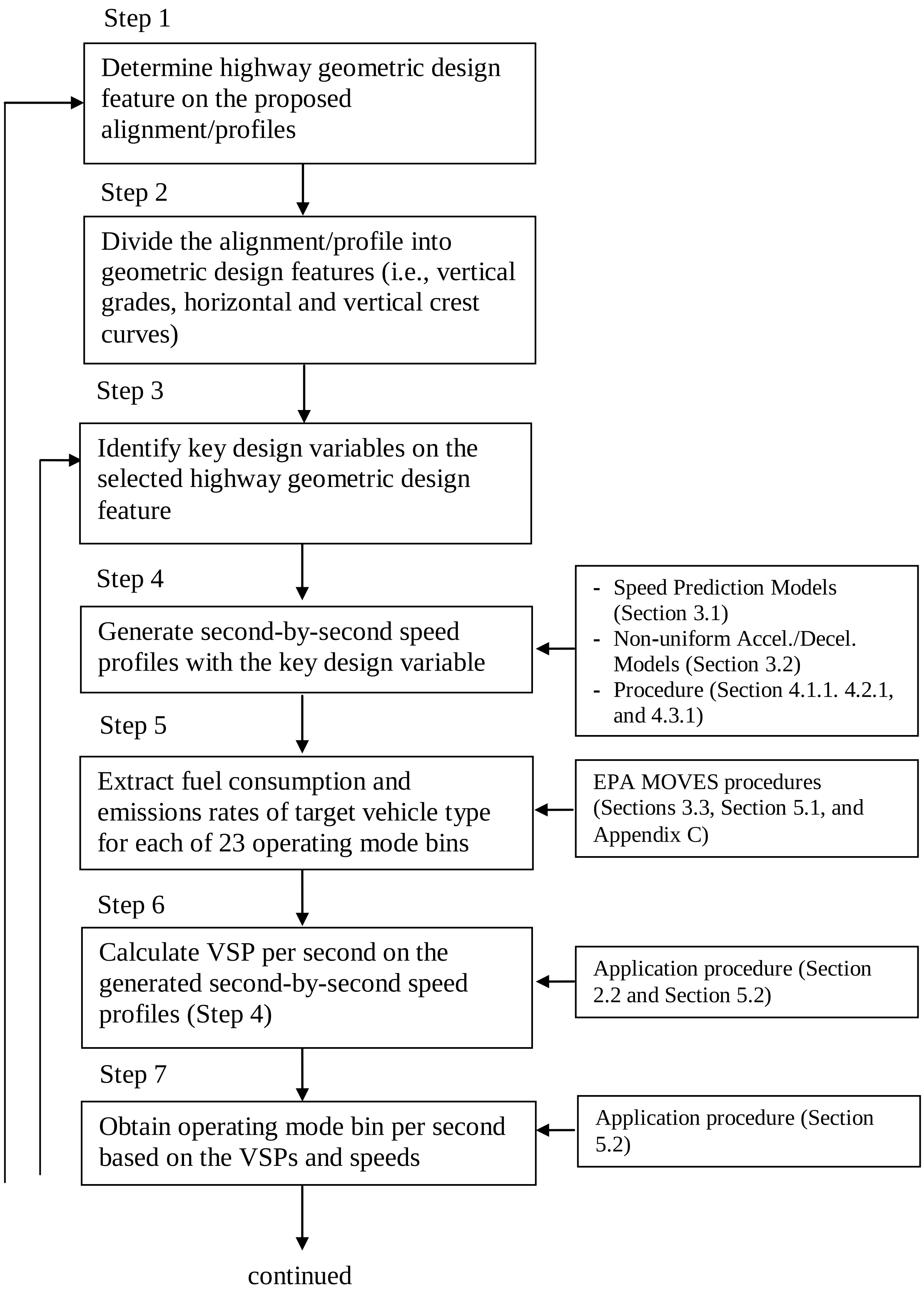


Figure 6.4 Overview of quantitative evaluation procedures

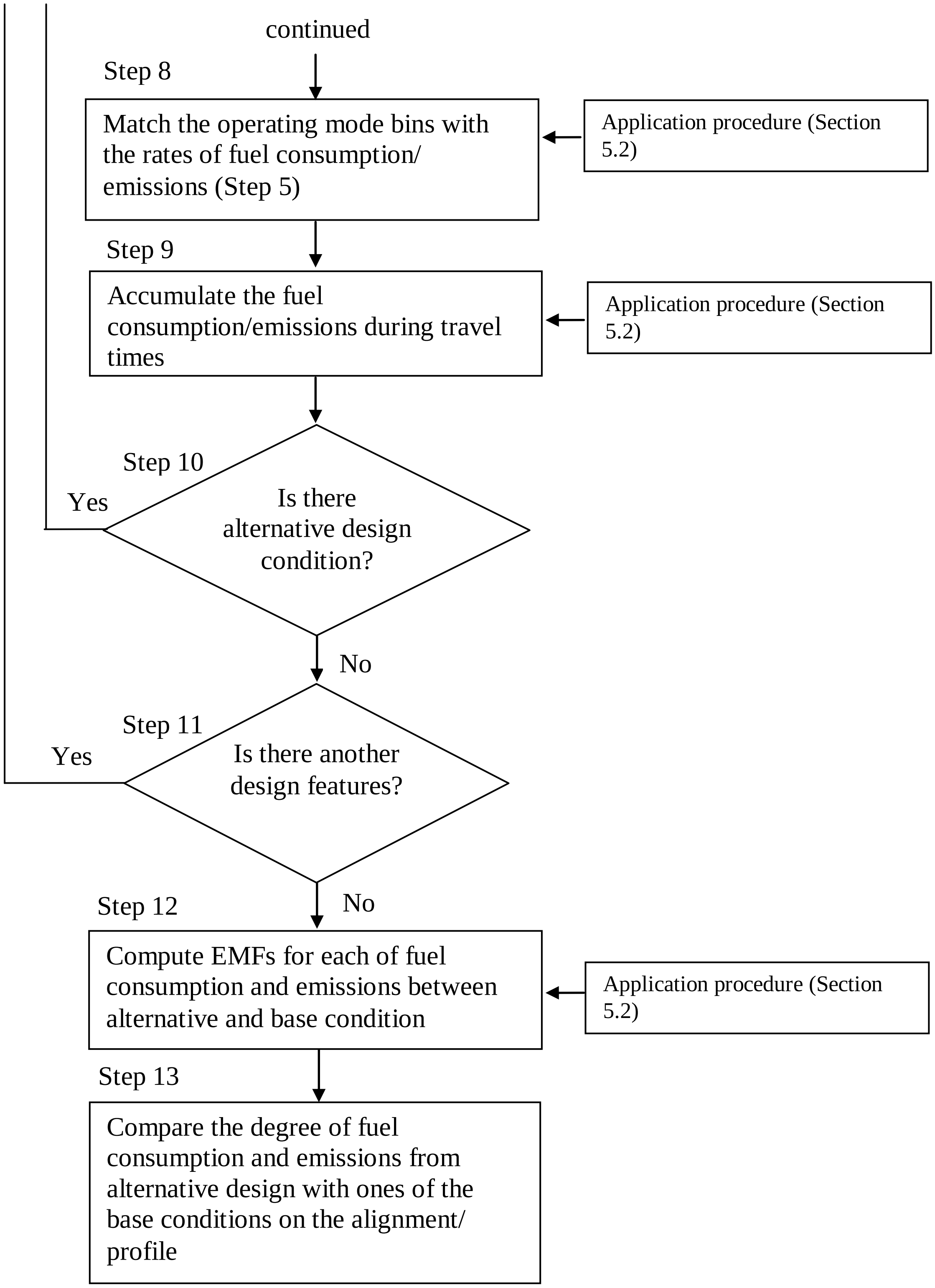


Figure 6.4 continued

- Step 3: Identify design conditions with key design variables on the selected design feature, such as the critical length of vertical grade segment, the curve radius, or the rate of vertical curvature. The design condition with the minimum standards will be the base condition in the analysis. When the highway already exists, the existing design condition will be considered as “the base.”
- Step 4: Generate second-by-second speed profiles with the key design variable on the selected design features. There are several factors affecting speed profiles: 1) design vehicle characteristics such as vehicle weight, size, and power, 2) roadway characteristics such as roadway grade, 3) operating condition such as vehicle speed and acceleration/deceleration, 4) key design variables such as design speed, curve radius, or rate of vertical curvatures, and 5) micro simulation models such as vehicle dynamics model, speed prediction model, or acceleration model. The speed profiles considering relevant factors will provide a better fit to actual driving profiles. When a selected segment includes more than one highway geometric design feature, such as horizontal curve design on the vertical grades, the speed profiles should be generated from appropriate combinations of the design features.
- Step 5: Extract fuel consumption and emissions rates. There are several simulation models for predicting vehicle emissions. The EPA MOVES was used in this study because MOVES is based on a large amount of data and is available to the public. Furthermore, the EPA provides technical background documents and manuals for applying the software; all the subsequent steps are based on MOVES. At this step, roadway designers and engineers can extract the fuel consumption and emissions rates for each of the 23 operating mode bins during a vehicle running exhaust process. The detailed procedures for using MOVES are explained in Sections 3.3 and 5.1 and Appendix C.
- Step 6: Calculate the VSP for each second on the generated second-by-second speed profiles. The calculation of the VSP is based on data from the speed

profiles, vehicle characteristics, and roadway characteristics using Equation (2.1).

- Step 7: Categorize the operating mode bin for each second using the VSPs and vehicle speeds. The explanation on the categorization is included in Section 3.3 and Table 3.1.
- Step 8: Match the extracted fuel consumption and emissions rates with the calculated operating mode bins with the VSPs and vehicle speeds.
- Step 9: Accumulate the second-by-second fuel consumption and emissions during a vehicle trip.
- Step 10: Repeat Steps 3 to 9 for fuel consumption and emissions with alternative design conditions (the below- or above-minimum standard; especially, the minimum standard will be alternative condition when the existing highway is designed with the below-minimum standard).
- Step 11: Repeat Steps 1 to 10 for different highway geometric design features.
- Step 12: Compute EMFs for each of fuel consumption and emissions between the alternative design condition and the base condition.
- Step 13: Compare the fuel consumption and emissions from the alternative designs with those of the base conditions on the alignment/profile.

6.3 Chapter Summary

This chapter describes how to incorporate the provided tools and guidelines in this research into the highway design process. The quantitative environmental evaluations related to various geometric design features are connected to the current design process evaluating mobile emissions inventory prediction in the project area. The quantitative evaluation tasks can be used in the preliminary design and PS&E development stages. At these stages, environmental impacts and mitigation measures in the project design are considered. The application of the quantitative evaluation will provide reasonable and accurate results for the environmental impacts on the proposed alignment and profile.

In addition, the detailed procedures for the quantitative evaluation were illustrated for the purpose of the application of design features that are not analyzed in this research. Based on the proposed evaluation tools and guidelines, the next chapter presents the application of the evaluation on fuel consumption and emissions in relation to highway geometric field data.

CHAPTER VII

APPLICATION ON HIGHWAY GEOMETRIC FIELD DATA

In Chapter V, the researcher quantified the changes in fuel consumption and emissions related to various highway geometric design conditions on the vertical grades, as well as for horizontal and vertical crest curves. However, the quantification was performed under controlled design conditions. In practice, there are numerous combinations of design conditions. For example, a horizontal curve radius was changed while other design variables, such as superelevation, a deflection angle, and a tangent speed, remained fixed. In reality, the environmental evaluation may be affected not only by each variable alone, but also by intertwined effects among variables. The objective of this chapter is to describe how the methodology described in Chapters III and IV can be used to quantify environmental evaluations. This description is based on actual highway geometric data. The results from selected actual design conditions that did not meet the minimum standard were compared with those of the conditions satisfying the minimum standard. In addition, this chapter provides outputs of benefit-cost analyses based on the previous comparison. However, the results provided in this chapter are dependent on the assumptions of the design vehicle characteristics, fuel type, weather condition, and/or a truck proportion of total traffic volume. The results should not be taken at face-value and should not be used for decision-making purposes.

7.1 Highway Geometric Field Data

A few states in the U.S. have detailed inventory databases about key highway geometric design variables. The researcher selected actual geometric data on U.S. Route 101 (called US 101 below) in Jefferson County, Washington. Figure 7.1 illustrates the alignment of US 101 located in the western region of Washington State. It has a total length of 588 km, and most segments are defined as a two-lane rural principal arterial. The available geometric data were retrieved from the Washington Department of Transportation websites[7] and the Highway Safety Information System[8].

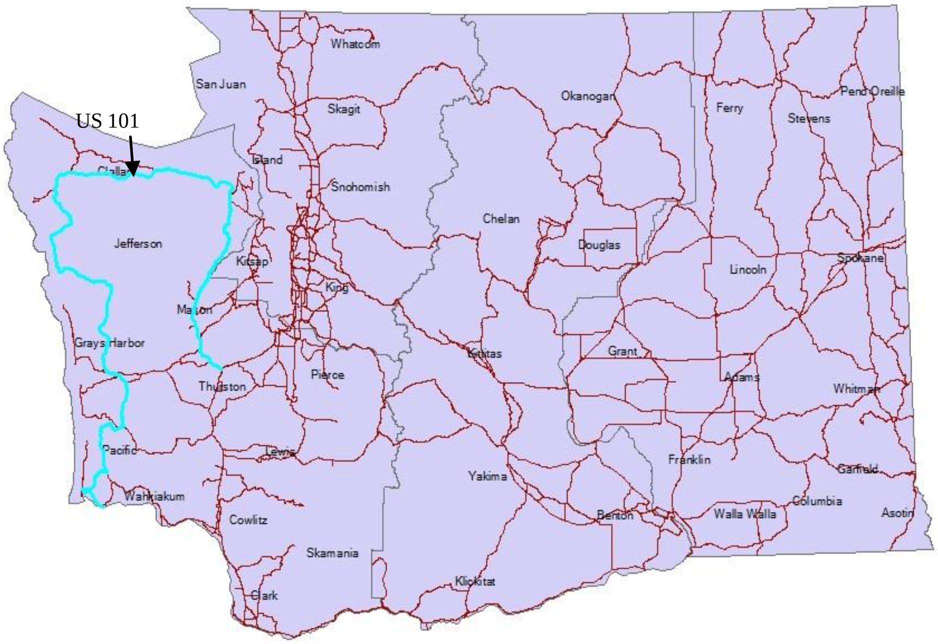


Figure 7.1 US 101 route evaluated with real geometric data

7.2 Fuel Consumption and Emission Rates

For the area including the selected route, the researcher extracted the rates of fuel consumption and emissions related to each of the 23 operating mode bins according to

---

[7] http://www.wsdot.wa.gov/mapsdata/geodatacatalog/Maps/noscale/DOT_TDO/RoadwayDatamart/RoadwayDatamartIDX.htm

[8] http://www.hsisinfo.org/index.cfm

the step-by-step procedures in the Appendix C. Table 7.1 specifies the base condition for the simulation using MOVES. The fuel consumption and emission rates for each operating mode bin were generated with the same processes introduced in Chapter III. The outputs of MOVES processing are provided in Figure 5.1 and Appendices H and I for accounting for the single-vehicle age and multi-vehicle ages (Appendix G), respectively. As a result, there were almost no differences in the rates between Jefferson County, Washington (Appendix H) and Dallas County, Texas (Figure 5.1) under the single-vehicle age scenario, even though the rates of fuel consumption, CO_2, and CO were slightly higher in Jefferson County than for the Dallas County. In the comparison with the multi-vehicle ages from zero to 30 years old, there were some differences (Appendices H and I). For a passenger car, the fuel consumption and emissions rates from accounting for the multi-vehicle ages are higher than those using a single-vehicle age (i.e., four years old vehicle) because of greater cumulative distribution of vehicles older than four years old (Appendix G). On the other hand, for a heavy duty truck, the fuel consumption and emissions rates for the multi-vehicle age scenario are lower than those of the single-vehicle age because of greater cumulative distribution on vehicles newer than four years old. In this chapter, the fuel consumption and emissions rates accounting for the multi-vehicle ages were used to reflect actual traffic conditions. The extracted fuel consumption and emission rates were matched with the operating mode bins calculated from the speed profiles and then aggregated during trips on the curves and grades.

Table 7.1 Basic conditions for MOVES simulation

Variable			Specification	
Input	Vehicle	Type	A Single Passenger Car	
			A Single Heavy Duty Diesel Truck (HDDT)	
		Mass (ton)	Passenger Car	1.478
			Heavy Duty Truck	31.404
		Model Year	Passenger Car	Age Distribution[1]
			Heavy Duty Truck	Age Distribution[1]
		Fuel	Passenger Car	Conventional Gasoline (Market share: 28 percent)
				Gasohol (E10) (Market share: 72 percent)
			Heavy Duty Truck	Conventional Diesel Fuel
	Roadway	Type	Rural Unrestricted Access	
		Grade	Level	
	Area		Jefferson County, WA	
	Year		2010	
	month		May	
	Temperature (℉)		60.8	
	Relative Humidity (percent)		63.9	
Output	Fuel Consumption		Rate (gal/s) on each operating mode by each vehicle type	
	Emissions		Rates (g/s) of CO_2, NO_x, HC, CO, and $PM_{2.5}$ on each operating mode by each vehicle type	

NOTE: [1] vehicle age distribution (source: User Guide for MOVES2010a (EPA, 2010b)).

7.3 Vertical Grades

The researcher identified the highway segments built with longer graded lengths than the critical values in relation to the speed reductions of 10 and 20 km/h on the grades. These speed reductions, in turn, were categorized as fair and poor designs, as specified in Chapter III. Table 7.2 lists three segments as the fair design and one segment as the poor design identified on US 101.

Table 7.2 Characteristics of selected graded segments on US 101

Case	Speed Limit (km/h)	Grade (%)	Truck Crawl Speed (km/h)	Design Category	Actual Length of Grade (m)	Critical Length of Grade^1 (m)	Critical Length of Grade^2 (m)
1	80	6	39	Fair	306	147	-
2	88	6	37	Poor	483	139	282
3	72	4	50	Fair	563	336	-
4	88	2	77	Fair	2,559	1,147	-

NOTE: [1] critical length for good design; [2] critical length for fair design.

Figure 7.2 shows the EMFs of the HDDT's fuel consumption and emissions from the design improvement of original the fair/poor designs to the good design. The environmental evaluation on the grades was done with the assumption that speed limits on each segment were in the 85th percentile of initial speeds, and that a typical heavy truck (i.e., design vehicle) used maximum engine-generated power. It was estimated that about 7 to 35 percent more fuel was consumed for the selected segments, relative to the hypothetical condition that these segments were built under the concept of good design. In addition, the EMFs for emissions, except for $PM_{2.5}$, were similar to those of the fuel consumption. If the selected segments were designed under the concept of good design, emissions produced from the vehicle traveling on the grades would have been reduced by up to 35 percent. For $PM_{2.5}$, there were higher EMFs than other emissions. Up to 62 percent more $PM_{2.5}$ was produced in the actual highway grades, as opposed to the scenario in which the grades were designed by the good design concept.

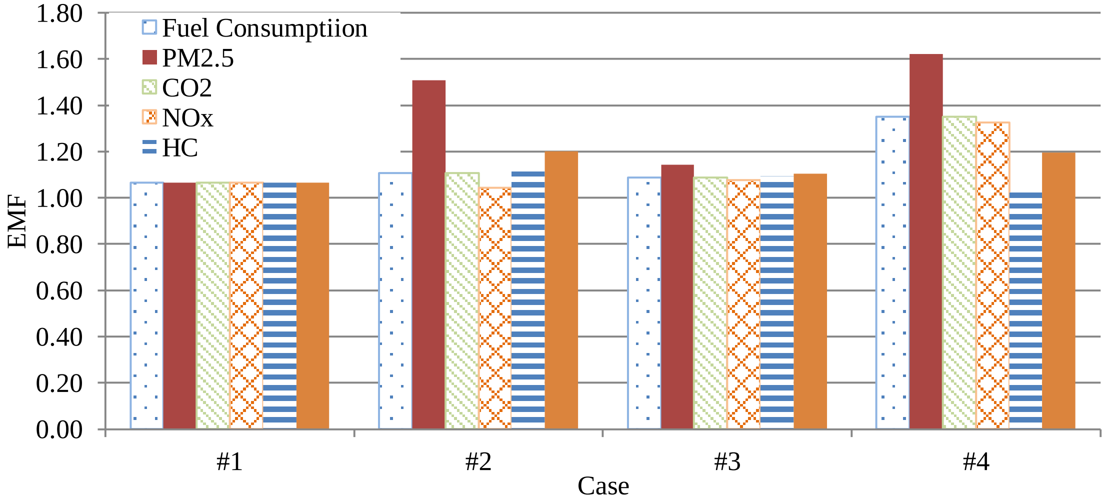


Figure 7.2 EMFs from actual vertical grades selected relative to the hypothetical condition of the good design (base scenario: meet minimum design standards)

In this section, the researcher identified segments that did not satisfy the speed reduction criteria, less than 10 km/h, on the grades of US 101, and compared the aggregated fuel consumption and emissions of current design conditions with the hypothesized design conditions (i.e., the good design). Most vertical grade segments on US 101 met the good design criteria. However, there were a few segments that caused speed reductions greater than 10 km/h; the vehicle consumed more fuel and produced more emissions on these segments, as expected.

7.3.1 Benefit-Cost Analysis

In the previous section, the researcher quantitatively analyzed fuel consumption and emissions with the design criteria in relation to a speed reduction on roadway vertical grades. In addition to those environmental quantifications, this section provides the analyses for benefits and costs resulted from the design improvement from the fair to good designs on the actual vertical grade design conditions listed in Table 7.2.

7.3.1.1 Highway Construction Costs

A grade adjustment can affect highway construction costs throughout the change of a lane-length or roadway earthworks. For the selected graded segments (Table 7.2), the grade design improvement from the fair/poor designs to the good design, i.e., graded to non-graded adjustment on the section beyond the critical length of vertical grade segment, increased the construction cost for additional earthwork. However, this grade adjustment did not make any changes greater than one meter in the lane-length for the selected segments; thus, the cost related to a lane-length was not considered in the analysis. The earthwork volumes were determined using the average area method under the assumptions that the width of a two-lane highway was nine meters and cut side slopes were 2:1. Additional construction costs for the earthwork were estimated with the amount of volumes and the unit price (i.e., the price of one cubic meter earthwork was $9.4, WSDOT, 2011a). The additional construction costs are provided in Table 7.3. The costs accounted for about $130,000 to $3 million depending on the amount of earthwork. These costs can be reduced by a construction method for minimizing earthwork throughout balancing cut and fill volumes, but the researcher estimated the costs without any consideration of the cut and fill balance.

Table 7.3 Estimation on additional earthwork volumes and costs (in 2010 dollars)

Case	Additional Earthwork	Unit Price ($/cubic meter)	Additional Construction Cost ($)
	Quantity (cubic meter)		
1	13,791	9.4	129,638
2	69,590		654,147
3	19,648		184,692
4	306,747		2,883,419

As described in Case 4, actual vertical grade was designed by two-percent grade and about 2,560 m graded length, and the grade design caused a speed reduction of 14 km/h in the design truck traveling. To control a speed reduction less than 10 km/h on the grade, the length of vertical grade segment should be less than 1,147 m. Simultaneously, the length of non-graded segment should be greater than 1,413 m (=2,560-1,147). When this design improvement was applied, it caused additional earthwork of 306,747 m^3 and it cost approximately $3 million in year 2010 dollars.

7.3.1.2 Fuel Cost

There was a reduction in fuel consumption due to the design improvement from the fair/poor to the good design for four selected segments (Table 7.4). Less vehicle engine loads on the leveled segments contributed in fuel savings. Annual fuel costs during trips were estimated with 1) fuel consumption per a single passenger car/heavy duty diesel truck, 2) annual traffic volume, and 3) the unit price of gasoline/diesel. Since the WSDOT did not provide traffic volume for each type of vehicles, the researcher considered various traffic conditions that traffic volumes for the passenger car and the HDDT accounted for 95 percent and five percent, 90 percent and 10 percent, 85 percent and 15 percent, and 80 percent and 20 percent of annual average daily traffic (AADT), respectively. AADTs for the selected cases were 4,600, 1,300, 2,600, and 2,000 vehicles in 2010, respectively (WSDOT, 2011b). According to the U.S. Energy Information Administration (2011), the average unit price of gasoline and diesel were $2.89 and $2.99 in Washington in 2010, respectively. The consumed fuel costs from the good design condition were subtracted from those of the fair/poor design condition for each of the passenger car and heavy duty truck. The estimated savings in the fuel cost are calculated with the procedures as shown in Table 7.4. Under the assumption of traffic volumes for the passenger car and the HDDT accounted for 90 percent and 10 percent of AADT, there were estimated fuel savings by up to approximately $35,000 from traffic operation in 2010 since the design improvement controlling a speed reduction less than 10 km/h was implemented on the selected vertical graded segments.

Table 7.4 Estimation on fuel consumption and cost saving in 2010

Case	Fuel Consumption (gal/veh.)						Annual Traffic Volume		Unit Price ($/gal)		Fuel Cost Saving($)	
	PC[1]			Truck[2]								
	Fair Design (1)	Good Design (2)	Diff. (1-2)	Fair Design (3)	Good Design (4)	Diff. (3-4)	PC[3] (5)	Truck[4] (6)	Gas (7)	Diesel (8)	PC ((1-2)×5×7)	Truck ((3-4)×6×8)
1	0.013	0.010	0.003	0.045	0.042	0.003	1,511,100	167,900	2.89	2.99	11,077	1,399
2	0.015	0.013	0.002	0.071	0.064	0.007	394,200	43,800			2,683	971
3	0.020	0.016	0.004	0.089	0.082	0.007	854,100	94,900			10,609	2,067
4	0.072	0.063	0.009	0.341	0.253	0.089	657,000	73,000			17,050	19,329

NOTE: [1] passenger car; [2] a typical heavy duty diesel truck of 120 kg/kW; [3] 90 percent of total traffic volume; [4] 10 percent of total traffic volume.

Table 7.5 shows the fuel cost savings for different traffic volume proportions between the passenger car and the HDDT. The fuel cost saving due to the design improvement increased with higher proportion of the HDDT volume in total traffic volume. As described in Case 4, the fuel cost saving was estimated for approximately $28,000 under the assumption of the five-percent truck volume. The cost saving increased to $53,814 with the assumption of the 20-percent truck volume because there is a greater fuel reduction for the truck than the passenger car. The weighed truck consumes more fuel than the passenger car during the same trip. Consequently, the effect of fuel saving related to the design improvement is more beneficial in the truck operation.

Table 7.5 Estimation on fuel cost savings for various truck proportions in 2010

Case	Fuel Cost Saving ($)			
	5%[1]	10%[2]	15%[3]	20%[4]
1	12,391	12,475	12,559	12,643
2	3,318	3,655	3,991	4,328
3	12,232	12,676	13,120	13,564
4	27,662	36,380	45,097	53,814

NOTE: [1] 5 percent truck volume and 95 percent passenger car volume of total traffic volume; [2] 10 percent truck and 90 percent passenger car volumes; [3] 15 percent truck and 85 percent passenger car volumes; [4] 20 percent truck and 80 percent passenger car volumes.

7.3.1.3 Societal and Health Costs

Emissions from vehicle movements affect public health and welfare issues. The adverse effects of mobile-sourced emissions were discussed in Chapter II. For example, children residing close to main roads are at a higher risk of respiratory symptoms (Kim et al., 2004; Middleton et al., 2010). Reductions in emissions from the improvement of highway vertical grade design are beneficial for the society; economic benefits from the emissions reductions were monetized with the unit values of reduced CO_2, NO_x, and $PM_{2.5}$ estimated as $21, $4,000, and $168,000 per metric ton, respectively, in 2007 U.S. dollars (Burris, 2011). Each amount of differences for three emissions due to the design improvement by a single vehicle was multiplied by the annual traffic volume and the unit prices of emissions per metric ton. For reference, the unit prices of emissions were adjusted to the value in year 2010 dollars using a conversion factor[9]. The estimated cost savings related to the improvement on the societal and health are presented in Table 7.6. As described in Case 4, about 970 g of CO_2 for the operation of a single passenger car and heavy duty diesel truck could be reduced from the design improvement, and the cost due to the CO_2 reduction could be saved by up to about $2,500 in 2010 under the consideration of the 10-percent truck volume of the annual traffic volume and the unit value of CO_2 reduction.

---

[9] http://oregonstate.edu/cla/polisci/download-conversion-factors

Table 7.6 Estimation of societal and health costs saving in 2010

Vehicle	Case	Emission Diff.[1] (Fair/Poor to Good Design)			Emissions Cost Saving (in 2010 $)		
		CO_2	NO_x	$PM_{2.5}$	CO_2	NO_x	$PM_{2.5}$
HDDV	1	28.0	0.1119	0.0059	104	79	174
	2	68.9	0.1236	0.0468	72	25	392
	3	73.3	0.2546	0.0234	154	102	393
	4	890.7	3.4774	0.2395	1,436	1,068	3,089
PC	1	22.1	0.0550	0.0004	738	350	118
	2	19.0	0.0472	0.0004	179	85	29
	3	37.5	0.0961	0.0004	707	345	68
	4	78.3	0.1738	0.0003	1,136	480	36

NOTE: [1] unit is g/vehicle.

Similar to Table 7.5, the emissions cost savings from the design improvement under various truck volume conditions are presented in Table 7.7. The effect on the emissions cost savings is stronger with higher proportion of truck volume in total traffic volume. In addition, the outcome could be explained that the truck produced more emissions than the passenger car for the same trip characteristics.

Table 7.7 Emission cost savings with various truck proportions in 2010

Case	Emissions Cost Saving ($)			
	5%[1]	10%[2]	15%[3]	20%[4]
1	1,451	1,563	1,674	1,786
2	553	781	1,009	1,237
3	1,506	1,768	2,029	2,291
4	4,540	7,245	9,949	12,653

NOTE: [1] 5 percent truck volume and 95 percent passenger car volume of total traffic volume; [2] 10 percent truck and 90 percent passenger car volumes; [3] 15 percent truck and 85 percent passenger car volumes; [4] 20 percent truck and 80 percent passenger car volumes.

7.3.1.4 Travel Time Costs

On the roadway vertical grades controlling a speed reduction less than 10 km/h, vehicles can travel with less time. In terms of the design truck, there were reductions by up to 11 seconds in travel time on the segments designed using the good design criteria; however, the design improvement did not cause travel time saving for the passenger car (130 kW power and 1,478 kg mass) because the car could travel without any speed reduction. Related to the reduced travel time, the amount of cost saving was estimated under the assumption that the value of truck travel time per hour was $22.91[10]. Table 7.8 provides the travel time savings due to the design improvement on the vertical grades. As described in Case 4, the design improvement could save 11 second travel time per truck, and annual cost savings related to the reduced travel time reached up to about $10,200 in year 2010 dollars. The travel time cost saving increased with higher proportion of the truck volume.

Table 7.8 Estimation on travel time cost saving in 2010

Case	Travel Time (sec)			Travel Time Cost Saving ($)			
	Original Design	Improved Design	Difference	5%[1]	10%[2]	15%[3]	20%[4]
1	16	15	1	534	1,069	1,603	2,137
2	25	21	4	604	1,208	1,812	2,416
3	32	29	3	906	1,812	2,718	3,624
4	118	107	11	2,555	5,111	7,666	10,221

NOTE: [1] 5 percent truck volume and 95 percent passenger car volume of total traffic volume; [2] 10 percent truck and 90 percent passenger car volumes; [3] 15 percent truck and 85 percent passenger car volumes; [4] 20 percent truck and 80 percent passenger car volumes.

---

[10] http://ostpxweb.dot.gov/policy/Data/VOTrevision1_2-11-03.pdf

7.3.2 *Summary Results*

In this study, the benefit-cost analysis was conducted using 10 year-, 20 year-, and 30-year design periods, where the basic design year is assumed to be in 2010. Consequently, the benefits and costs were adjusted to the year 2010 dollars with a three percent discount rate for the societal and health cost and a seven-percent discount rate for the fuel and travel time costs (NHTSA, 2009). For a 20 year-design period, the benefits surpassed the costs for the half of the cases; the design improvement that controls a speed reduction less than 10 km/h on the vertical grades was beneficial. As described in Case 1, the ratio between benefits and costs under the assumption of the 10-percent trucks of total traffic volume was two (Table 7.9); this means that cost savings from the design improvement were twice greater than the construction cost for the additional earthwork and a 20 year-design period. However, for the half of the selected cases, the design improvements were not beneficial for a 30-year design period because of a significant amount of additional construction costs. In addition, the ratios of the benefits to the cost increased with higher truck proportion of total traffic volumes.

Table 7.9 Estimation on benefits and costs in future (in 2010 dollars)

Case	Benefit-Cost Ratios											
	5%[1]			10%[2]			15%[3]			20%[4]		
	10-Yr	20-Yr	30-Yr	10-Yr	20-Yr	30-Yr	10-Yr	20-Yr	30-Yr	10-Yr	20-Yr	30-Yr
1	1.09	1.92	2.76	1.14	2.00	2.89	1.19	2.09	3.01	1.25	2.18	3.14
2	0.07	0.12	0.17	0.08	0.14	0.21	0.10	0.17	0.25	0.12	0.20	0.28
3	0.78	1.37	1.97	0.86	1.50	2.17	0.94	1.64	2.36	1.02	1.78	2.56
4	0.12	0.20	0.34	0.16	0.28	0.50	0.21	0.36	0.65	0.26	0.44	0.81

NOTE: [1] 5 percent truck volume and 95 percent passenger car volume of total traffic volume; [2] 10 percent truck and 90 percent passenger car volumes; [3] 15 percent truck and 85 percent passenger car volumes; [4] 20 percent truck and 80 percent passenger car volumes.

7.4 Vertical Crest Curves

There are 970 vertical crest curves on US 101. Of these, about 15 percent (i.e., 143 curves) were built with less than half of minimum K-values provided in the GreenBook (AASHTO, 2004). The researcher also found that 502 vertical crest curves, accounting for about 52 percent of total curves, were built with greater than 1.5 times the minimum K-values. Similar to the previous section, sites that do not meet the minimum standards were selected. The researcher identified four curves with the following features:

- less than the minimum standard K-values;
- greater than or equal to 48 km/h design speed; and,
- greater than four percent of algebraic difference of approach and departure tangent grades (G_2- G_1).

The characteristics of selected curves are provided in Table 7.10.

Table 7.10 Characteristics of analyzed vertical crest curves on US 101

Case	Design Speed (km/h)	G_1 (%)	G_2 (%)	Actual		Minimum		Design Category
				L (m)	K (m/%)	L (m)	K (m/%)	
1	128	3.01	-2.50	1,500	272	2,116	384	Below-minimum
2	128	-0.60	-3.60	800	267	1,152	384	Below-minimum
3	128	0.43	-2.68	853	274	1,194	384	Below-minimum
4	128	3.30	-0.70	1,000	272	1,409	384	Below-minimum

NOTE: G_1= approach tangent grade; G_2=departure tangent grade.

Based on Table 7.10, the researcher generated speed profiles by the design vehicle (i.e., the passenger car) on both the actual geometric conditions (i.e., the below-minimum design standard) and the hypothetical design conditions with the minimum design standard values in the GreenBook (AASHTO, 2004). Those speed profiles, in turn, were matched with fuel consumption and emissions rates in terms for the 23 operating mode bins. Table 7.11 provides the EMFs comparing the actual conditions with the hypothetical conditions with the minimum design standard values on the vertical curves. In general, the ratios were greater than one, meaning that the vertical crest curves, with less than the minimum design standard K-values, caused more fuel consumption and emissions. Up to five percent more fuel consumptions were consumed and up to 22 percent more emissions were produced at the selected actual vertical curves (as expected), relative to the curves that were designed with the minimum design K-values. However, for $PM_{2.5}$ at Case 2, the EMF was less than one. The reason for this opposite result can be explained by the pattern on the rate of $PM_{2.5}$ (Appendix I). For the passenger car, the rates for the emissions, except for $PM_{2.5}$, increased as the mode bins moved from #33 to #37. However, the pattern of the rates for $PM_{2.5}$ was different; the rate increased from #33 to #35 but decreased from #35 to #37. Conclusively, this pattern made the different result on $PM_{2.5}$.

The primary reason for the increases on fuel consumption and emissions for the actual vertical crest curves could be explained by the length of vertical curve. Lower K-values created shorter length of the vertical curves and provided sharper changes on the curvature than the curve designed by higher K-values. This sharpening, in turn, could increase vehicle engine loads on the curves. The increased demand on the engine power led to more fuel usage and emissions.

Table 7.11 EMFs of fuel consumption and emissions for selected vertical curves

Case	Fuel Consumption	CO2	NO_x	CO	HC	$PM_{2.5}$
1	1.00	1.00	1.03	1.08	1.10	1.05
2	1.02	1.02	1.02	1.05	1.03	0.92
3	1.03	1.03	1.05	1.03	1.02	1.03
4	1.05	1.05	1.09	1.01	1.11	1.22

NOTE: the base condition reflects curves that are designed with the minimum standard K-values.

7.4.1 Benefit-Cost Analysis

For the vertical curves used in the previous section, the researcher conducted a benefit-cost analysis between the curves designed with the minimum design standard K-values in the GreenBook (AASHTO, 2004) and those with actual K-values (i.e., the below-minimum design standard). The assumptions and unit values for earthwork, fuel, and emissions were based on the ones used in the benefit-cost analysis for the vertical grades, unless specified.

When a vertical curve is designed using the minimum standard relative to the actual curve condition, it causes additional earthwork because of the flattening of the curve. For the selected cases (Table 7.10), the curve design with the minimum standard K-values caused addition construction costs by up to $77,897 (Table 7.12). In terms of fuel costs, the flattened curvature design reduced vehicle engine loads and consequently reduced fuel consumptions during the trips on the vertical curves. The fuel consumption per vehicle (i.e., a single passenger car and HDDT) was multiplied by annual traffic volume. The fuel consumption on the actual curves was subtracted from the one related to the minimum standard K-value, and then the difference was monetized based on the unit price of fuel. The cost savings from the reduced fuel consumption are presented in Table 7.12. Similar to the fuel cost savings, less pollution was produced on the vertical crest curves when the minimum design standard is met. The amounts of reduced emissions, CO_2, NO_x, and $PM_{2.5}$, were monetized with the unit values for each emission, and the savings on the societal and health costs are listed in Table 7.12. For reference, the design changes related to flattening vertical curvature did not make any difference in travel time. A cost saving related to travel time was not considered in the analysis.

Table 7.12 Benefits and costs on vertical curves in 2010 dollars (10% truck)

Case	Cost[1,2]	AADT[3] (veh)	Fuel Cost Saving[1]	Societal & Health Costs Saving[1]	B-C			B/C		
					Design Period			Design Period		
					10-Year	20-Year	30-Year	10-Year	20-Year	30-Year
1	77,897	4,200	2,839	209	-46,425	1,434	88,072	0.40	1.02	2.13
2	19,736	3,000	1,146	82	-16,002	-10,404	-303	0.19	0.47	0.98
3	22,752	13,000	6,676	477	345,418	962,990	2,104,596	16	43	93
4	23,069	2,900	2,961	207	1,206	37,879	104,168	1.05	2.64	5.52

NOTE: [1] estimation in the year of 2010; [2] construction cost; [3] sourced from the WSDOT (2011b).

Finally, the reduced costs (i.e., benefits) from the fuel consumption and societal and health and the increased construction costs for each case in 2010 are presented in Table 7.12. In addition, the expected benefits and costs during 10-year, 20-year, and 30-year design periods were adjusted to the year 2010 dollars. As described in Case 3, the benefits due to the flattening of the curve using the minimum design standard exceeded the cost for a 10-year design period; the benefits were greater than 16 times of the cost. Furthermore, about 93 times more benefits relative to the cost were expected in a 30-year design period. The high benefit-cost ratios could be explained with the high traffic volume. The expected benefits resulted from the cost savings in the fuel and emissions increase with traffic volume. For more than half cases, the benefits surpassed the costs for a 20-year design period. Especially, in the results with various truck proportions of total traffic volumes, the ratios of the benefits to the cost increased with higher truck proportion (Appendix J).

7.5 Horizontal Curves

There are 953 horizontal curves on US 101. Of these, 294 curves have a radius greater than 1.5 times that the minimum design standard provided in the GreenBook (AASHTO, 2004); 151 curves have a radius less than half of what is the minimum. The researcher identified six horizontal curves with the following criteria:

- a radius reduction more than 80 percent of the minimum standard;
- a less than 120 degree deflection angle; and,
- an 80 km/h speed limit.

Since the database for horizontal curves did not include information on the design speed, the researcher assumed the speed limit as the design speed on horizontal curves. Table 7.13 lists the characteristics of the selected horizontal curves on US 101 for the environmental evaluation.

Table 7.13 Characteristics of selected horizontal curves on US 101

Case	Speed Limit (km/h)	Deflection Angle (degree)	e (%)	Actual Curve Radius (m)	Minimum Curve Radius (m)	Design Type	Operating Speed[1] (km/h)
1	80	90	0	71	363	Below-minimum	50
2	80	79	0	46	363	Below-minimum	40
3	80	45	0	76	363	Below-minimum	50
4	80	38	0	58	363	Below-minimum	56
5	80	36	0	76	363	Below-minimum	51
6	80	112	0	76	363	Below-minimum	53

NOTE: [1] predicted operating speed at the middle of horizontal curve.

The researcher generated speed profiles using the prediction model for the operating speeds at the middle of curves and the polynomial model, considering acceleration/deceleration. Then, those profiles were matched with the rates of fuel consumption and emissions in the 23 operating mode bins. On the selected curves, there were speed reductions of up to 40 km/h according to the speed prediction model (Table 7.13). For reference, there was no speed reduction on the curves with the minimum design standard radiuses. Table 7.14 provides the EMFs comparing the actual conditions with the hypothetical conditions that the curves were designed with the minimum standard radiuses. In general, the ratios were greater than or equal to one. This means that the design vehicle (i.e., the passenger car) consumed more fuel and produced more emissions on the curves with the below-minimum standard scenario. Particularly, about two times more $PM_{2.5}$ was emitted on the curves because of higher rates on the operating mode bins of #29 and #30. The results significantly changed whether or not the mode bins of #29 and #30 were included in the profiles.

Table 7.14 EMFs of fuel consumption and emissions for selected horizontal curves

Case	Fuel Consumption	CO_2	NO_x	CO	HC	$PM_{2.5}$
1	1.10	1.10	1.18	1.15	1.22	2.21
2	1.11	1.11	1.19	1.16	1.27	2.51
3	1.16	1.16	1.26	1.23	1.32	2.62
4	1.14	1.14	1.22	1.18	1.25	2.24
5	1.19	1.19	1.31	1.27	1.36	2.78
6	1.02	1.02	1.04	1.02	1.07	1.82

NOTE: the base condition reflects curves that are designed with the minimum standards.

7.5.1 Benefit-Cost Analysis

For the horizontal curves, the researcher conducted a benefit-cost analysis when the horizontal curves were designed with the minimum standards as documented in the GreenBook (AASHTO, 2004) versus the existing design (i.e., the below-minimum standard values). The assumptions and unit values for fuel, emissions, and travel time were based on the ones used in the benefit-cost analysis for the vertical grades, unless specified.

When a horizontal curve is designed using the minimum standard relative to the actual below-standard curve radius, it increases a length of the highway alignment. The longer length causes additional construction cost. According to the WSDOT[11], the construction

---

[11] http://www.wsdot.wa.gov/biz/construction/constructioncosts.cfm

cost per highway lane-mile was $1.45 million in 2002. In the study, the cost was adjusted to $1.75 million in year 2010 dollars using the conversion factor[12]. In addition, the cost for highway operating and maintenance due to the increased length of the highway alignment was considered; the cost was dependent on traffic volume and segment length (AASHTO, 2010). For the selected cases, the curve design using the minimum standard relative to actually below-designed curve caused addition construction costs up to about $250,000 (Table 7.15). However, the curve design by the minimum design standard radius reduced the costs from vehicle operation such as fuel, emissions, and travel time.

Table 7.15 Benefits and costs on horizontal curves in 2000 dollars (10% truck)

Case	Cost[1,2]	Operating Cost[1,3]	AADT[4] (veh)	Fuel Saving[1]	Societal & Health[1]	Travel Time Saving[1]	Benefit-cost Ratios		
							Design Period		
							10-Yr	20-Yr	30-Yr
1	101,260	200	1,900	11,825	2,411	44,992	3.80	7.85	12.22
2	224,514	444	1,900	12,571	2,694	52,491	1.46	3.53	5.73
3	206,439	408	1,900	5,237	836	52,491	1.30	3.24	5.24
4	246,290	487	1,900	8,944	1,638	37,494	0.58	1.90	3.27
5	56,836	112	1,900	12,826	2,425	52,491	8.80	17.10	26.07
6	177,695	481	2,600	11,564	2,583	30,784	1.06	2.76	4.58

NOTE: [1] estimation in the year of 2010; [2] additional highway construction cost; [3] highway operating and maintenance cost; [4] sourced from the WSDOT (2011b).

Based on the previous analysis of fuel consumption, vehicles consumed less fuel on the horizontal curve designed by the minimum-design standard radius relative to actual below-standard curve because vehicles could travel without a speed reduction on the curve. The annual fuel consumption was estimated with fuel consumption per vehicle (i.e., a single passenger car and HDDT) and annual traffic volume. The estimated fuel

---

[12] http://oregonstate.edu/cla/polisci/download-conversion-factors

consumption was subtracted from one from the actual below-standard curves, and then the differences were monetized based on the unit price of fuel. The cost savings from the reduced fuel consumption are presented in Table 7.15. Similar to the fuel cost savings, the reduced emissions on the curves with the minimum standards were also beneficial to the cost related to the societal and health issue. The reduced amount of emissions, CO_2, NO_x, and $PM_{2.5}$, was monetized by the unit values for each emission, and the savings on the societal and health costs are listed in Table 7.15. In terms of travel time cost, vehicles could travel with less travel time on the curves designed by the minimum-standards than the actual below-standard curves because no speed reduction on the curves could be observed. Related to the reduced travel time, the amount of cost saving was estimated under the assumption that the values of travel time per hour for the passenger car and HDDT were $20.34[13] with a vehicle occupancy factor of 1.25 and $22.91, respectively. The travel time cost was monetized by the multiplication with annual traffic volume and the unit price of travel time.

Finally, the cost savings (i.e., benefits) from the reduced fuel consumption and travel time and improved societal and health and the increased construction costs due to the longer highway alignment for each case are presented in Table 7.15. Also, the expected benefits and costs for 10-year, 20-year, and 30-year design periods were adjusted to the value in year 2010 dollars. As described in Case 5, the benefits resulted from the improved curve design exceeded the cost for a 10-year design period; the benefits were greater than eight times of the cost. Generally, the benefits surpassed the cost for all cases, except for one case, in a 10-year design period. In addition, in the results with various truck proportions of total traffic volumes, the benefit-cost ratios increased with higher truck proportions (Appendix K).

---

[13] http://mobility.tamu.edu/ums/report/appendix_a.pdf

7.6 Chapter Summary

In this chapter, the researcher described how the methodology documented in Chapter III and IV can be utilized using real data. The quantification process was done using both the actual design conditions and the hypothetical conditions with the recommended minimum standards. The comparisons of fuel consumption and emissions between two conditions were represented by EMFs. In addition, this chapter presents the benefits and costs. The benefits were represented by the cost savings in relation to fuel consumption, emissions, societal and health issue, and travel time, and the costs were related to construction and maintenance costs. The benefits and costs were estimated for 10-year, 20-year, and 30-year design periods.

In contrast to actual design conditions causing greater than 10 km/h speed reductions represented by the fair/poor design, the improved design conditions (i.e., the good design) preventing speed reductions of greater than 10 km/h could have saved fuel and reduced emissions. In terms of a benefit-cost analysis, the benefits from the design improvement at the half of the selected actual vertical grades surpassed the cost for a 30-year design period.

In terms of vertical crest curves, there are the curves on US 101 were built with less than the recommended minimum standard K-values in the guidebook. On these curves, vehicles consumed more fuel and produced more emissions. The primary reason for those outcomes can be explained via shorter length of vertical curves with smaller K-values. The shorter length made the curves sharper, and this increased vehicle engine loads. In addition, the benefits from the vertical curve design with the minimum standards at the selected cases exceeded the cost for a 30-year design period.

According to the speed prediction model on horizontal curves, the design vehicle decelerated at the middle of the curve and then accelerated to recover original tangent speed. When the radius was smaller than the recommended minimum standard, the operating speed at the middle of the curve was smaller than the initial tangent speed. For the environmental evaluation of the actual horizontal curves, the adverse impacts on fuel consumption and emissions increased with smaller radius than the minimum standard. In the benefit-cost analysis, the monetized benefits surpassed the increased construction cost for a 10-year design period for most selected cases. The next chapter presents a summary of the research and a discussion on the environmental evaluation.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The objectives of this research were to provide the evaluation tools and guidelines to quantify the impacts of various highway geometric design features on fuel consumption and emissions using the vehicle emission model and speed profile methods. The quantified results were compared with those from the minimum standard design conditions. This chapter presents a summary of this research, which includes a discussion of the results. It ends with recommendations for further research.

8.1 Summary and Discussion

There are several negative externalities related to transportation networks. Among them, we find that transportation networks create a significant amount of pollution. Environmentally-friendly highway geometric design should be considered as one of the strategies to reduce these adverse impacts, along with vehicle fuel efficiency increases and the development of alternative fuels. However, environmentally-friendly designs cannot be fully utilized without any information regarding the quantitative environmental impacts of highway geometric design features on fuel consumption and emissions.

For the quantitative environmental impacts that can be utilized as a part of the highway design process, the researcher analyzed fuel consumption and emissions on various highway geometric design conditions related to vertical grades as well as horizontal and vertical crest curves. The speed profiles in relation to the various conditions were generated based on: 1) the vehicle dynamic model and linear/non-linear decreasing acceleration models for vertical grade design and 2) the speed prediction models and polynomial model for horizontal and vertical crest curves. The generated speed profiles were matched with the rates of fuel consumption and emissions from the most recently developed EPA MOVES which categorizes a vehicle running exhaust process into the 23 operating mode bins; then fuel consumption and emissions per second were aggregated during a trip.

The extracted fuel consumption and emissions rates were based on VSPs and speed values. These rates linearly or exponentially increased along with their VSPs. Higher engine loads represented by higher VSPs needed more fuel as an input to the combustion process and consequently produced more emissions as an output. VSP is associated with several factors such as vehicle speed, acceleration/deceleration, and grades within the same vehicle type. Each factor had its own impact on fuel consumption and emissions; significantly slow/fast speeds, acceleration/deceleration driving patterns, and steeper grades were associated with adversely environmental impacts. However, it is difficult to predict the impacts when the factors are intertwined. For example, the design vehicle consumed less fuel not only when retaining a constant speed without any acceleration/deceleration, but also when excessive speed (greater than the optimum speed) decreased due to the design of a sharp curve radius. Because of relatively low speeds resulting from deceleration on the sharp curve, the design vehicle consumed less fuel than if it were to maintain a constant excessive speed (without deceleration/acceleration) on the curve.

In the following section, various outputs of fuel consumption and emissions are summarized and discussed, along with vehicle travel-related factors and the geometric design of vertical grades and vertical crest and horizontal curves.

8.1.1 Vertical Grades

Regarding the design of highway vertical grades, the results were based on three key variables: initial speeds, grades, and critical length of grades. The amount of fuel consumption and emissions increased with initial speeds on the 6,000-m graded segment. According to Barth and Boriboonsomsin (2008), there is a bowl-shaped relationship between CO_2 and speed; the amount of CO_2 per trip decreases up to a steady-state speed, around 70 to 80 km/h, and then increases when the vehicle travels at a higher speed. At lower constant speeds, a vehicle has lower emission rates because of lower VSPs, but longer travel time can offset the reduction from the lower emission rates. At higher constant speeds, shorter travel time can offset the higher emission rates from higher VSPs. Finally, the total amount of fuel consumed and emissions produced by trips with lower/higher constant speeds than the optimum speed range (70 to 80 km/h) were higher than those by trips with the optimum speeds. The researcher, however, found that less fuel was consumed and less pollution was produced with increasing initial speeds. These different results could be explained based on the assumption that the design vehicle (a typical heavy-duty truck) used maximum power on vertical grades. Under this assumption, the vehicle speeds changed on the grades until reaching crawl speeds, depending on the length of grades. However, Barth and Boriboonsomsin (2008) assumed that a vehicle remained in the steady-state speed condition.

The researcher generated speed profiles in relation to the vertical grade design. According to the speed profiles, speed reductions were dependent on initial speeds, grades, and/or length of grades. When the design vehicle started traveling with an initial speed lower than a crawl speed, the vehicle could accelerate up to the crawl speed due to available tractive force. However, the vehicle decelerated to the crawl speed due to grade resistance forces when starting with an initial speed higher than the crawl speed. The positive impact of high speeds on VSPs was neutralized by the negative impact of deceleration on VSPs[14]. In addition, shorter travel times resulting from higher initial speeds assisted in saving fuel and reducing emissions during the trip. According to the EMFs related to initial speeds, the design vehicle (i.e., a typical heavy duty truck) consumed 14 percent more fuel and produced up to 15 percent more emissions with the

---

[14] Based on Equation 2.1, deceleration, negative of acceleration, reduced VSP value.

initial speed of 110 km/h than 10 km/h. Higher initial speeds in the grade design would be beneficial in reducing fuel consumption and emissions.

In terms of the grade variable, the impact was more distinctive than that from the initial speed. Steeper grades caused more speed reductions and increased travel times on the vertical grade segments. The truck consumed more than six times fuel on a nine-percent grade than a flat grade during the trip. In addition, emissions have a similar trend with fuel consumption. The reduced traveling speeds and increased travel times increased fuel consumption and emissions during the trip on the steep grades. In other words, steeper grades caused more fuel to be consumed and emissions to be produced due to high vehicle engine loads and longer travel times. The design guidebook (i.e., GreenBook, 2004) specifies that most passenger cars can travel vertical grade highways as steep as four to five percent without significant speed reduction. However, it is clear that steep grades have adverse environmental impacts on the vehicle movement.

For the critical length of variable grades, the researcher used the concept of design categories of good, fair, and poor. These categories were defined based on speed reductions on grades. In the GreenBook (AASHTO, 2004), 15 km/h is considered a marginal speed reduction; highway grades or length of graded segments should be less than those that incur a 15-km/h reduction in speed of trucks below the average running speed of the remaining traffic. When a speed reduction of greater than 15 km/h is inevitable, highway designers/engineers should consider a climbing lane on a two-lane highway. In lieu of the 15-km/h guideline, the researcher applied consistency evaluation criteria introduced by Lamm et al. (1988), that measures the disparity between highway design speed and operating speed and then utilizes this disparity in the highway safety evaluation. According to the EMFs related to the critical length of grades, when the fair design criteria was applied for the grade design, the fuel consumption and emissions increased because of extended travel time resulting from the speed reduction; the design vehicle consumed fuel and produced emissions of up to 85 percent more in the fair design than the good design. The poor design criteria had even more severe results. Fuel consumption and emissions in the poor design increased by a factor of up to six relative to the good design criteria, due to significantly longer travel time. Good grade design preventing significant speed reduction improved not only highway safety but also reduced the degree of adverse environmental impacts.

The researcher also conducted a benefit-cost analysis in terms of the improvement of grade design. Although the improved grade design, controlling a speed reduction by less than 10 km/h, caused additional construction cost, the benefits were also incurred. The design improvement could lead to reductions in the (direct, indirect and societal) costs related to 1) vehicle fuel, 2) societal and public health, and 3) travel time. For a 30-year design period, the benefits exceeded the cost at the half of selected actual vertical grades. In other words, the monetary savings surpassed the construction cost resulted from additional earthwork. However, the design improvements on the other half of the segments were not beneficial for the design period because of much additional construction costs. These costs for additional earthworks were estimated without a balance between fill and cut volumes. When considering a cost reduction throughout a construction method minimizing earthwork or operation during a longer design period, the design improvements reducing the degree of speed reduction on the vertical grades might be beneficial economically and environmentally.

8.1.2 Vertical Crest Curves

There were two key factors that affected fuel consumption and emissions during the trips on vertical crest curves: speed reduction by the rate of vertical curvature (K) and the flattening curvature resulting from the K-value. According to the speed prediction model, the operating speed in the middle of the vertical crest curve was reduced by the K-value. However, the researcher did not find an important reduction in speed in the middle of the curve under the scenarios evaluated. Less than three km/h speed reduction was found on the curves designed with only 50-percent and 40-percent reduced K-values. Alternately, deceleration and acceleration did not have a great impact on environmental analyses because there was little difference between approaching tangent speeds and operating speeds on the curve. Rather than the K-value influencing the speed reduction, it was the curvature adjustment by the K-value that actually affected environmental analyses. Greater K-values allowed for longer vertical curvature length, and the longer length allowed for gradual flattening changes on the curves. According to Figures 4.3 (a) and 4.4, a 50-percent increase in the K-value reduced the grades changes on the curve. As a result, greater K-value played a role in making the vertical curve flatter, and the design vehicle respectively consumed and produced 10 percent less fuel and CO_2. For other emissions analyzed, there were also reductions by up to 31 percent. Flattening curvatures resulted in reduced fuel consumption and emissions production from the trip on the vertical crest curve. In addition, from the application of environmental analysis on the selected actual vertical curves, this study showed that the actual vertical curve designed with smaller K-values (the below-minimum standard design) increased fuel consumption and emissions by up to nine percent; the below-minimum standard K-values provided sharper changes on the curves than the minimum standards (Figure 4.3 (a)). The increased vehicle engine power on the sharpened curves led to more fuel usage and emissions. In the benefit-cost analysis, the monetized benefits from the recommended minimum standards exceeded the additional construction cost for a 30-year design period for all selected cases.

8.1.3 Horizontal Curves

There were several factors affecting environmental analyses on horizontal curves: curve radius, the 85th percentile tangent speed, the operating speed at the middle of the curve, and the acceleration/deceleration between the tangent speed and the operating speed. The researcher predicted the vehicle speeds at the middle of the curves under different design conditions, i.e. tangent speeds and curve radiuses. There were speed reductions of up to 15 km/h in the middle of the curve if it was designed with a radius less than that documented in the GreenBook (AASHTO, 2004). In the case of the 85th percentile tangent speed of 70 km/h, the design vehicle consumed 12 percent more fuel on the curve with a radius less than 50 percent of the minimum standard; up to 27 percent more emissions were produced. Acceleration to recover the original tangent speed from the reduced operating speed played a significant role, offsetting the savings from reduced engine loads due to the lower operating speed. When the curves were designed with radii greater than the minimum standards, there was no change in fuel consumption and emissions because there was no speed reduction. For reference, travel times were not significantly different in the comparison among various radii of the curves.

However, the results from the tangent speeds of 90 and 110 km/h differed with the previous results. Despite the acceleration related to the speed recovering activity within the reduced curves, the least fuel was consumed and less pollution was produced. These results may be related to higher tangent speeds. According to Barth and Boriboonsomsin (2008), the amount of CO_2 emitted during a trip was minimal when speeds stayed in the range of 70 to 80 km/h. The reduced speeds due to sharp radius on the curve played a role in saving fuel and reducing emissions. On the other hand, speeds of 90 and 110 km/h without any speed reduction on those curves with radius designs greater than or equal to the minimum standards actually increased overall fuel consumption and emissions. In terms of CO and HC, the emissions were greater on the curve with reduced radius than without a reduction in radius. CO and HC have sensitive and positive characteristics to acceleration and deceleration, respectively. Thus, the emissions were greater when driving on a curve where acceleration and deceleration occurs.

For reference, the benefit-cost analysis based on the selected horizontal curves from US 101 confirmed that the curve design with the recommended minimum standards in the guidebook contributed in reducing fuel consumption, emissions, and travel time, although the design increased the construction cost by longer length of highway alignment. The benefits surpassed the cost for a 20-year design period at the selected actual vertical curves.

8.1.4 Application in the Highway Design Process

Based on the objectives providing the tools and guidelines for quantitative environmental evaluation, this research described how the tools and guidelines could be incorporated into the TxDOT highway development process. During the preliminary design stage, the basic features and preliminary criteria for a project design are established and evaluated in terms of safety, cost, operational and environmental impacts of the proposed and alternative designs. When the quantitative environmental evaluation is applied for various design conditions related to the selected highway geometric design features, the evaluations will provide the objective guidelines necessary for making engineering and environmental decisions related to the design conditions. More importantly, the evaluations will be critical on the design features that are applied for a design exception.

In this research, the quantitative environmental evaluations were conducted for the highway design features of vertical grades and horizontal and vertical crest curves. To apply the evaluation for the design features that are not analyzed in this research, the step-by-step procedures are described. The application of the procedures will allow highway designer and engineers to utilize quantitative environmental evaluations on various alternative design conditions and features.

In summary, this research has demonstrated that:

1. Vertical grade design with higher initial speed reduced fuel consumption and emissions during a trip by a typical heavy truck on the grades because of shorter travel times.

2. Grades have more distinctive impacts than the initial speeds. Steeper grades cause significantly increased fuel consumption and emissions due to high vehicle engine loads and longer travel time.
3. On higher grades, the environmental impacts of the length of vertical grade segment that causes a speed reduction of greater than 20 km/h were much more severe than the design that caused speed reduction of less than 20 km/h.
4. On the vertical curves, the K-value affected the grade differential. Greater K-value flattened the curvatures between two tangent grades, and reduced fuel consumption and emissions.
5. When an approach tangent speed was within the range of 70 to 80 km/h, a curve with a radius smaller than the minimum standard had adverse environmental impacts on the horizontal curve design due to acceleration/deceleration. With high tangent speeds, such as 90 or 110 km/h, although the curve design with a reduced radius little helped reduce the impacts on fuel consumption and CO_2; however, the design increased the amount of emissions, CO and HC. In general, the design with the minimum standard radius alleviated adverse environmental impacts.
6. Highway design of 1) the vertical grades controlling a speed reduction less than 10 km/h, 2) the vertical curve with flattening curvature, and 3) the horizontal curve with the minimum standards as documented in the guidebook can be environmentally and economically beneficial throughout the life of the highway.
7. The proposed tools and guidelines for the quantitative environmental evaluation can be utilized at the preliminary design and PS&E development stages in the TxDOT highway development process.

8.2 Recommendations

Based on the findings from this research, the following recommendations can be suggested to the design for vertical grades and vertical crest and horizontal curves:

1. On roadway vertical grades, a vehicle has to start traveling with an initial speed close to the designated design speed on the vertical grade segment. A vehicle can travel on the grades with an initial speed less than the design speed due to restricted conditions on the segment, such as sharp horizontal/vertical curves, insufficient accelerating distance to reach the design speed, or driver sight limitations. These types of conditions reduce vehicle speeds. A vehicle traveling with a lower initial speed than the designated design speed will have increased fuel consumption and emissions on the grades.
2. The length of vertical grade segment should be shorter than the critical length of grades, or the vertical grade segment should be designed with a length incurring a speed reduction of less than 20 km/h. A grade design incurring a speed reduction of greater than 20 km/h has more severe environmental impacts than those incurring less than 20 km/h. When there is a speed reduction of greater than 20 km/h on the vertical grade segment, the design truck consumes fuel and produces the emissions by as much as six times more than ones from less than 20 km/h speed reduction under the simulated conditions in this research.
3. A vertical curve should be designed so that the rate of vertical curvature is greater than or equal to the minimum standard in design handbooks. A longer curvature allows the curve to be flatter and reduces vehicle engine loads. In turn, the vehicle consumes less fuel and produces less pollution. When the rate of vertical curvature is increased by 1.5 times of the minimum standard, the emissions can be reduced by as much as 30 percent under the simulated conditions in this research.
4. A horizontal curve should be designed using the minimum standard radius in the guidebook. When the design speed was 70 km/h, the design vehicle consumed 12 percent of more fuel on the curve of a 50-percent reduced radius than the minimum standard because of the deceleration/acceleration driving pattern on the curve. A curve design causing disparity between designated design speed and actual operating speed cannot be recommended. For reference, a horizontal curve

with a longer radius than the minimum standard does not mitigate the adverse environmental impacts.

The researcher has quantitatively evaluated the environmental impacts on roadway vertical grades and horizontal and vertical crest curves. Grades and curves are inevitable highway design features unless the landscape is uniform. From the quantified results of fuel consumption and emissions related to various geometric design conditions, this research provides the guidelines and tools to quantify environmental impacts that highway designers and engineers can use as part of the highway design process. The proposed guidelines and tools can be incorporated into the four stages: the preliminary design and PS&E development. More importantly, in the preliminary design stage, the quantitative evaluations among several alternative design conditions will be useful for the determination the environmental impacts and cost-effectiveness. In addition, the guidelines and tools proposed in this research can reduce the uncertainty associated with the engineering judgment for environmentally-friendly highway design. Finally, this research shows that adverse environmental impacts from vehicle movements can be controlled and reduced throughout environmentally conscious highway design.

8.3 Future Research

The scope of this research was limited to the grades and curves design features. Moreover, this research could not include all possible design criteria and conditions; there exist many other design criteria and available design conditions relative to the conditions analyzed in this research. Future research should include an environmental impact analysis on other design features, such as vertical sag curves, intersections, and interchanges. Especially, since intersections and interchanges are the sites at which two or more highways merge, often with high traffic volumes, the environmental evaluation on various related design features will play an important role in environmentally-friendly highway design.

According to various geometric design conditions, this research has quantified the environmental impacts through the calculation of more or less complex mathematical equations from the models for predicting operating speed and acceleration/deceleration, and the repetitive processing for the emission rates. This means that highway designers and engineers should use the same complex processes for the application of an environmental impact analysis on their selected design conditions. Furthermore, there is still uncertainty in engineering judgment on the quantitative environmental impacts in terms of non-geometric features that should be considered in the highway development process, such as traffic conditions, which include the composition between passenger cars and heavy duty trucks and weather conditions (e.g., air temperature). Beyond the limitations of this research, a systematic tool predicting fuel consumption and emissions in consideration of not only selected geometric design conditions but also non-geometric design conditions will be beneficial; highway designers and engineers can predict the environmental impact based on the selected geometric/non-geometric design conditions and compare that impact with the other design conditions without any complex calculation and repetitive processing. This system can be utilized based on the database, reflecting many possible design conditions. Ultimately, the development of this system will be a main objective in future research. By providing the key methods and processes for the environmental evaluation, this study will play an important role in that future research.

In summary, the following contexts will be included in the environmental impact analysis of the future research beyond the scope of this research:

1. Highway geometric design features/criteria on two-lane highways that are not considered in this research, such as combinations of horizontal and vertical alignment, intersection, or interchange
2. Highway geometric design features/criteria in urban/suburban arterials and freeway

3. Vehicles of different types, weights, model years, or powers, except for the design vehicles that were used in this research; vehicles have different environmental impacts in the highway design due to their own operating characteristics.
4. Weather conditions; a unique weather condition in the project area, like snowy or hot weather, may have different environmental impacts in the highway development process.
5. Driver performance, such as drivers' aggressiveness or aging.
6. Environmental impacts prediction system; a systematic tool predicting fuel consumption and emissions merely by inputting the selected conditions into the system.

REFERENCES

AASHTO, 1994. GreenBook-A Policy on Geometric Design of Highways and Streets (3rd ed.). American Association of State and Highway Transportation Officials, Washington, D.C.

AASHTO, 2004. GreenBook-A Policy on Geometric Design of Highways and Streets (5th ed.). American Association of State and Highway Transportation Officials, Washington, D.C.

AASHTO, 2010. User and Non-user Benefits Analysis for Highways. American Association of State and Highway Transportation Officials, Washington, D.C.

Abdul-Mawjoud, A., Sofia, G., 2008. Development of models for predicting speed on horizontal curves for two-lane rural highways. The Arabian Journal for Science and Engineering 33 (2B), 365-377.

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. Journal of Transportation Engineering 128 (2), 182-190.

Akcelik, R., Besley, M., 2001. Acceleration and deceleration models. 23rd Conference of Australian Institute of Transportation Research, Monash University, Melbourne, Australia.

Akcelik, R., Biggs, D. C., 1987. Acceleration profile models for vehicles in road traffic. Transportation Science 21 (1), 36-54.

Alaska, 2009. Greenhouse Gas Inventory and Forecast and Policy Recommendations Addressing Greenhouse Gas Reduction in Alaska. Alaska Climate Change Strategy Mitigation Advisory Group, Alaska.

Barth, M., & Boriboonsomsin, K., 2008. Real-world carbon dioxide impacts of traffic congestion. Transportation Research Record 2058, 163-171.

Bester, C. J., 2000. Truck speed profiles. Transportation Research Record 1701, 110-115.

Bonneson, J. A., Pratt, M. P., 2009. Model for predicting speed along horizontal curves on two-lane highways. Transportation Research Record 2092, 19-27.

Bonneson, J., Zimmerman, K., Fitzpatrick, K., 2006. Interim Roadway Safety Design Workbook. Report No. FHWA/TX-06/0-4703-P4, Texas Transportation Institute, College Station, Texas.

Boriboonsomsin, K., Barth, M., 2009. Impacts of road grade on fuel consumption and carbon dioxide emissions evidenced by use of advanced navigation systems. Journal of the Transportation Research Board 2139, 21-30.

Burris, M., 2011. Seattle/LWC Urban Partnership Agreement National Evaluation: Cost Benefit Analysis Test Plan, Texas Transportation Institute, College Station, Texas.

Cappiello, A., Chabini, I., Nam, E. K., Lue, A., Abou Zeid, M., 2002. A statistical model of vehicle emissions and fuel consumption. The IEEE 5th International Conference 2002, 801-809.

Chowdhury, M. A., Warren, D. L., Bissell, H., 1991. Analysis of advisory speed setting criteria. Public Roads 55 (3), 65-71.

Deakin, E., 2001. Sustainable Development and Sustainable Transportation: Strategies for Economic Prosperity, Environmental Quality, and Equity. University of California at Berkeley, California.

El-Shawarby, I., Ahn, K., Rakha, H., 2005. Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions. Transportation Research Part D 10, 13-30.

EPA, 1994. Air Toxics from Motor Vehicles. Reprot No. EPA-400-F-92-004, EPA, Washington, D.C. Retrieved September 2011 from http://www.epa.gov/oms/toxics.htm#b.

EPA, 2010a. 2010 U.S. Greenhouse Gas Inventory Report. EPA, Washington, D.C. Retrieved August 2010 from http://www.epa.gov/climatechange/emissions/index.html.

EPA, 2010b. User Guide for MOVES2010a. Report No. EPA-420-B-10-036, EPA, Washington, D.C. Retrieved October 2010 from http://www.epa.gov/oms/models/moves/movesback.htm.

Ericsson, E., Larsson, H., Brundell-Freij, K., 2006. Optimizing route choice for lowest fuel consumption - potential effects of a new driver support tool. Transportation Research Part C 14, 369-383.

FHWA, 2010. Key Highway Geometric Design Features. Federal Highway Administration. Retrieved November 2010 from http://www.fhwa.dot.gov/ design/t504028.cfm.

Fitzpatrick, K., Collins, J. M., 2000. Speed-profile model for two-lane rural highways. Transportation Research Record 1737, 42-49.

GAO, 2008. Physical Infrastructure: Challenges and Investment Options for the Nation's Infrastructure. Report No. GAO-08-763T, U.S. Government Accountability Office, Washington, D.C.

Hallmark, S. L., Guensler, R., Fommunung, I., 2002. Characterizing on-road variables that affect passenger vehicle modal operation. Transportation Research Part D 7, 81-98.

Islam, M. N., Seneviratne, P. N., 1994. Evaluation of design consistency of two-lane rural highways. Institute of Transportation Systems Journal, 28-31.

Kean, A. J., Harley, R. A., Kendall, G. R., 2003. Effects of vehicle speed and engine load on motor vehicle emissions. Environmental Science & Technology 37(17), 3739-3746.

Kim, J. J., Smorodinsky, S., Lipsett, M., Singer, B. C., Hodgson, A. T., Ostro1, B., 2004. Traffic-related air pollution near busy roads: the East Bay children’s respiratory health study. The American Thoracic Society 170 (5), 550-553.

Koupal, J., 2003. Design and Implementation of MOVES: EPA’s New Generation Mobile Source Emission Model. Presented at 2003 International Emission Inventory Conference. Retrieved September 2010 from http://www.epa.gov/oms /models/moves/movesback.htm.

Koupal, J., Michaels, H., Cumberworth, M., Bailey, C., Brzezinski, D., 2002. EPA's Plan for MOVES: A Comprehensive Mobile Source Emissions Model. EPA, Washington, D.C. Retrieved August 2010 from http://www.epa.gov/otaq/models /moves/index.htm.

Krammes, R. A., 2000. Design speed and operating speed in rural highway alignment design. Transportation Research Record 1701, 68-75.

Lamm, R., Psarianos, B., Mailaender, T., Choueiri, M., Heger, R., Steyer, R., 1999. Highway Design and Traffic Safety Engineering Handbook. McGraw-Hill, New York.

Lan, C.-J., Menendez, M., 2003. Truck speed profile models for critical length of grade. Journal of Transportation Engineering 129 (4), 408-419.

Maine, 2011. Auto Emissions Dangers. Retrieved September 2011 from http://www.maine.gov/dep/air/lev4me/effects.htm.

Mannering, F. L., Washburn, S. S., Kilareski, W. P., 2009. Principles of Highway Engineering and Traffic Analysis. John Wiley & Sons, New Jersey.

Middleton, N., Yiallouros, P., Nicolaou, N., Kleanthous, S., Pipis, S., Zeniou, M., Demokritou, P., Koutrakis, P., 2010. Residential exposure to motor vehicle emissions and the risk of wheezing among 7-8 year-old schoolchildren: a city-wide cross-sectional study in Nicosia, Cyprus. Environmental Health 9 (28).

Misaghi, P., & Hassan, Y., 2005. Modeling operating speed and speed differential on two-lane rural roads. Journal of Transportation Engineering 131 (6), 408-417.

NHTSA, 2009. Final Regulatory Impact Analysis: Corporate Average Fuel Economy for MY 2011 Passenger Cars and Light Trucks, Office of Regulatory, Analysis and Evaluation, National Center for Statistics and Analysis, National Highway Transportation Safety Administration.

Park, S., & Rakha, H., 2006. Energy and environmental impacts of roadway grades. Transportation Research Record 1987, 148-160.

Qi, Y. G., Teng, H. H., Yu, L., 2004. Microscale emission models incorporating acceleration and deceleration. Journal of Transportation Engineering 130 (3), 348-359.

Rakha, H., Lucic, I., Demarchi, S. H., Setti, J. R., Van Aerde, M., 2001. Vehicle dynamics model for predicting maximum truck acceleration levels. Journal of Transportation Engineering 127 (5), 418-425.

Rakha, H., Snare, M., Dion, F., 2004. Vehicle dynamics model for estimating maxiumum light-duty vehicle acceleration levels. Transportation Research Record 1883, 40-49.

Schrank, D., Lomax, T., Eisele, B., 2011. Urban Mobility Report. Texas Transportation Institute, College Station, Texas. Retrieved October 2011 from http://tti.tamu.edu/documents/mobility-report-2011.pdf.

Servin, O., Boriboonsomsin, K., Barth, M., 2006. An energy and emission impact evaluation of intelligent speed adaptation. The IEEE Intelligent Transportation Systems Conference 2006, 1257-1262.

Song, G., Yu, L., 2009. Estimation of fuel efficiency of road traffic by characterization of vehicle-specific power and speed based on floating car data. Transportation Research Record 2139, 11-20.

Stevanovic, A., Stevanovic, J., Zhang, K., Batterman, S., 2009. Optimizing traffic control to reduce fuel consumption and vehicular emissions: integrated approach with VISSIM, CHEM, and VISGAOST. Transportation Research Record 2128, 105-113.

TxDOT, 2009. Project Development Process Manual. Texas Department of Transportation, Austin, Texas.

TxDOT, 2010. Roadway Design Manual. Texas Department of Transportation, Austin, Texas.

U.S. Energy Information Administration, 2011. Average Fuel Price of Washington in 2010, Washington, D. C. Retrieved June 2011 from www.eia.gov/dnav/pet /pet_pri_gnd_dcus_nus_a.htm.

U.S. House of Representatives Committee on Science and Technology, 2008. Sustainable, Energy Efficient Transportation Infrastructure. Science and Technology, Washington, D.C. Retrieved August 2010 from http://democrats.science.house.gov/Media/File/Commdocs/hearings/2008/Tech/24june/Hearing_Charter.pdf.

Wang, J., Dixon, K. K., Li, H., Ogle, J., 2005. Normal deceleration behavior of passenger vehicles at stop sign-controlled intersections evaluated with in-vehicle global positioning system data. Transportation Research Record 1937, 120-127.

Washington Department of Transportation (WSDOT), 2011a. WSDOT Construction Cost Trend. Retrieved June 2011 from http://www.wsdot.wa.gov/biz /construction /constructioncosts.cfm.

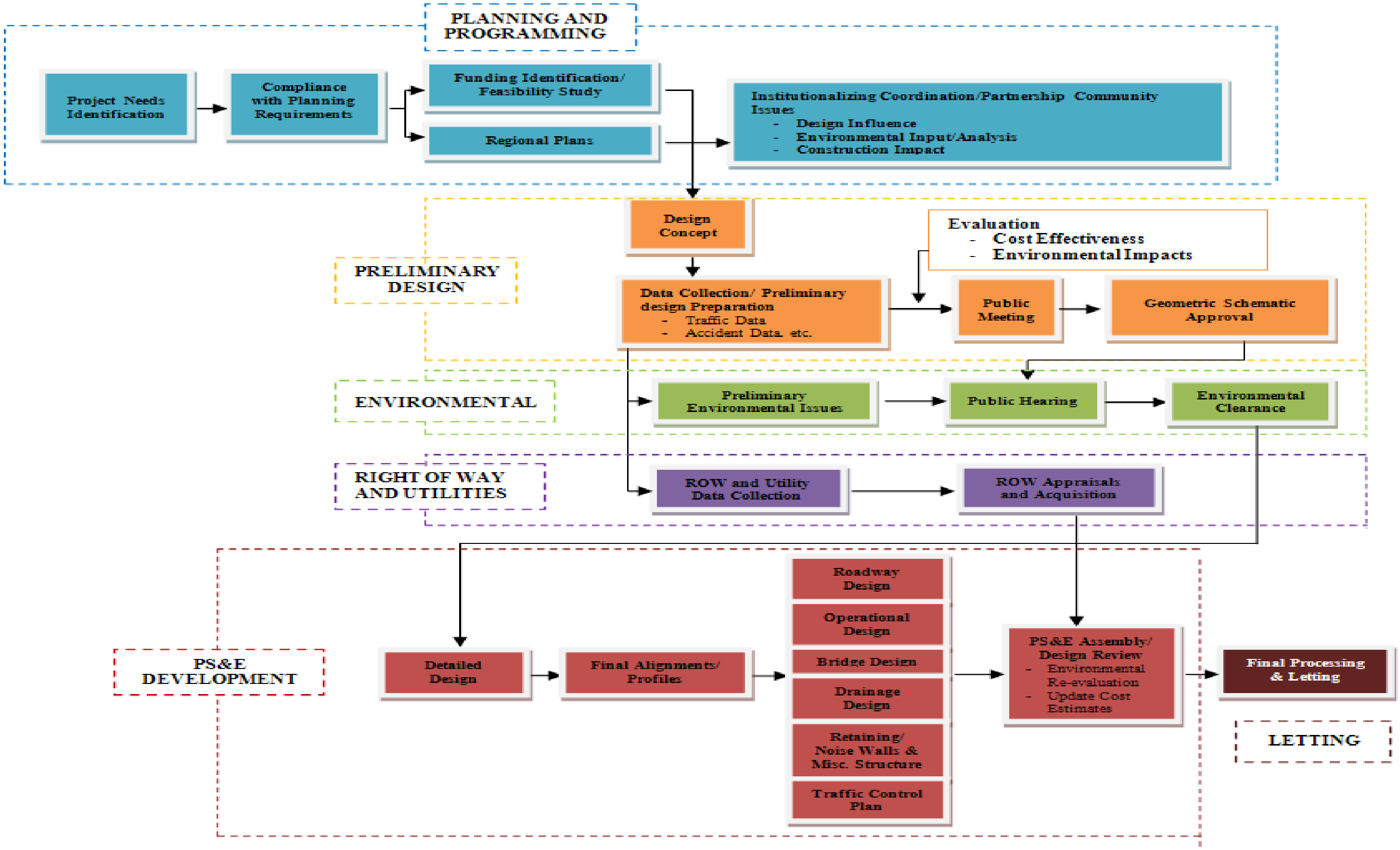
Washington Department of Transportation (WSDOT), 2011b. 2010 Annual Traffic Report. Retrieved June 2011 from http://www.wsdot.wa.gov/mapsdata/travel /pdf/Annual_Traffic_Report_2010.pdf.

Zhai, H., Frey, H. C., Rouphail, N. M., 2008. A vehicle specific power approach to speed- and facility-specific emissions estimates for diesel transit buses. Environmental Science & Technology 42 (21), 7985-7991.

Zhang, K., Frey, H. C., 2006. Road grade estimation for on-road vehicle emissions modeling using light detection and ranging data. Journal of the Air & Waste Management 56, 777-788.

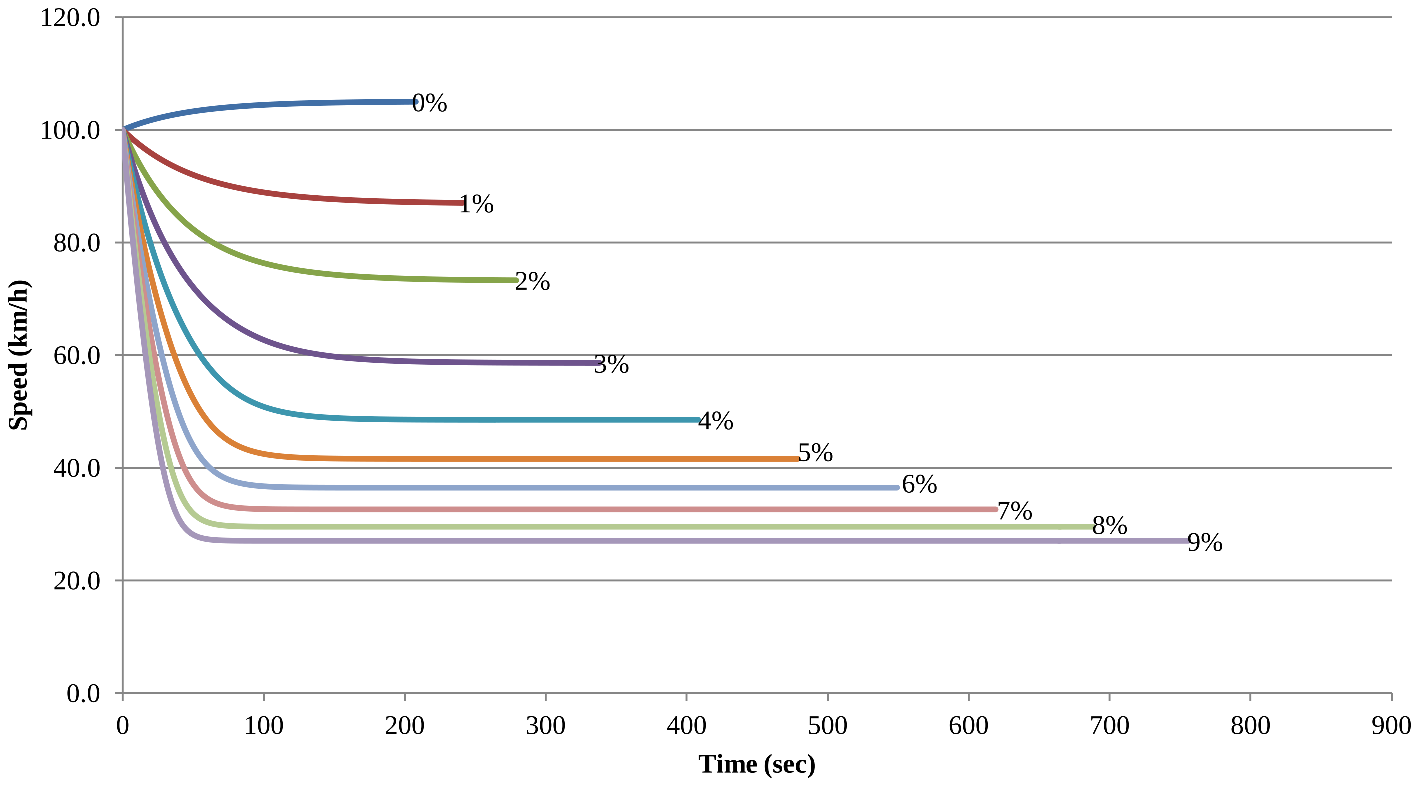
APPENDIX A

TXDOT PROJECT DEVELOPMENT PROCESS (source: TxDOT Project Development Process Manual, 2009)

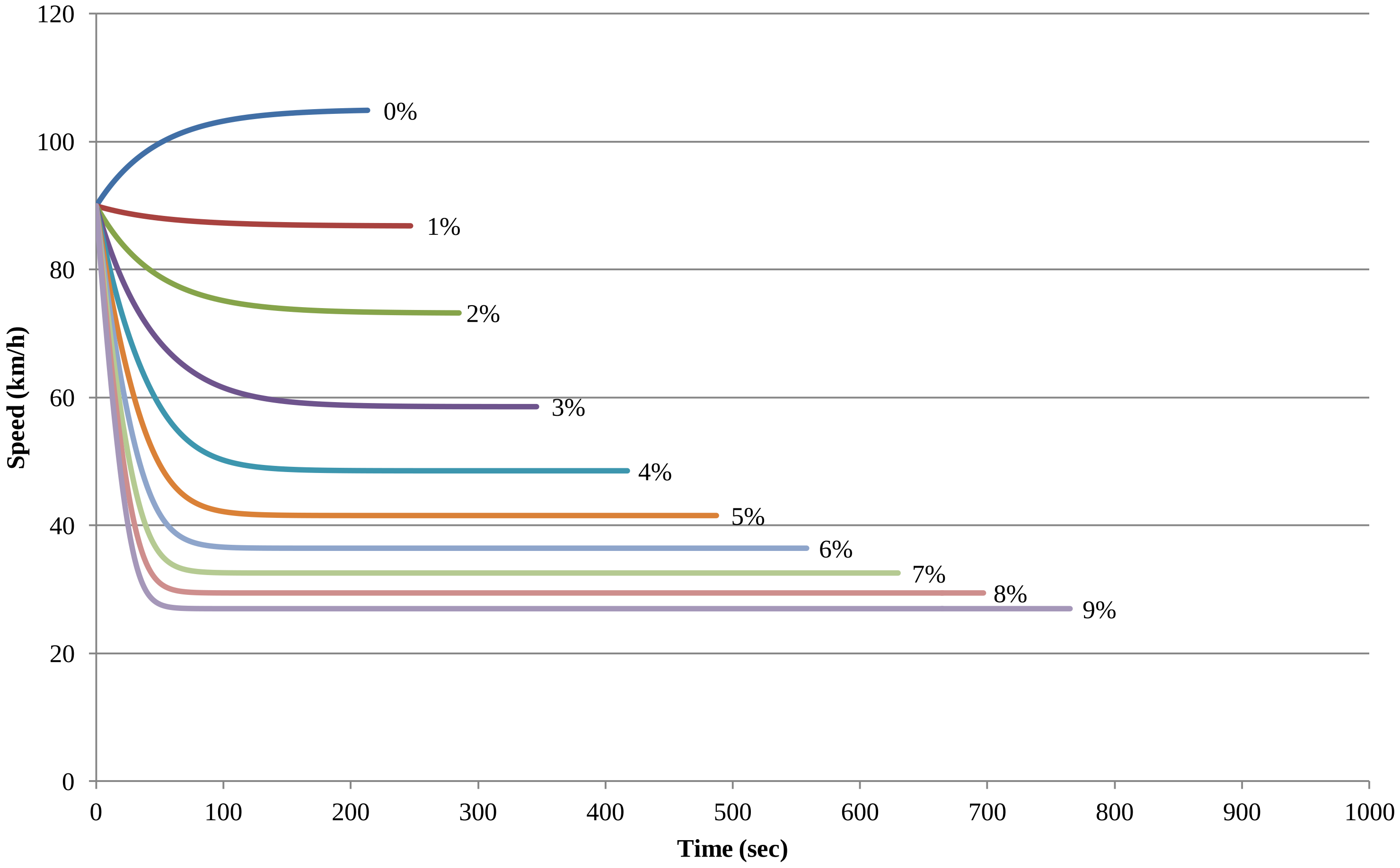


APPENDIX B

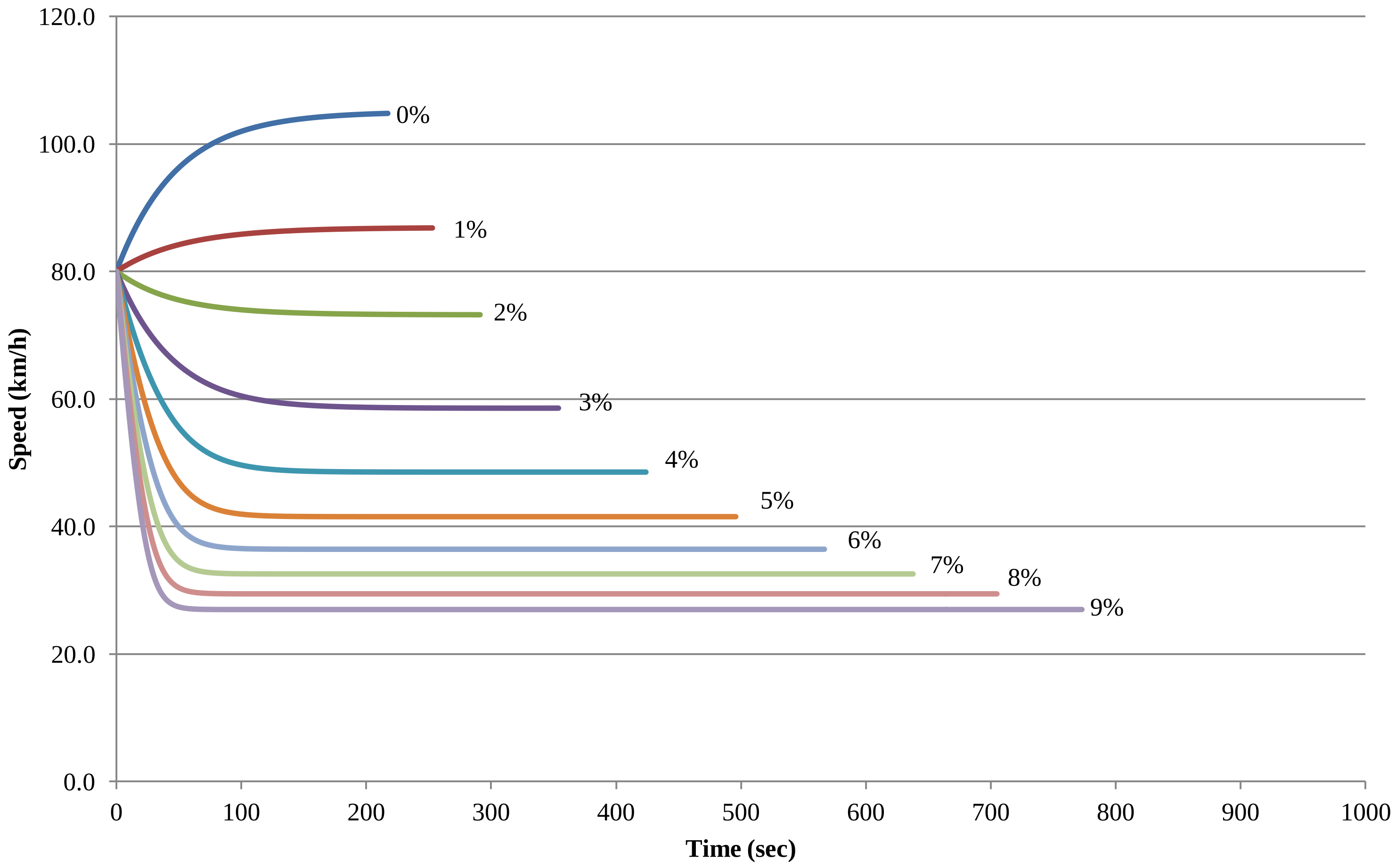
SECOND-BY-SECOND SPEED PROFILES BY INITIAL SPEEDS



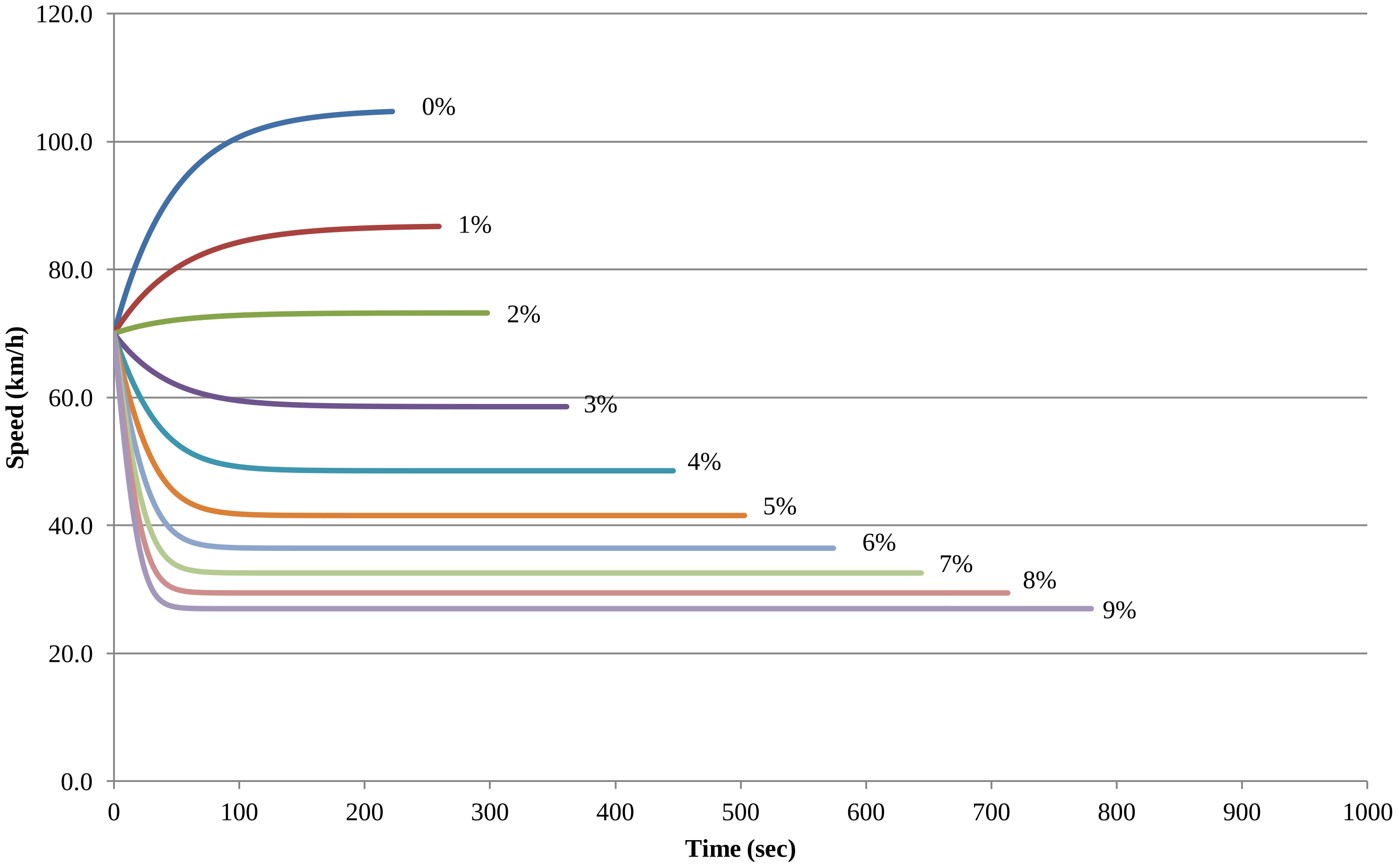
(a) Initial speed of a 100 km/h



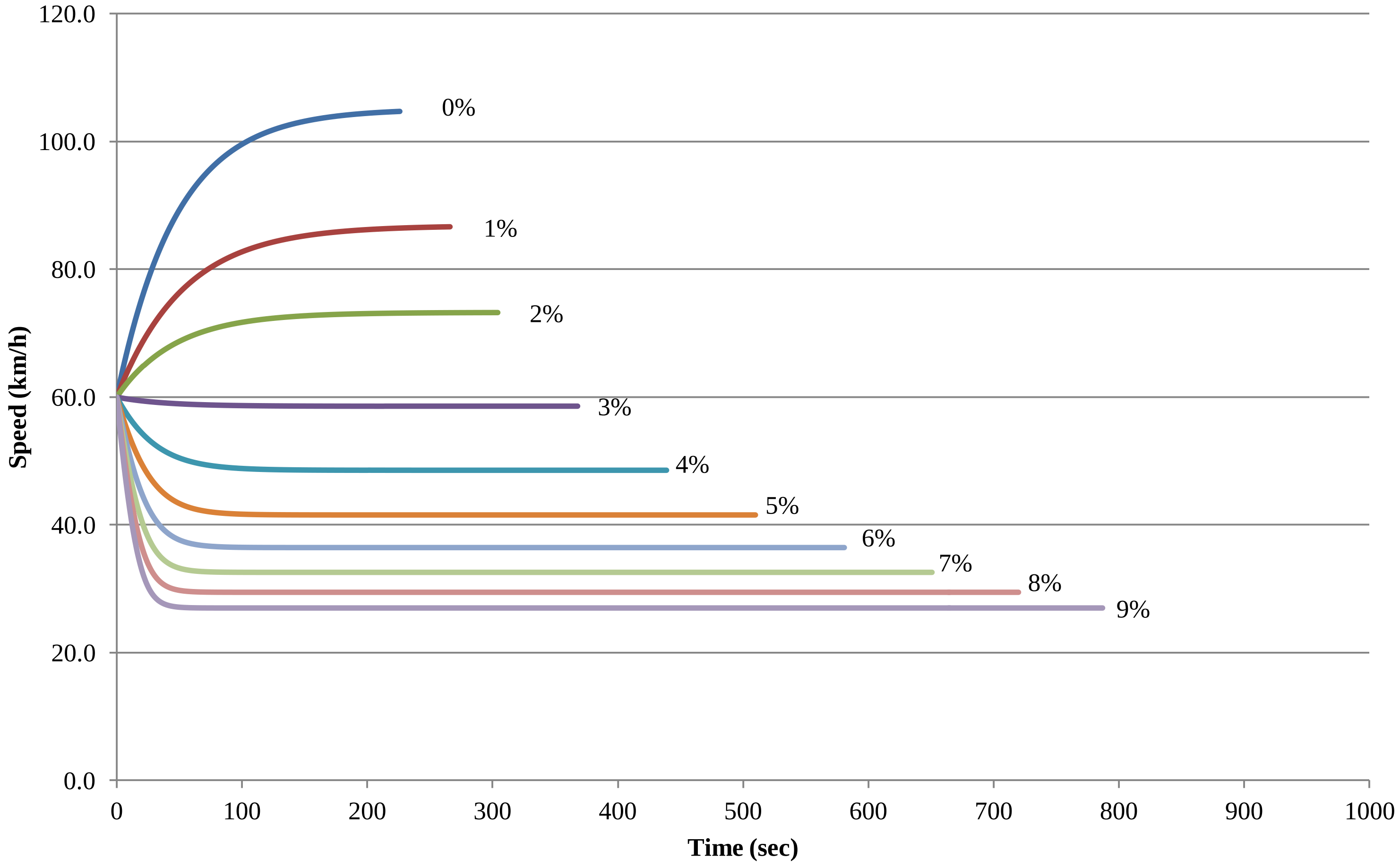
(b) Initial speed of a 90 km/h



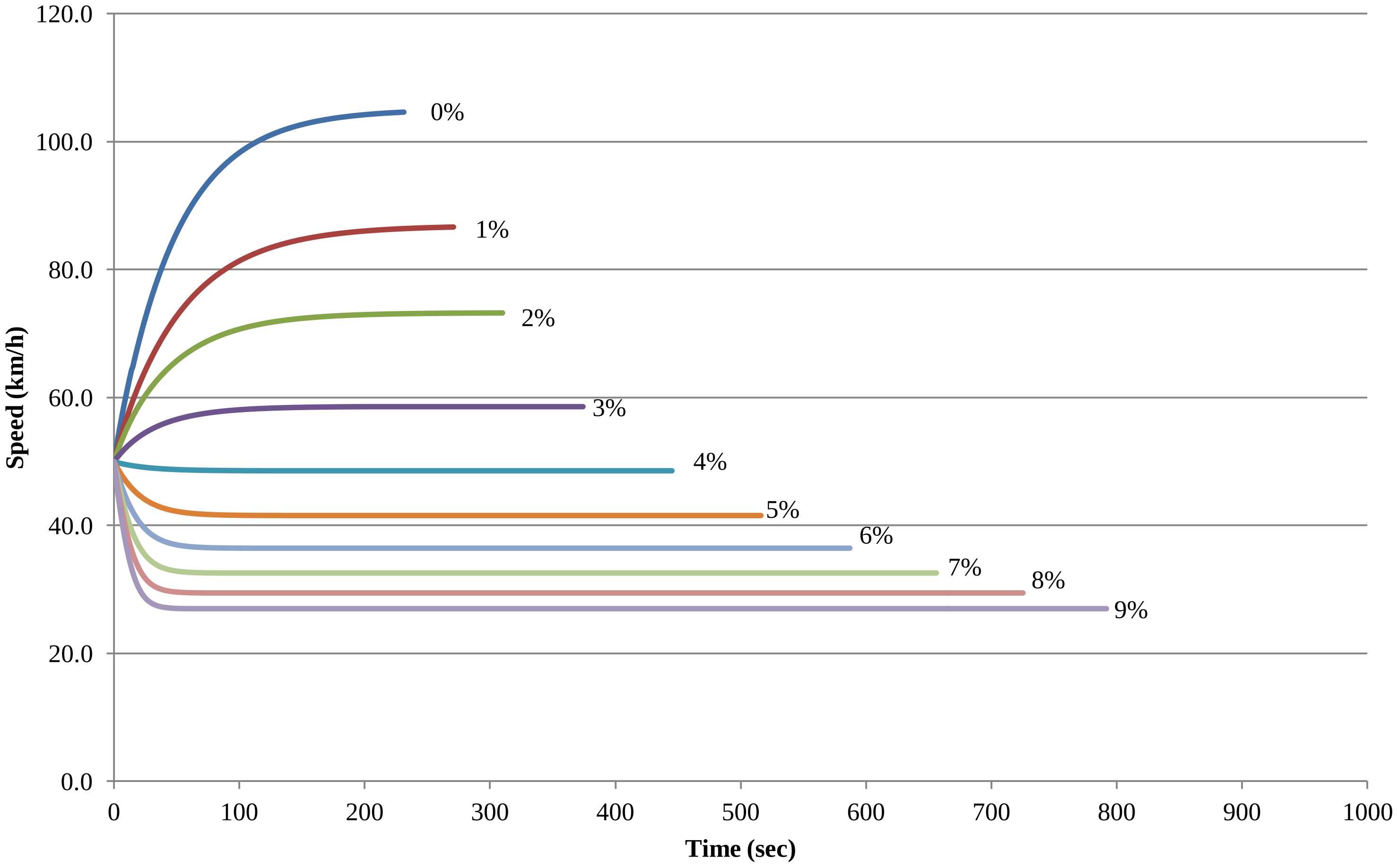
(c) Initial speed of a 80 km/h



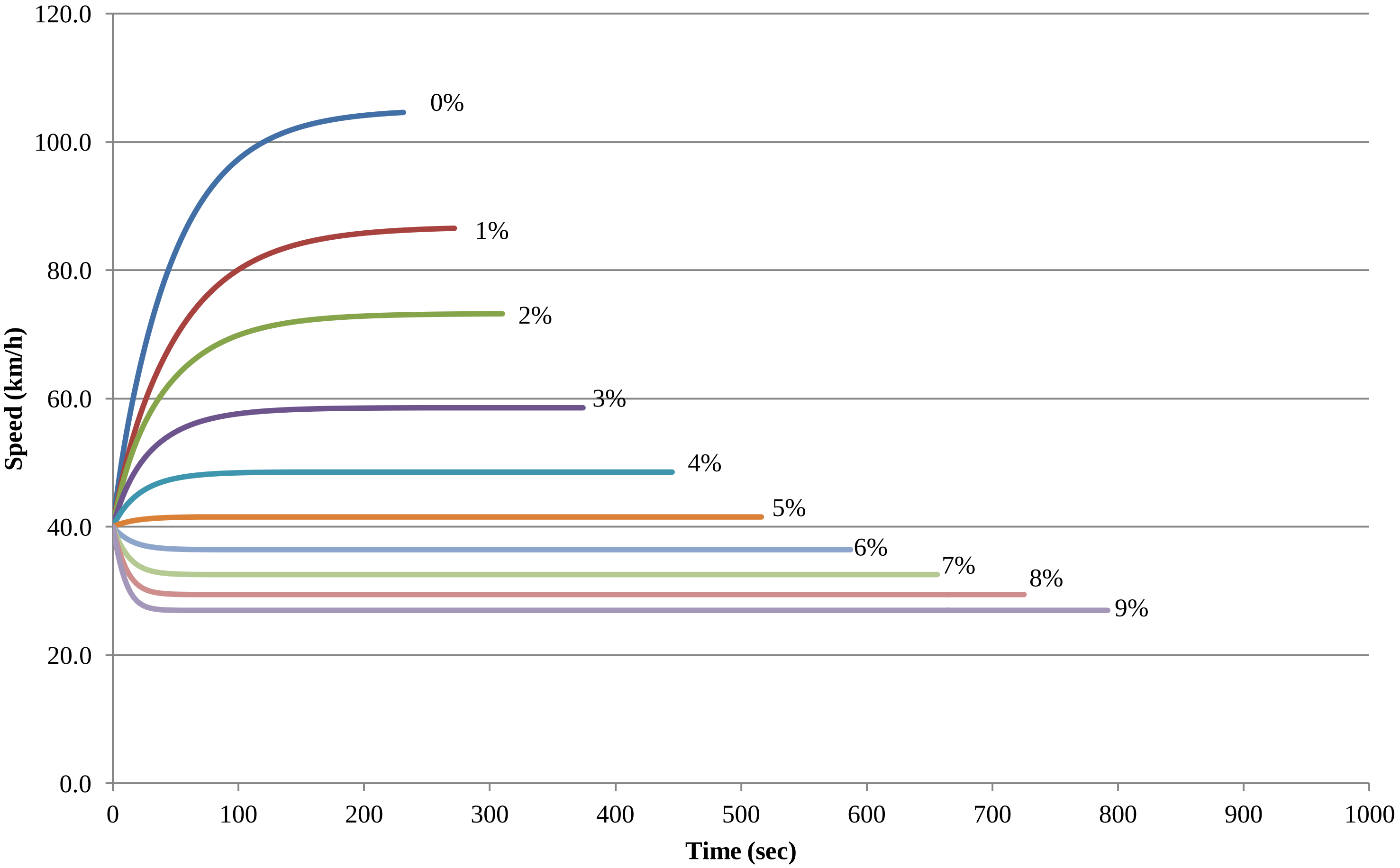
(d) Initial speed of a 70 km/h



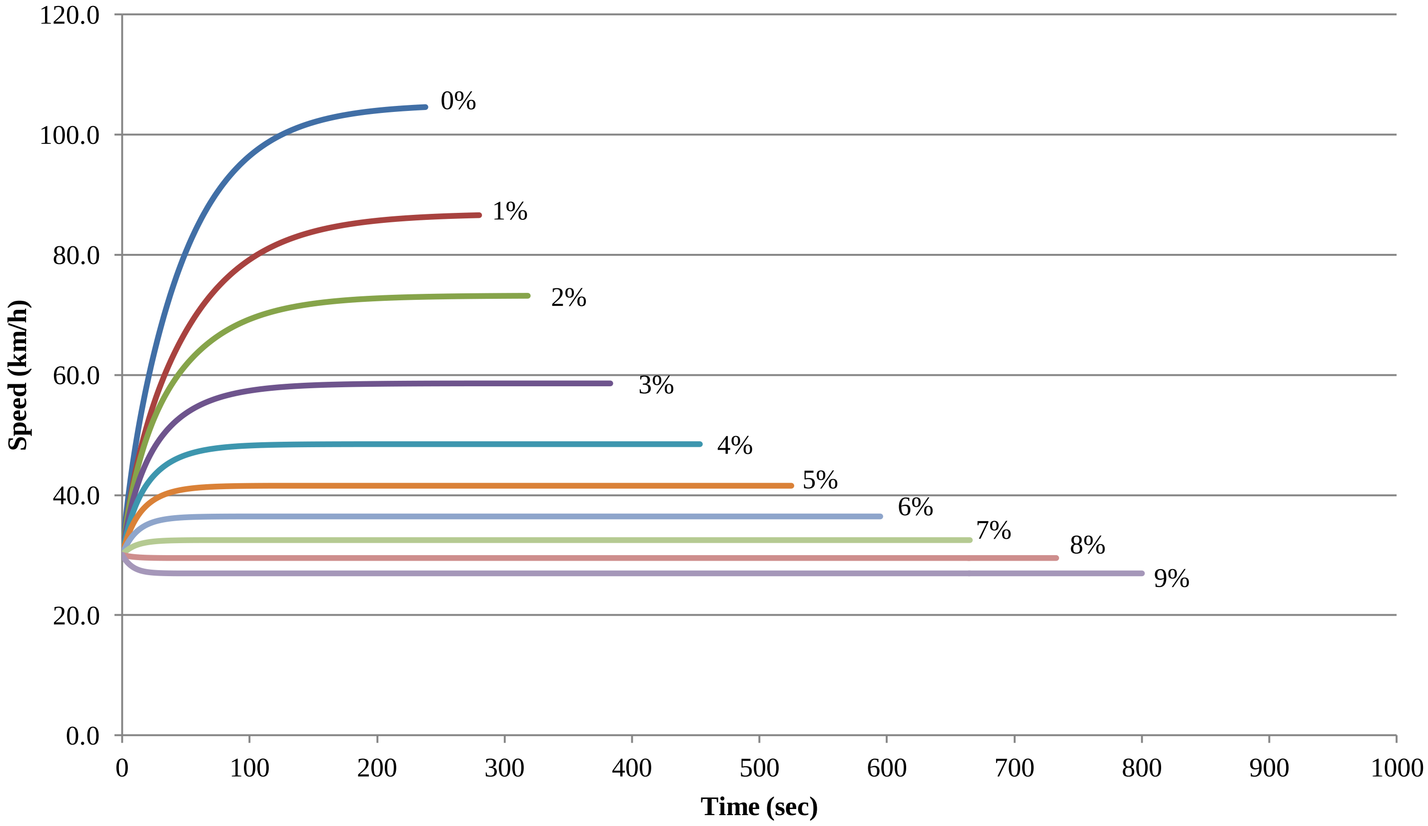
(e) Initial speed of a 60 km/h



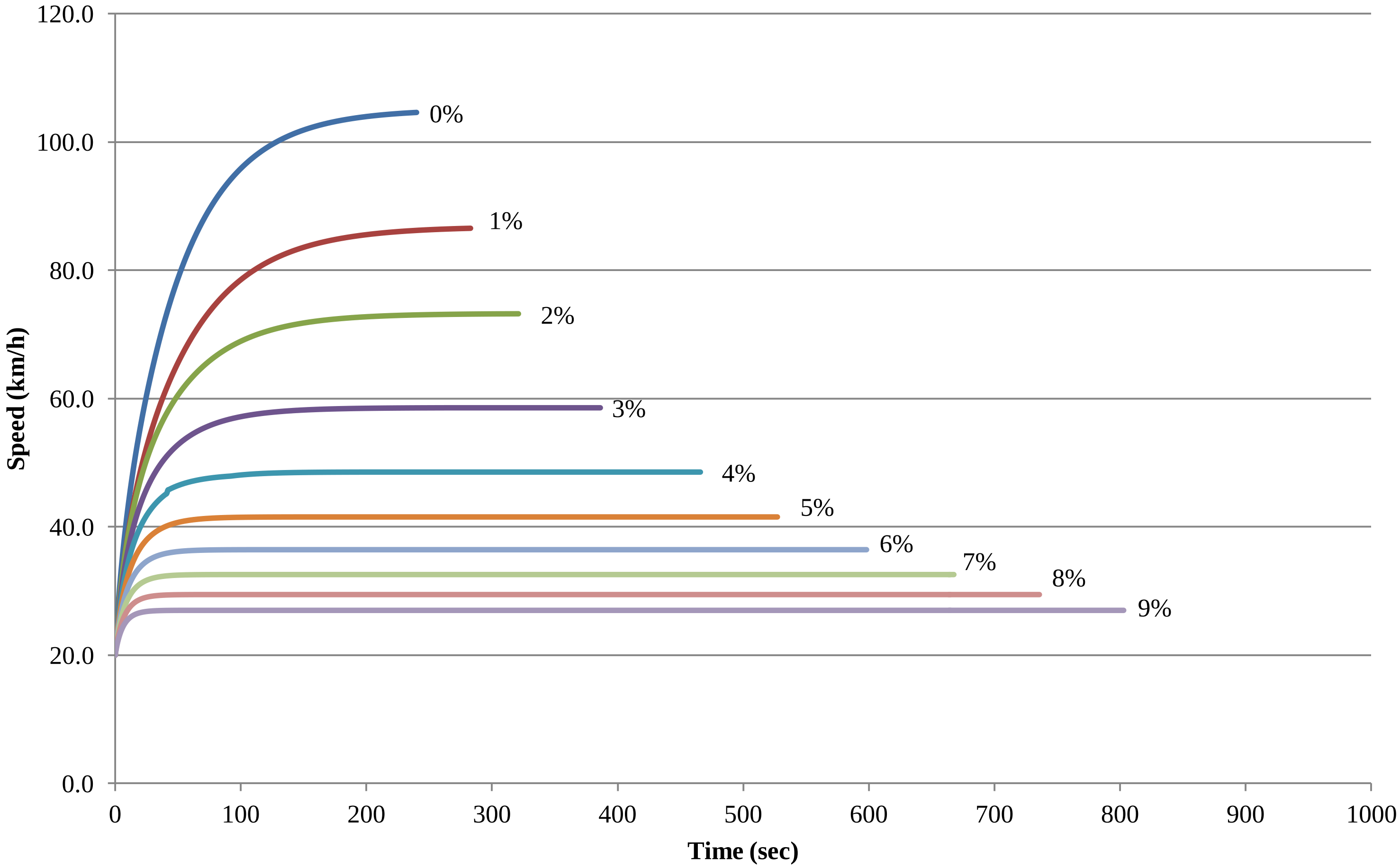
(f) Initial speed of a 50 km/h



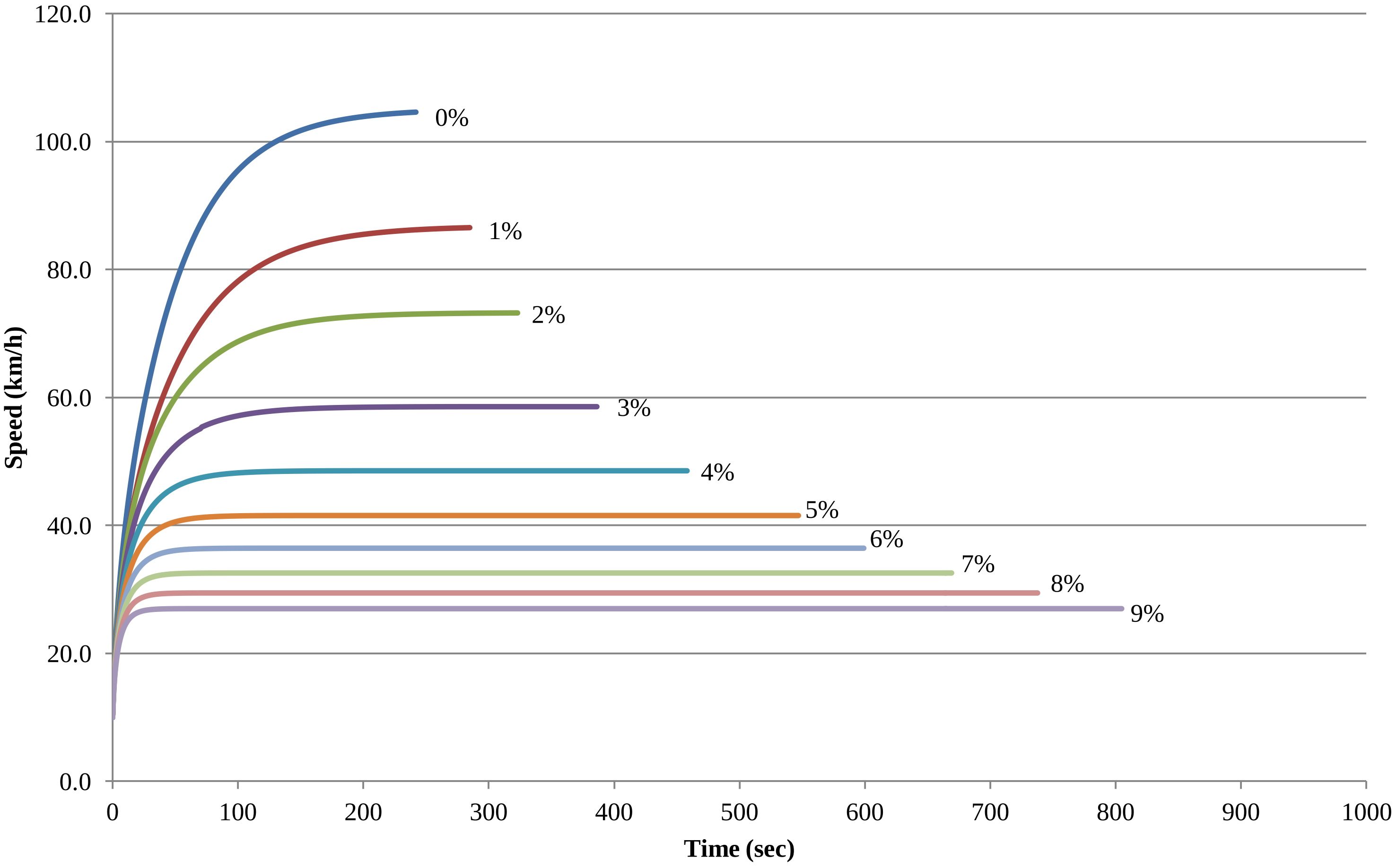
(g) Initial speed of a 40 km/h



(h) Initial speed of a 30 km/h



(i) Initial speed of a 20 km/h



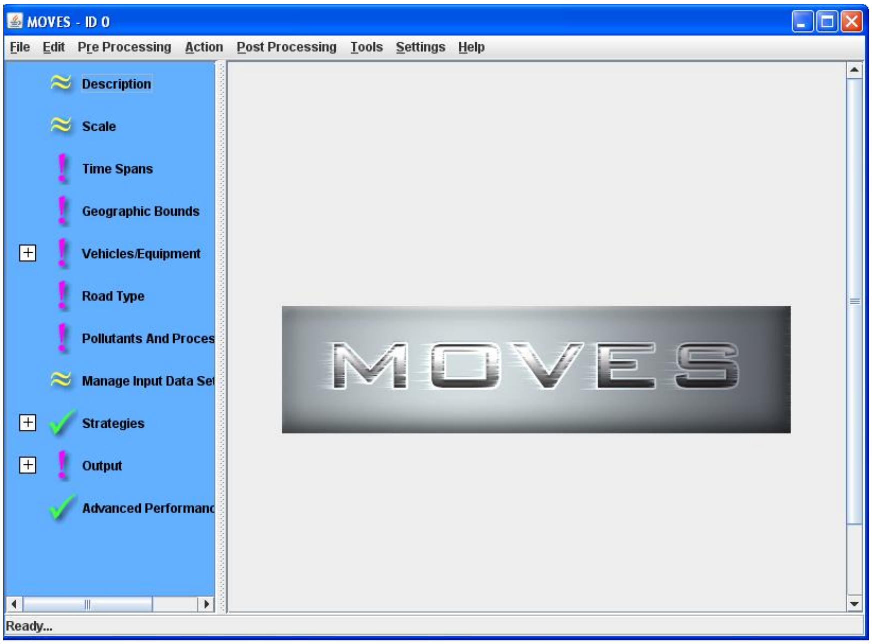
(j) Initial speed of a 10 km/h

APPENDIX C

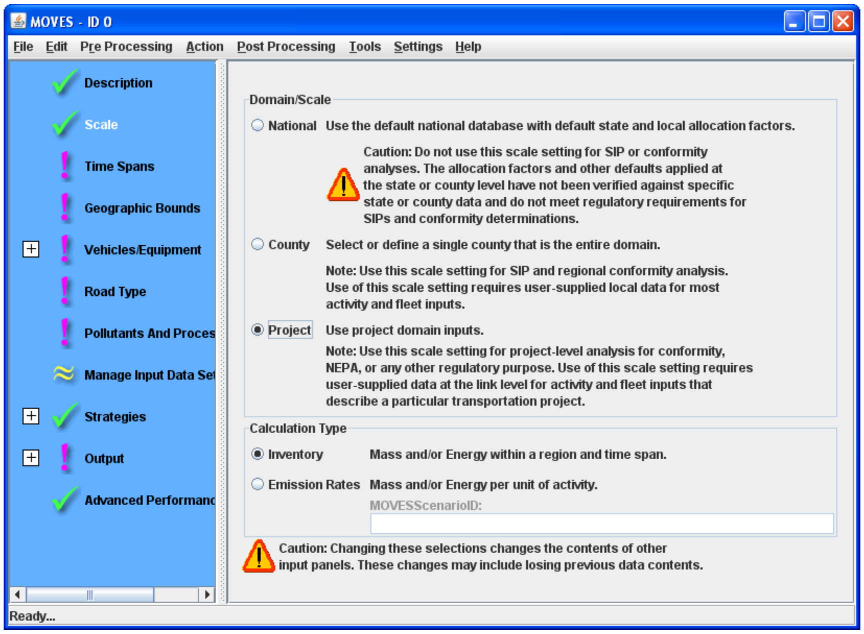
STEP-BY-STEP MOVES PROCEDURES

Fuel consumption and emission rates were extracted throughout the following procedures:

Step 1. Open “MOVES Master”.



Step 2. On the Scale menu, choose "Project" option for domain/scale and "Inventory" option for calculation type.



Domain/Scale

○ National Use the default national database with default state and local allocation factors.

Caution: Do not use this scale setting for SIP or conformity analyses. The allocation factors and other defaults applied at the state or county level have not been verified against specific state or county data and do not meet regulatory requirements for SIPs and conformity determinations.

○ County Select or define a single county that is the entire domain.

Note: Use this scale setting for SIP and regional conformity analysis. Use of this scale setting requires user-supplied local data for most activity and fleet inputs.

● Project Use project domain inputs.

Note: Use this scale setting for project-level analysis for conformity, NEPA, or any other regulatory purpose. Use of this scale setting requires user-supplied data at the link level for activity and fleet inputs that describe a particular transportation project.

Calculation Type

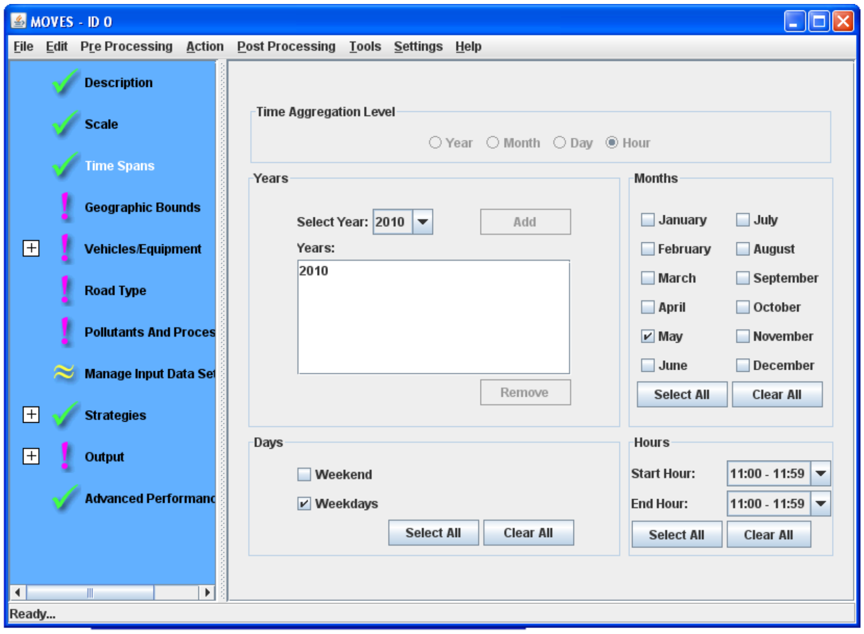
● Inventory Mass and/or Energy within a region and time span.

○ Emission Rates Mass and/or Energy per unit of activity.

MOVESScenarioID:

Caution: Changing these selections changes the contents of other input panels. These changes may include losing previous data contents.

Step 3. On the Time Span menu, select hours (11:00 ~ 11:59), days (weekdays), months (May), and year (2010).



Time Aggregation Level

○ Year ○ Month ○ Day ● Hour

Years

Select Year: 2010

Years:

2010

Months

☐ January ☐ July
☐ February ☐ August
☐ March ☐ September
☐ April ☐ October
☑ May ☐ November
☐ June ☐ December

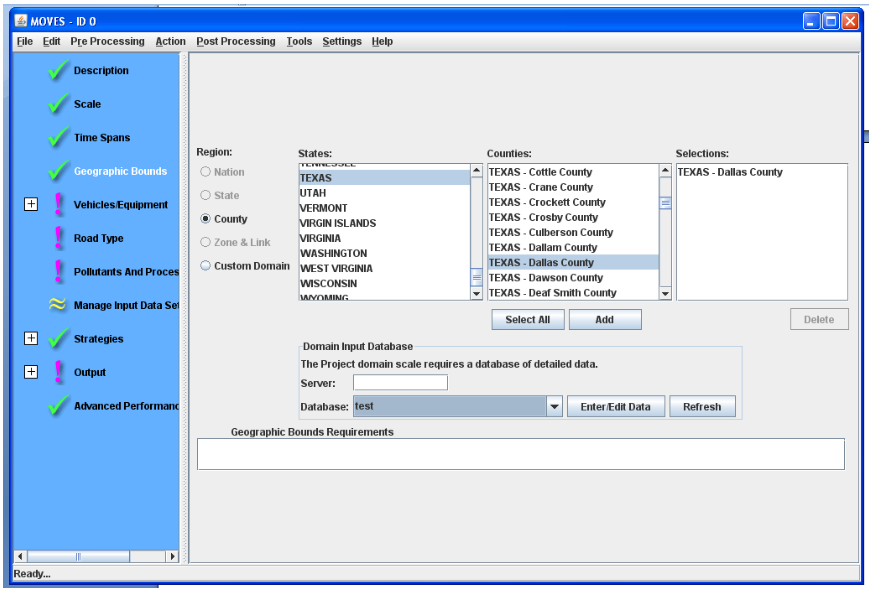
Days

☐ Weekend
☑ Weekdays

Hours

Start Hour: 11:00 - 11:59
End Hour: 11:00 - 11:59

Step 4. On the Geographic Bounds menu, choose state (Texas) and county (Dallas County) and specify database domain.



Region:
○ Nation
○ State
● County
○ Zone & Link
○ Custom Domain

Selections: TEXAS - Dallas County

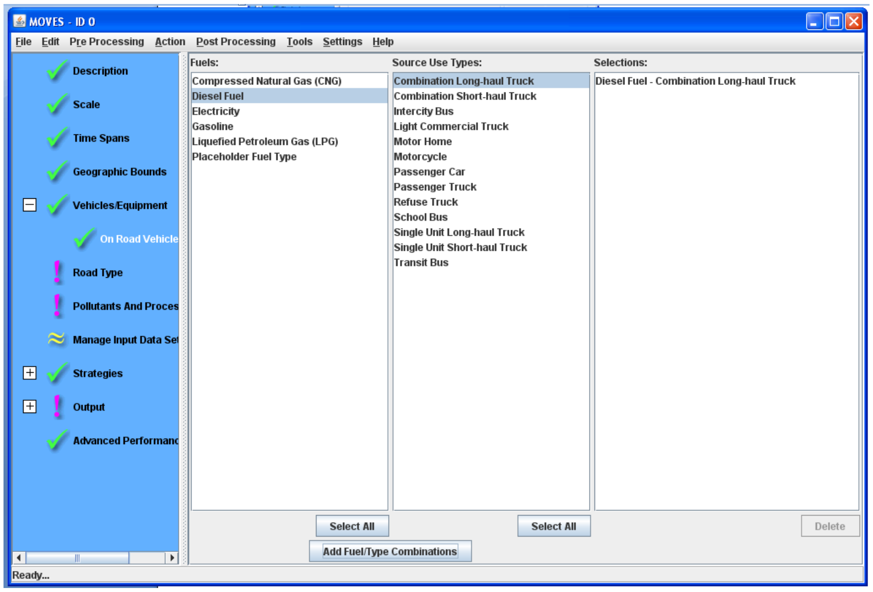
Domain Input Database

The Project domain scale requires a database of detailed data.

Server:

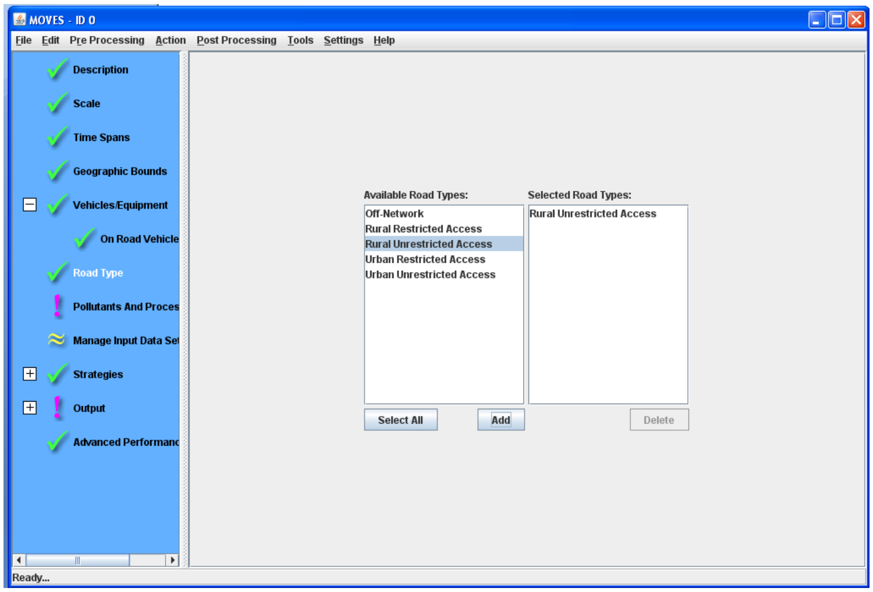
Database: test

Step 5. On the Vehicle/Equipment menu, select fuel type (Diesel Fuel) and vehicle type (Combination Long-haul Truck).



Selections: Diesel Fuel - Combination Long-haul Truck

Step 6. On the Road Type mene, select available road type (Rural Unrestricted Access).



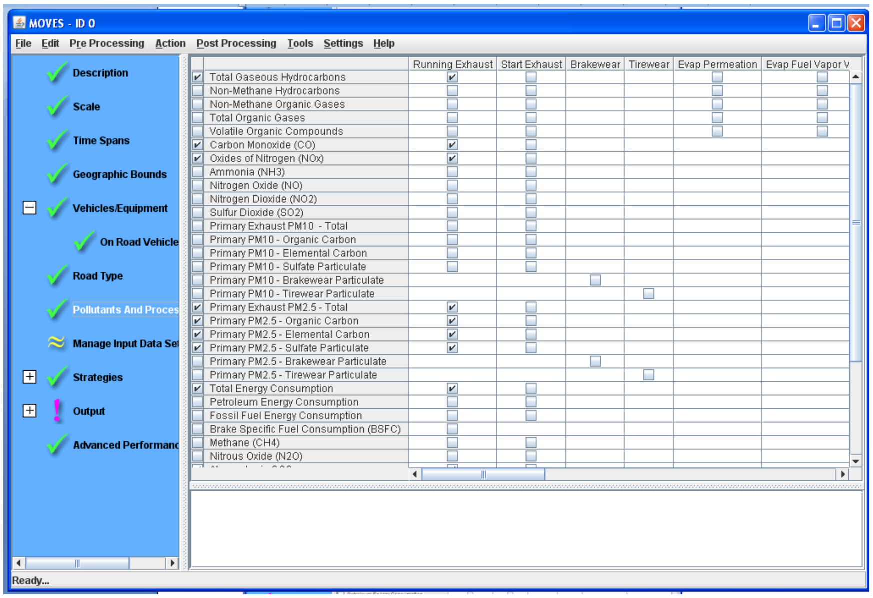
Available Road Types:

Off-Network
Rural Restricted Access
Rural Unrestricted Access
Urban Restricted Access
Urban Unrestricted Access

Selected Road Types:

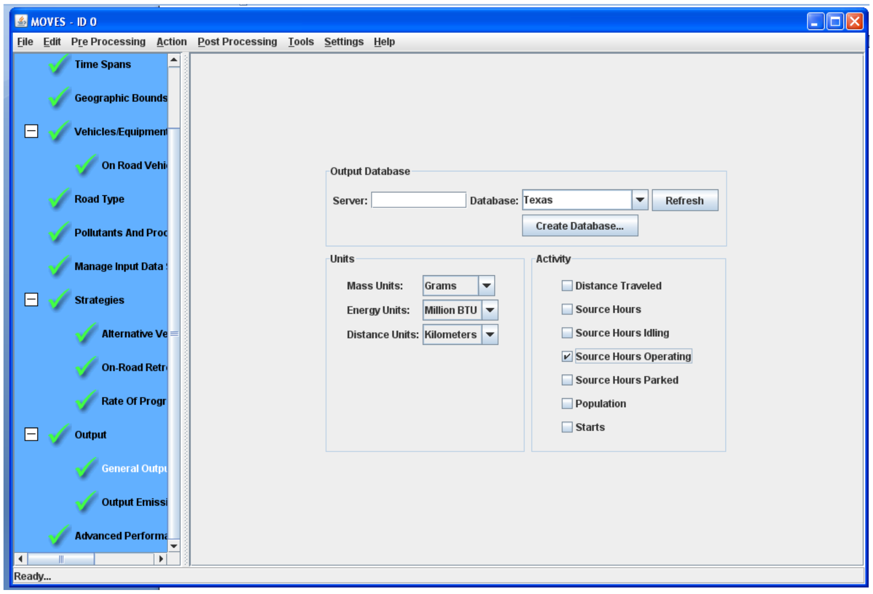
Rural Unrestricted Access

Step 7. On the Pollutant and Process menu, select pollutant (HC, CO, NOx, PM2.5, CO2, and Total Energy Consumption) and process (Running Exhaust).



		Running Exhaust	Start Exhaust	Brakewear	Tirewear	Evap Permeation	Evap Fuel Vapor V
☑	Total Gaseous Hydrocarbons	☑	☐			☐	☐
☐	Non-Methane Hydrocarbons	☐	☐			☐	☐
☐	Non-Methane Organic Gases	☐	☐			☐	☐
☐	Total Organic Gases	☐	☐			☐	☐
☐	Volatile Organic Compounds	☐	☐			☐	☐
☑	Carbon Monoxide (CO)	☑	☐				
☑	Oxides of Nitrogen (NOx)	☑	☐				
☐	Ammonia (NH3)	☐	☐				
☐	Nitrogen Oxide (NO)	☐	☐				
☐	Nitrogen Dioxide (NO2)	☐	☐				
☐	Sulfur Dioxide (SO2)	☐	☐				
☐	Primary Exhaust PM10 - Total	☐	☐				
☐	Primary PM10 - Organic Carbon	☐	☐				
☐	Primary PM10 - Elemental Carbon	☐	☐				
☐	Primary PM10 - Sulfate Particulate	☐	☐				
☐	Primary PM10 - Brakewear Particulate			☐			
☐	Primary PM10 - Tirewear Particulate				☐		
☑	Primary Exhaust PM2.5 - Total	☑	☐				
☑	Primary PM2.5 - Organic Carbon	☑	☐				
☑	Primary PM2.5 - Elemental Carbon	☑	☐				
☑	Primary PM2.5 - Sulfate Particulate	☑	☐				
☐	Primary PM2.5 - Brakewear Particulate			☐			
☐	Primary PM2.5 - Tirewear Particulate				☐		
☑	Total Energy Consumption	☑	☐				
☐	Petroleum Energy Consumption	☐	☐				
☐	Fossil Fuel Energy Consumption	☐	☐				
☐	Brake Specific Fuel Consumption (BSFC)	☐					
☐	Methane (CH4)	☐	☐				
☐	Nitrous Oxide (N2O)	☐	☐				

Step 8. On the Output menu, specify output database, units (grams for mass, million BTU for energy unit, and kilometers for distance unit).

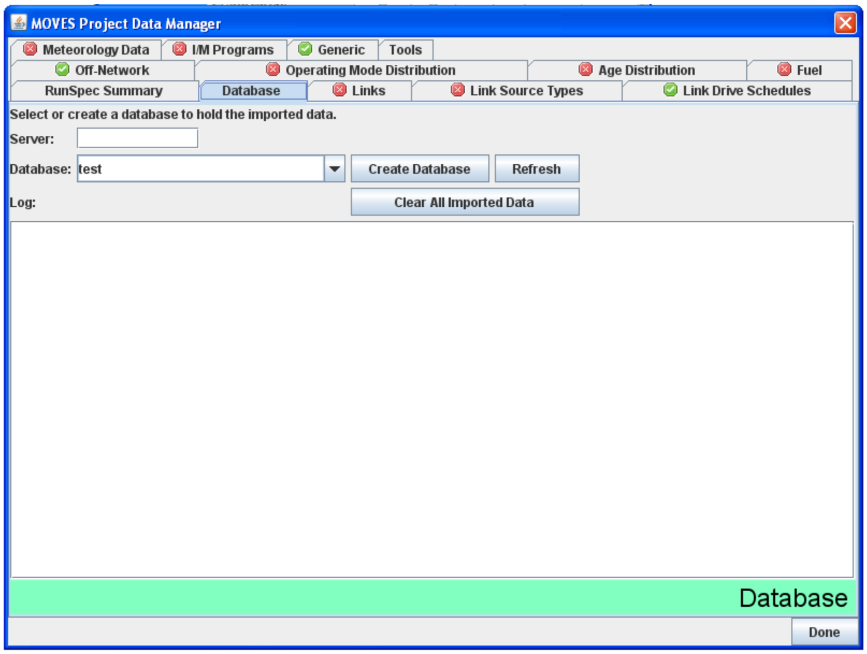


Output Database
Server:
Database: Texas

Units
Mass Units: Grams
Energy Units: Million BTU
Distance Units: Kilometers

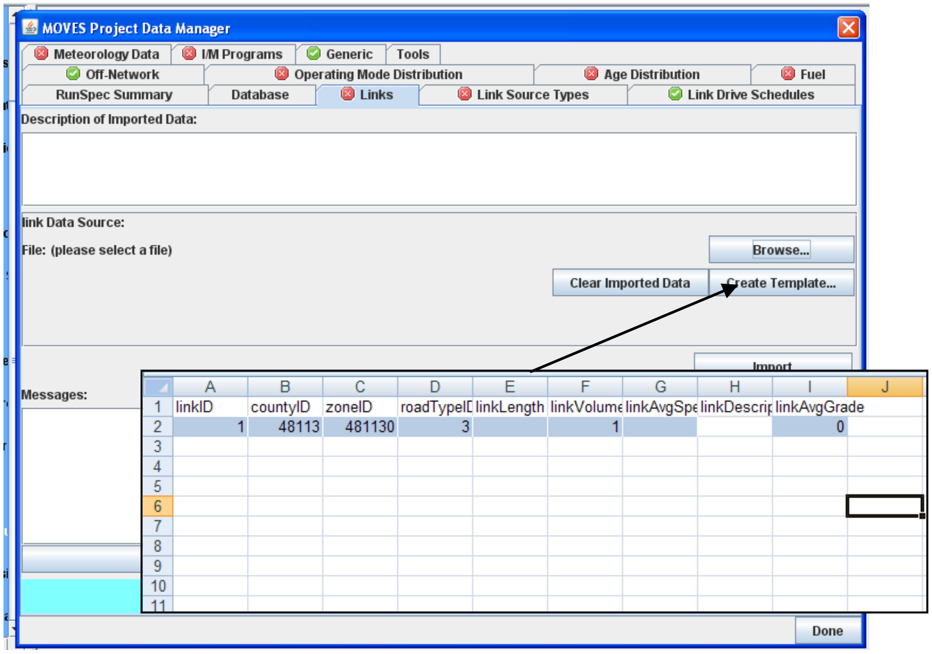
Activity
☐ Distance Traveled
☐ Source Hours
☐ Source Hours Idling
☑ Source Hours Operating
☐ Source Hours Parked
☐ Population
☐ Starts

Step 9. Open the Project Data Manager under the menu.



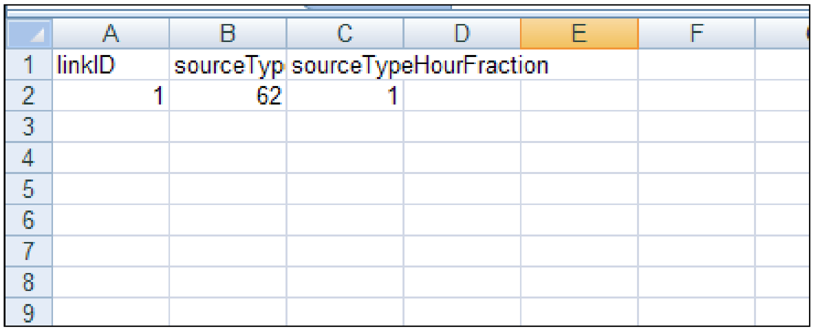
Select or create a database to hold the imported data.
Server:
Database: test
Log:

Step 10. Select Links tab, and then create “Links” template. Then, specify the values for linkID (1), countyID (48113), zoneID (481130), roadTypeID (3), and linkVolume (1) in created spreadsheet.



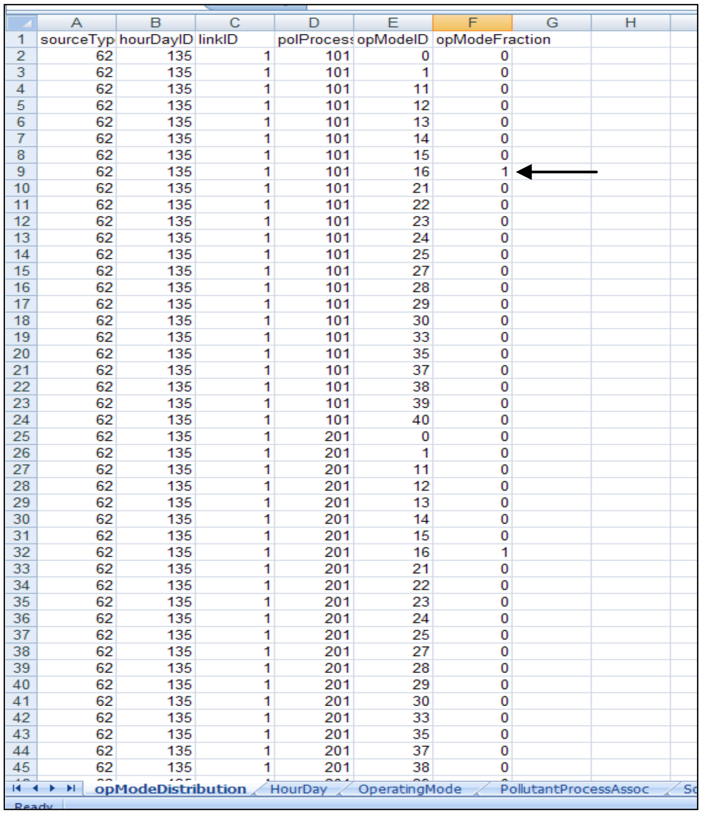
	A	B	C	D	E	F	G	H	I	J
1	linkID	countyID	zoneID	roadTypeI	linkLength	linkVolume	linkAvgSpe	linkDescrip	linkAvgGrade	
2	1	48113	481130	3		1			0	

Step 11. Select the tab for Link Source Types, and create template. Then specify the linkID (1).



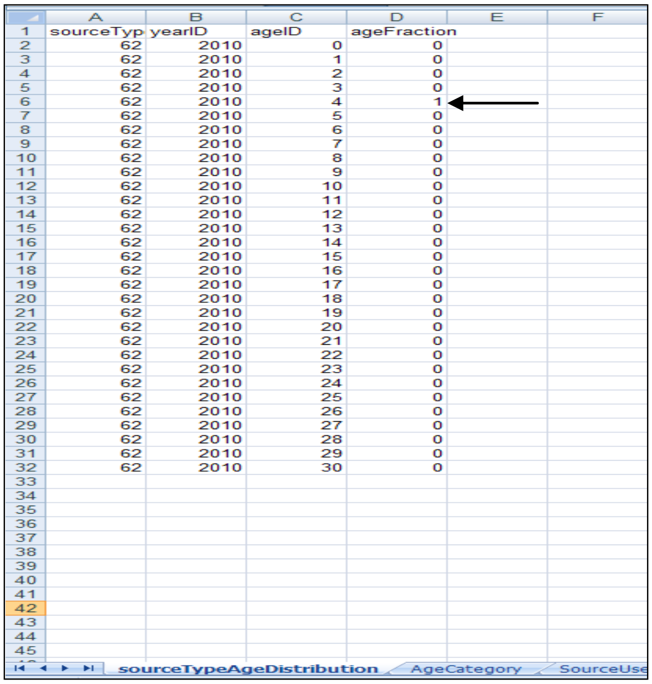
	A	B	C	D	E	F
1	linkID	sourceTyp	sourceTypeHourFraction			
2	1	62	1			

Step 12. Select the tab for Operating Mode Distribution, and create template. Then specify the value for the column of operating mode fraction (e.g., to extract the fuel consumption and emissions for operating mode bin # 16, the fraction for #16 is 1 and 0 for others).



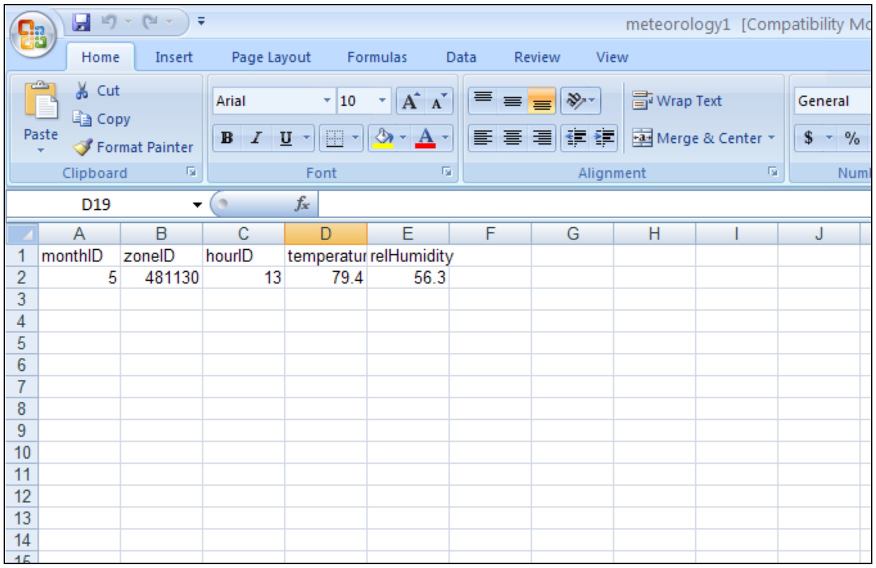
	A	B	C	D	E	F	G	H
1	sourceTyp	hourDayID	linkID	polProcess	opModeID	opModeFraction		
2	62	135	1	101	0	0		
3	62	135	1	101	1	0		
4	62	135	1	101	11	0		
5	62	135	1	101	12	0		
6	62	135	1	101	13	0		
7	62	135	1	101	14	0		
8	62	135	1	101	15	0		
9	62	135	1	101	16	1		
10	62	135	1	101	21	0		
11	62	135	1	101	22	0		
12	62	135	1	101	23	0		
13	62	135	1	101	24	0		
14	62	135	1	101	25	0		
15	62	135	1	101	27	0		
16	62	135	1	101	28	0		
17	62	135	1	101	29	0		
18	62	135	1	101	30	0		
19	62	135	1	101	33	0		
20	62	135	1	101	35	0		
21	62	135	1	101	37	0		
22	62	135	1	101	38	0		
23	62	135	1	101	39	0		
24	62	135	1	101	40	0		
25	62	135	1	201	0	0		
26	62	135	1	201	1	0		
27	62	135	1	201	11	0		
28	62	135	1	201	12	0		
29	62	135	1	201	13	0		
30	62	135	1	201	14	0		
31	62	135	1	201	15	0		
32	62	135	1	201	16	1		
33	62	135	1	201	21	0		
34	62	135	1	201	22	0		
35	62	135	1	201	23	0		
36	62	135	1	201	24	0		
37	62	135	1	201	25	0		
38	62	135	1	201	27	0		
39	62	135	1	201	28	0		
40	62	135	1	201	29	0		
41	62	135	1	201	30	0		
42	62	135	1	201	33	0		
43	62	135	1	201	35	0		
44	62	135	1	201	37	0		
45	62	135	1	201	38	0		

Step 13. Select the tab for Age Distribution, and create template. Then, input the value for the column of Age Faction (e.g., for the fuel consumption and emission of 4 year old truck, the fraction for ageID 4 is 1 and 0 for others).



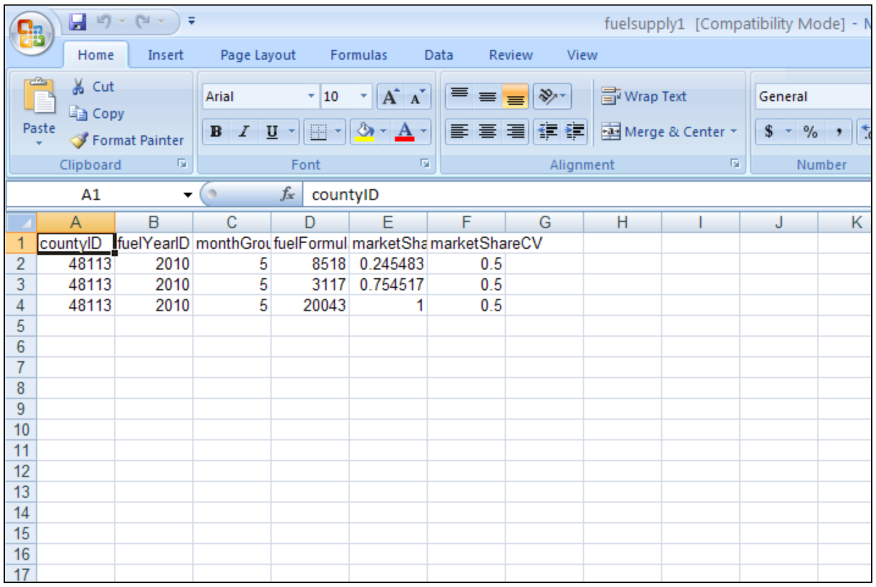
sourceTyp	yearID	ageID	ageFraction
62	2010	0	0
62	2010	1	0
62	2010	2	0
62	2010	3	0
62	2010	4	1
62	2010	5	0
62	2010	6	0
62	2010	7	0
62	2010	8	0
62	2010	9	0
62	2010	10	0
62	2010	11	0
62	2010	12	0
62	2010	13	0
62	2010	14	0
62	2010	15	0
62	2010	16	0
62	2010	17	0
62	2010	18	0
62	2010	19	0
62	2010	20	0
62	2010	21	0
62	2010	22	0
62	2010	23	0
62	2010	24	0
62	2010	25	0
62	2010	26	0
62	2010	27	0
62	2010	28	0
62	2010	29	0
62	2010	30	0

Step 14. Specify the values in the tabs of Methodology Data. The values for temperature and humidity are determined by the average during the specified period.



monthID	zoneID	hourID	temperatur	relHumidity
5	481130	13	79.4	56.3

Step 15. In the tab of Fuel, specify market share to fuel type in the specified area.



	A	B	C	D	E	F	G	H	I	J	K
1	countyID	fuelYearID	monthGrou	fuelFormul	marketSha	marketShareCV					
2	48113	2010	5	8518	0.245483	0.5					
3	48113	2010	5	3117	0.754517	0.5					
4	48113	2010	5	20043	1	0.5					
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											

Step 16. Click "Done" button on the window of project data manger, and then execute MOVES processing.

APPENDIX D

FUEL CONSUMPTION AND EMISSIONS BY INITIAL SPEEDS AND GRADES

Initial Speed	Grade (%)	Travel Time(sec)	Fuel Consumption	CO_2	NO_x	CO	HC	$PM_{2.5}$
			(gal/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)
10	0	242	0.381	3837	17.971	9.251	2.022	1.397
10	1	285	0.398	3999	18.911	10.725	2.380	1.499
10	2	323	0.895	9006	41.295	14.287	2.595	3.579
10	3	386	1.070	10760	49.348	17.068	3.102	4.276
10	4	458	1.268	12756	58.540	20.214	3.685	5.067
10	5	547	1.509	15172	69.846	23.938	4.425	6.012
10	6	599	1.446	14542	74.179	19.458	5.665	5.283
10	7	644	1.555	15635	79.752	20.919	6.091	5.680
10	8	737	1.779	17893	91.269	23.940	6.971	6.500
10	9	805	1.943	19543	99.690	26.149	7.614	7.100
20	0	240	0.378	3799	17.736	9.223	1.998	1.386
20	1	283	0.393	3957	18.689	10.666	2.363	1.481
20	2	321	0.891	8957	41.048	14.222	2.576	3.562
20	3	386	1.071	10768	49.356	17.092	3.099	4.281
20	4	466	1.291	12988	59.573	20.597	3.745	5.161
20	5	527	1.454	14619	67.294	23.068	4.263	5.793
20	6	598	1.443	14518	74.055	19.425	5.656	5.274
20	7	644	1.555	15635	79.752	20.919	6.091	5.680
20	8	736	1.777	17868	91.145	23.908	6.961	6.492
20	9	803	1.938	19495	99.442	26.084	7.595	7.083
30	0	238	0.370	3726	17.402	9.125	1.983	1.356
30	1	280	0.388	3900	18.376	10.593	2.337	1.455
30	2	318	0.884	8888	40.680	14.137	2.546	3.537
30	3	383	1.064	10703	48.993	17.019	3.067	4.259
30	4	453	1.257	12646	57.933	20.089	3.633	5.030
30	5	525	1.451	14589	67.067	23.064	4.237	5.787
30	6	595	1.436	14445	73.684	19.328	5.628	5.248
30	7	644	1.555	15635	79.752	20.919	6.091	5.680
30	8	733	1.769	17795	90.773	23.810	6.933	6.465
30	9	800	1.931	19422	99.070	25.987	7.566	7.056
40	0	235	0.360	3625	16.883	9.036	1.953	1.320

Initial Speed	Grade (%)	Travel Time(sec)	Fuel Consumption	CO_2	NO_x	CO	HC	$PM_{2.5}$
			(gal/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)
40	1	276	0.379	3814	17.891	10.512	2.302	1.414
40	2	314	0.875	8802	40.197	14.043	2.504	3.509
40	3	379	1.056	10624	48.519	16.950	3.022	4.236
40	4	450	1.254	12615	57.608	20.126	3.588	5.029
40	5	521	1.451	14597	66.689	23.277	4.157	5.818
40	6	591	1.427	14348	73.188	19.198	5.590	5.213
40	7	644	1.555	15635	79.752	20.919	6.091	5.680
40	8	730	1.762	17723	90.402	23.713	6.904	6.439
40	9	797	1.924	19349	98.699	25.889	7.538	7.030
50	0	231	0.344	3457	16.121	8.833	1.923	1.258
50	1	271	0.365	3672	17.237	10.282	2.264	1.364
50	2	310	0.864	8690	39.685	13.864	2.472	3.465
50	3	374	1.042	10484	47.879	16.727	2.982	4.180
50	4	445	1.240	12474	56.968	19.902	3.548	4.973
50	5	516	1.438	14465	66.057	23.078	4.114	5.767
50	6	587	1.425	14330	72.781	19.325	5.521	5.227
50	7	644	1.559	15680	79.802	21.066	6.073	5.708
50	8	725	1.753	17631	89.816	23.649	6.845	6.413
50	9	792	1.914	19250	98.105	25.800	7.482	7.000
60	0	226	0.323	3251	15.185	8.574	1.884	1.170
60	1	266	0.346	3475	16.341	10.023	2.227	1.295
60	2	304	0.847	8522	38.917	13.596	2.424	3.397
60	3	368	1.026	10316	47.110	16.458	2.934	4.113
60	4	439	1.224	12306	56.200	19.634	3.500	4.906
60	5	519	1.396	14043	64.427	22.353	4.042	5.586
60	6	581	1.415	14229	72.088	19.277	5.446	5.202
60	7	644	1.562	15710	79.835	21.164	6.061	5.727
60	8	720	1.744	17536	89.226	23.572	6.788	6.386
60	9	787	1.904	19151	97.511	25.711	7.426	6.970
70	0	222	0.298	2998	14.049	8.328	1.857	1.067
70	1	259	0.316	3177	14.981	9.648	2.178	1.190
70	2	298	0.831	8354	38.149	13.328	2.376	3.330
70	3	361	1.006	10120	46.214	16.145	2.878	4.035
70	4	446	1.243	12502	57.096	19.947	3.556	4.984
70	5	503	1.402	14100	64.393	22.496	4.011	5.621
70	6	574	1.401	14089	71.254	19.147	5.368	5.159
70	7	644	1.565	15736	79.865	21.250	6.051	5.744

Initial Speed	Grade (%)	Travel Time(sec)	Fuel Consumption	CO_2	NO_x	CO	HC	$PM_{2.5}$
			(gal/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)
70	8	713	1.729	17385	88.380	23.406	6.714	6.336
70	9	780	1.889	18997	96.661	25.533	7.354	6.917
80	0	217	0.265	2666	12.552	8.012	1.822	0.933
80	1	253	0.267	2683	12.744	9.199	2.145	1.018
80	2	291	0.811	8157	37.253	13.015	2.320	3.252
80	3	354	0.987	9924	45.318	15.832	2.823	3.956
80	4	424	1.182	11886	54.279	18.963	3.381	4.739
80	5	496	1.382	13904	63.497	22.183	3.955	5.543
80	6	567	1.387	13949	70.421	19.018	5.290	5.116
80	7	638	1.552	15613	79.147	21.128	5.985	5.705
80	8	705	1.711	17210	87.410	23.207	6.631	6.277
80	9	773	1.874	18845	95.815	25.367	7.280	6.867
90	0	213	0.223	2244	10.661	7.736	1.806	0.852
90	1	247	0.259	2602	12.363	8.971	2.095	0.988
90	2	285	0.808	8130	37.107	12.701	2.253	3.045
90	3	346	0.970	9757	44.549	15.456	2.751	3.809
90	4	417	1.166	11726	53.543	18.638	3.320	4.624
90	5	487	1.360	13677	62.456	21.773	3.880	5.418
90	6	558	1.370	13775	69.427	18.792	5.193	5.030
90	7	630	1.536	15452	78.241	20.925	5.900	5.632
90	8	697	1.695	17048	86.504	23.004	6.546	6.204
90	9	756	1.835	18455	93.770	24.848	7.113	6.714
100	0	208	0.218	2191	10.411	7.555	1.764	0.832
100	1	241	0.252	2539	12.063	8.753	2.044	0.964
100	2	279	0.774	7788	35.562	12.320	2.206	2.856
100	3	338	0.944	9491	43.341	15.055	2.685	3.663
100	4	408	1.142	11485	52.440	18.218	3.245	4.488
100	5	479	1.340	13478	61.544	21.407	3.812	5.303
100	6	549	1.352	13593	68.413	18.555	5.098	4.944
100	7	619	1.513	15222	76.979	20.623	5.786	5.529
100	8	688	1.676	16859	85.470	22.756	6.453	6.120
100	9	756	1.838	18484	93.850	24.892	7.105	6.709
110	0	204	0.214	2149	10.211	7.410	1.730	0.816
110	1	235	0.246	2476	11.762	8.536	1.993	0.940
110	2	272	0.729	7329	33.497	11.881	2.158	2.670
110	3	331	0.907	9120	41.665	14.658	2.634	3.513
110	4	402	1.111	11173	51.032	17.884	3.201	4.367

Initial Speed	Grade (%)	Travel Time(sec)	Fuel Consumption	CO_2	NO_x	CO	HC	$PM_{2.5}$
			(gal/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)	(g/trip)
110	5	470	1.305	13121	59.924	20.954	3.744	5.159
110	6	540	1.325	13327	67.024	18.289	5.007	4.844
110	7	608	1.484	14921	75.415	20.289	5.677	5.416
110	8	679	1.653	16621	84.228	22.482	6.364	6.029
110	9	746	1.812	18221	92.484	24.586	7.007	6.610

APPENDIX E

SPEED PROFILES ON THE FIVE-PERCENT AND SIX-PERCENT GRADES

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
0	30.56	33	30.56	33
1	30.05	33	29.96	33
2	29.56	33	29.38	33
3	29.09	33	28.81	33
4	28.62	33	28.25	33
5	28.16	33	27.71	35
6	27.71	33	27.18	35
7	27.27	35	26.66	35
8	26.84	35	26.15	35
9	26.43	35	25.65	35
10	26.02	35	25.17	35
11	25.62	35	24.69	35
12	25.22	35	24.23	35
13	24.84	35	23.77	35
14	24.47	35	23.33	35
15	24.10	35	22.90	35
16	23.74	35	22.47	35
17	23.39	35	22.06	24
18	23.05	35	21.65	24
19	22.71	35	21.26	24
20	22.38	35	20.87	24
21	22.06	24	20.49	24
22	21.75	24	20.12	24
23	21.44	24	19.76	24
24	21.14	24	19.40	24
25	20.85	24	19.06	24
26	20.57	24	18.72	24
27	20.28	24	18.39	24
28	20.01	24	18.06	24
29	19.74	24	17.75	24
30	19.48	24	17.44	24
31	19.22	24	17.14	24
32	18.97	24	16.84	24
33	18.73	24	16.56	24
34	18.49	24	16.28	24
35	18.25	24	16.01	24
36	18.03	24	15.74	24

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
37	17.80	24	15.49	24
38	17.58	24	15.24	24
39	17.37	24	15.00	24
40	17.16	24	14.77	24
41	16.96	24	14.54	24
42	16.76	24	14.33	24
43	16.56	24	14.12	24
44	16.37	24	13.91	24
45	16.19	24	13.72	24
46	16.01	24	13.53	24
47	15.84	24	13.35	24
48	15.67	24	13.18	24
49	15.51	24	13.02	24
50	15.35	24	12.86	24
51	15.19	24	12.71	24
52	15.05	24	12.56	24
53	14.90	24	12.42	24
54	14.76	24	12.29	24
55	14.63	24	12.17	24
56	14.50	24	12.05	24
57	14.37	24	11.94	24
58	14.25	24	11.83	24
59	14.13	24	11.73	24
60	14.02	24	11.63	24
61	13.91	24	11.54	24
62	13.80	24	11.45	24
63	13.70	24	11.37	24
64	13.60	24	11.29	24
65	13.51	24	11.22	24
66	13.42	24	11.15	14
67	13.33	24	11.09	14
68	13.25	24	11.02	14
69	13.17	24	10.97	14
70	13.10	24	10.91	14
71	13.02	24	10.86	14
72	12.95	24	10.81	14
73	12.89	24	10.77	14
74	12.82	24	10.73	14
75	12.76	24	10.69	14
76	12.70	24	10.65	14
77	12.65	24	10.62	14
78	12.59	24	10.58	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
79	12.54	24	10.55	14
80	12.49	24	10.53	14
81	12.45	24	10.50	14
82	12.40	24	10.47	14
83	12.36	24	10.45	14
84	12.32	24	10.43	14
85	12.28	24	10.41	14
86	12.24	24	10.39	14
87	12.21	24	10.37	14
88	12.17	24	10.35	14
89	12.14	24	10.34	14
90	12.11	24	10.32	14
91	12.08	24	10.31	14
92	12.06	24	10.30	14
93	12.03	24	10.29	14
94	12.01	24	10.28	14
95	11.98	24	10.27	14
96	11.96	24	10.26	14
97	11.94	24	10.25	14
98	11.92	24	10.24	14
99	11.90	24	10.23	14
100	11.88	24	10.22	14
101	11.86	24	10.22	14
102	11.85	24	10.21	14
103	11.83	24	10.21	14
104	11.82	24	10.20	14
105	11.80	24	10.20	14
106	11.79	24	10.19	14
107	11.78	24	10.19	14
108	11.76	24	10.18	14
109	11.75	24	10.18	14
110	11.74	24	10.17	14
111	11.73	24	10.17	14
112	11.72	24	10.17	14
113	11.71	24	10.17	14
114	11.70	24	10.16	14
115	11.70	24	10.16	14
116	11.69	24	10.16	14
117	11.68	24	10.16	14
118	11.67	24	10.15	14
119	11.67	24	10.15	14
120	11.66	24	10.15	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
121	11.65	24	10.15	14
122	11.65	24	10.15	14
123	11.64	24	10.15	14
124	11.64	24	10.14	14
125	11.63	24	10.14	14
126	11.63	24	10.14	14
127	11.62	24	10.14	14
128	11.62	24	10.14	14
129	11.62	24	10.14	14
130	11.61	24	10.14	14
131	11.61	24	10.14	14
132	11.61	24	10.14	14
133	11.60	24	10.14	14
134	11.60	24	10.14	14
135	11.60	24	10.13	14
136	11.59	24	10.13	14
137	11.59	24	10.13	14
138	11.59	24	10.13	14
139	11.59	24	10.13	14
140	11.58	24	10.13	14
141	11.58	24	10.13	14
142	11.58	24	10.13	14
143	11.58	24	10.13	14
144	11.58	24	10.13	14
145	11.58	24	10.13	14
146	11.57	24	10.13	14
147	11.57	24	10.13	14
148	11.57	24	10.13	14
149	11.57	24	10.13	14
150	11.57	24	10.13	14
151	11.57	24	10.13	14
152	11.57	24	10.13	14
153	11.56	24	10.13	14
154	11.56	24	10.13	14
155	11.56	24	10.13	14
156	11.56	24	10.13	14
157	11.56	24	10.13	14
158	11.56	24	10.13	14
159	11.56	24	10.13	14
160	11.56	24	10.13	14
161	11.56	24	10.13	14
162	11.56	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
163	11.56	24	10.13	14
164	11.56	24	10.13	14
165	11.56	24	10.13	14
166	11.56	24	10.13	14
167	11.55	24	10.13	14
168	11.55	24	10.13	14
169	11.55	24	10.13	14
170	11.55	24	10.13	14
171	11.55	24	10.13	14
172	11.55	24	10.13	14
173	11.55	24	10.13	14
174	11.55	24	10.13	14
175	11.55	24	10.13	14
176	11.55	24	10.13	14
177	11.55	24	10.13	14
178	11.55	24	10.13	14
179	11.55	24	10.13	14
180	11.55	24	10.13	14
181	11.55	24	10.13	14
182	11.55	24	10.13	14
183	11.55	24	10.13	14
184	11.55	24	10.13	14
185	11.55	24	10.13	14
186	11.55	24	10.13	14
187	11.55	24	10.13	14
188	11.55	24	10.13	14
189	11.55	24	10.13	14
190	11.55	24	10.13	14
191	11.55	24	10.13	14
192	11.55	24	10.13	14
193	11.55	24	10.13	14
194	11.55	24	10.13	14
195	11.55	24	10.13	14
196	11.55	24	10.13	14
197	11.55	24	10.13	14
198	11.55	24	10.13	14
199	11.55	24	10.13	14
200	11.55	24	10.13	14
201	11.55	24	10.13	14
202	11.55	24	10.13	14
203	11.55	24	10.13	14
204	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
205	11.55	24	10.13	14
206	11.55	24	10.13	14
207	11.55	24	10.13	14
208	11.55	24	10.13	14
209	11.55	24	10.13	14
210	11.55	24	10.13	14
211	11.55	24	10.13	14
212	11.55	24	10.13	14
213	11.55	24	10.13	14
214	11.55	24	10.13	14
215	11.55	24	10.13	14
216	11.55	24	10.13	14
217	11.55	24	10.13	14
218	11.55	24	10.13	14
219	11.55	24	10.13	14
220	11.55	24	10.13	14
221	11.55	24	10.13	14
222	11.55	24	10.13	14
223	11.55	24	10.13	14
224	11.55	24	10.13	14
225	11.55	24	10.13	14
226	11.55	24	10.13	14
227	11.55	24	10.13	14
228	11.55	24	10.13	14
229	11.55	24	10.13	14
230	11.55	24	10.13	14
231	11.55	24	10.13	14
232	11.55	24	10.13	14
233	11.55	24	10.13	14
234	11.55	24	10.13	14
235	11.55	24	10.13	14
236	11.55	24	10.13	14
237	11.55	24	10.13	14
238	11.55	24	10.13	14
239	11.55	24	10.13	14
240	11.55	24	10.13	14
241	11.55	24	10.13	14
242	11.55	24	10.13	14
243	11.55	24	10.13	14
244	11.55	24	10.13	14
245	11.55	24	10.13	14
246	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
247	11.55	24	10.13	14
248	11.55	24	10.13	14
249	11.55	24	10.13	14
250	11.55	24	10.13	14
251	11.55	24	10.13	14
252	11.55	24	10.13	14
253	11.55	24	10.13	14
254	11.55	24	10.13	14
255	11.55	24	10.13	14
256	11.55	24	10.13	14
257	11.55	24	10.13	14
258	11.55	24	10.13	14
259	11.55	24	10.13	14
260	11.55	24	10.13	14
261	11.55	24	10.13	14
262	11.55	24	10.13	14
263	11.55	24	10.13	14
264	11.55	24	10.13	14
265	11.55	24	10.13	14
266	11.55	24	10.13	14
267	11.55	24	10.13	14
268	11.55	24	10.13	14
269	11.55	24	10.13	14
270	11.55	24	10.13	14
271	11.55	24	10.13	14
272	11.55	24	10.13	14
273	11.55	24	10.13	14
274	11.55	24	10.13	14
275	11.55	24	10.13	14
276	11.55	24	10.13	14
277	11.55	24	10.13	14
278	11.55	24	10.13	14
279	11.55	24	10.13	14
280	11.55	24	10.13	14
281	11.55	24	10.13	14
282	11.55	24	10.13	14
283	11.55	24	10.13	14
284	11.55	24	10.13	14
285	11.55	24	10.13	14
286	11.55	24	10.13	14
287	11.55	24	10.13	14
288	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
289	11.55	24	10.13	14
290	11.55	24	10.13	14
291	11.55	24	10.13	14
292	11.55	24	10.13	14
293	11.55	24	10.13	14
294	11.55	24	10.13	14
295	11.55	24	10.13	14
296	11.55	24	10.13	14
297	11.55	24	10.13	14
298	11.55	24	10.13	14
299	11.55	24	10.13	14
300	11.55	24	10.13	14
301	11.55	24	10.13	14
302	11.55	24	10.13	14
303	11.55	24	10.13	14
304	11.55	24	10.13	14
305	11.55	24	10.13	14
306	11.55	24	10.13	14
307	11.55	24	10.13	14
308	11.55	24	10.13	14
309	11.55	24	10.13	14
310	11.55	24	10.13	14
311	11.55	24	10.13	14
312	11.55	24	10.13	14
313	11.55	24	10.13	14
314	11.55	24	10.13	14
315	11.55	24	10.13	14
316	11.55	24	10.13	14
317	11.55	24	10.13	14
318	11.55	24	10.13	14
319	11.55	24	10.13	14
320	11.55	24	10.13	14
321	11.55	24	10.13	14
322	11.55	24	10.13	14
323	11.55	24	10.13	14
324	11.55	24	10.13	14
325	11.55	24	10.13	14
326	11.55	24	10.13	14
327	11.55	24	10.13	14
328	11.55	24	10.13	14
329	11.55	24	10.13	14
330	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
331	11.55	24	10.13	14
332	11.55	24	10.13	14
333	11.55	24	10.13	14
334	11.55	24	10.13	14
335	11.55	24	10.13	14
336	11.55	24	10.13	14
337	11.55	24	10.13	14
338	11.55	24	10.13	14
339	11.55	24	10.13	14
340	11.55	24	10.13	14
341	11.55	24	10.13	14
342	11.55	24	10.13	14
343	11.55	24	10.13	14
344	11.55	24	10.13	14
345	11.55	24	10.13	14
346	11.55	24	10.13	14
347	11.55	24	10.13	14
348	11.55	24	10.13	14
349	11.55	24	10.13	14
350	11.55	24	10.13	14
351	11.55	24	10.13	14
352	11.55	24	10.13	14
353	11.55	24	10.13	14
354	11.55	24	10.13	14
355	11.55	24	10.13	14
356	11.55	24	10.13	14
357	11.55	24	10.13	14
358	11.55	24	10.13	14
359	11.55	24	10.13	14
360	11.55	24	10.13	14
361	11.55	24	10.13	14
362	11.55	24	10.13	14
363	11.55	24	10.13	14
364	11.55	24	10.13	14
365	11.55	24	10.13	14
366	11.55	24	10.13	14
367	11.55	24	10.13	14
368	11.55	24	10.13	14
369	11.55	24	10.13	14
370	11.55	24	10.13	14
371	11.55	24	10.13	14
372	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
373	11.55	24	10.13	14
374	11.55	24	10.13	14
375	11.55	24	10.13	14
376	11.55	24	10.13	14
377	11.55	24	10.13	14
378	11.55	24	10.13	14
379	11.55	24	10.13	14
380	11.55	24	10.13	14
381	11.55	24	10.13	14
382	11.55	24	10.13	14
383	11.55	24	10.13	14
384	11.55	24	10.13	14
385	11.55	24	10.13	14
386	11.55	24	10.13	14
387	11.55	24	10.13	14
388	11.55	24	10.13	14
389	11.55	24	10.13	14
390	11.55	24	10.13	14
391	11.55	24	10.13	14
392	11.55	24	10.13	14
393	11.55	24	10.13	14
394	11.55	24	10.13	14
395	11.55	24	10.13	14
396	11.55	24	10.13	14
397	11.55	24	10.13	14
398	11.55	24	10.13	14
399	11.55	24	10.13	14
400	11.55	24	10.13	14
401	11.55	24	10.13	14
402	11.55	24	10.13	14
403	11.55	24	10.13	14
404	11.55	24	10.13	14
405	11.55	24	10.13	14
406	11.55	24	10.13	14
407	11.55	24	10.13	14
408	11.55	24	10.13	14
409	11.55	24	10.13	14
410	11.55	24	10.13	14
411	11.55	24	10.13	14
412	11.55	24	10.13	14
413	11.55	24	10.13	14
414	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
415	11.55	24	10.13	14
416	11.55	24	10.13	14
417	11.55	24	10.13	14
418	11.55	24	10.13	14
419	11.55	24	10.13	14
420	11.55	24	10.13	14
421	11.55	24	10.13	14
422	11.55	24	10.13	14
423	11.55	24	10.13	14
424	11.55	24	10.13	14
425	11.55	24	10.13	14
426	11.55	24	10.13	14
427	11.55	24	10.13	14
428	11.55	24	10.13	14
429	11.55	24	10.13	14
430	11.55	24	10.13	14
431	11.55	24	10.13	14
432	11.55	24	10.13	14
433	11.55	24	10.13	14
434	11.55	24	10.13	14
435	11.55	24	10.13	14
436	11.55	24	10.13	14
437	11.55	24	10.13	14
438	11.55	24	10.13	14
439	11.55	24	10.13	14
440	11.55	24	10.13	14
441	11.55	24	10.13	14
442	11.55	24	10.13	14
443	11.55	24	10.13	14
444	11.55	24	10.13	14
445	11.55	24	10.13	14
446	11.55	24	10.13	14
447	11.55	24	10.13	14
448	11.55	24	10.13	14
449	11.55	24	10.13	14
450	11.55	24	10.13	14
451	11.55	24	10.13	14
452	11.55	24	10.13	14
453	11.55	24	10.13	14
454	11.55	24	10.13	14
455	11.55	24	10.13	14
456	11.55	24	10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
457	11.55	24	10.13	14
458	11.55	24	10.13	14
459	11.55	24	10.13	14
460	11.55	24	10.13	14
461	11.55	24	10.13	14
462	11.55	24	10.13	14
463	11.55	24	10.13	14
464	11.55	24	10.13	14
465	11.55	24	10.13	14
466	11.55	24	10.13	14
467	11.55	24	10.13	14
468	11.55	24	10.13	14
469	11.55	24	10.13	14
470	11.55	24	10.13	14
471			10.13	14
472			10.13	14
473			10.13	14
474			10.13	14
475			10.13	14
476			10.13	14
477			10.13	14
478			10.13	14
479			10.13	14
480			10.13	14
481			10.13	14
482			10.13	14
483			10.13	14
484			10.13	14
485			10.13	14
486			10.13	14
487			10.13	14
488			10.13	14
489			10.13	14
490			10.13	14
491			10.13	14
492			10.13	14
493			10.13	14
494			10.13	14
495			10.13	14
496			10.13	14
497			10.13	14
498			10.13	14

Time (s)	5 % Grade		6 % Grade	
	Speed (m/s)	Operating Mode Bin	Speed (m/s)	Operating Mode Bin
499			10.13	14
500			10.13	14
501			10.13	14
502			10.13	14
503			10.13	14
504			10.13	14
505			10.13	14
506			10.13	14
507			10.13	14
508			10.13	14
509			10.13	14
510			10.13	14
511			10.13	14
512			10.13	14
513			10.13	14
514			10.13	14
515			10.13	14
516			10.13	14
517			10.13	14
518			10.13	14
519			10.13	14
520			10.13	14
521			10.13	14
522			10.13	14
523			10.13	14
524			10.13	14
525			10.13	14
526			10.13	14
527			10.13	14
528			10.13	14
529			10.13	14
530			10.13	14
531			10.13	14
532			10.13	14
533			10.13	14
534			10.13	14
535			10.13	14
536			10.13	14
537			10.13	14
538			10.13	14
539			10.13	14
540			10.13	14

APPENDIX F

EMFs BY INITIAL SPEEDS

Initial Speed	Fuel Consumption		CO_2		NO_x		CO		HC		$PM_{2.5}$	
	(gal/trip)	EMF	(g/trip)	EMF	(g/trip)	EMF	(g/trip)	EMF	(g/trip)	EMF	(g/trip)	EMF
10	1.224	1.14	12314	1.14	60.080	1.14	18.595	1.11	4.455	1.13	4.639	1.15
20	1.219	1.13	12260	1.13	59.809	1.13	18.520	1.11	4.435	1.12	4.619	1.14
30	1.211	1.12	12175	1.12	59.373	1.13	18.407	1.10	4.402	1.11	4.587	1.14
40	1.204	1.12	12113	1.12	58.983	1.12	18.366	1.10	4.365	1.10	4.569	1.13
50	1.194	1.11	12013	1.11	58.445	1.11	18.253	1.09	4.322	1.09	4.535	1.12
60	1.179	1.09	11854	1.09	57.684	1.09	18.036	1.08	4.273	1.08	4.475	1.11
70	1.168	1.08	11746	1.08	57.104	1.08	17.923	1.07	4.234	1.07	4.438	1.10
80	1.142	1.06	11484	1.06	55.844	1.06	17.592	1.05	4.163	1.05	4.341	1.08
90	1.122	1.04	11287	1.04	54.862	1.04	17.284	1.04	4.086	1.03	4.232	1.05
100	1.105	1.02	11113	1.02	54.007	1.02	17.013	1.02	4.020	1.02	4.141	1.03
110	1.078	1.00	10846	1.00	52.724	1.00	16.697	1.00	3.952	1.00	4.036	1.00

APPENDIX G

VEHICLE AGE DISTRIBUTION

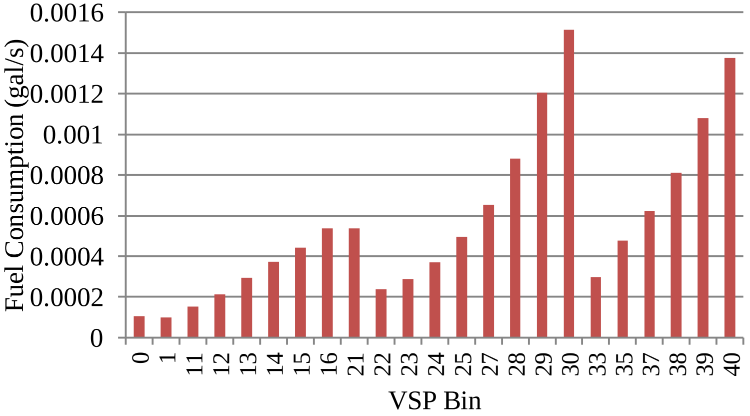
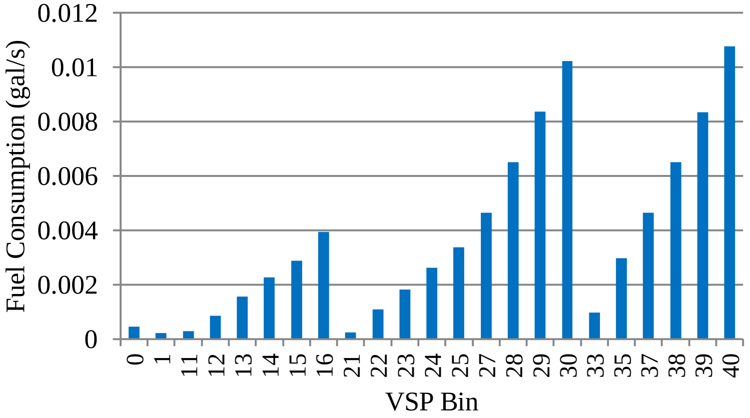
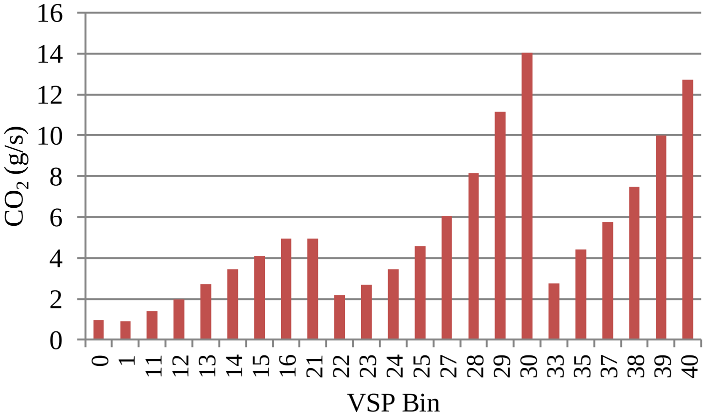
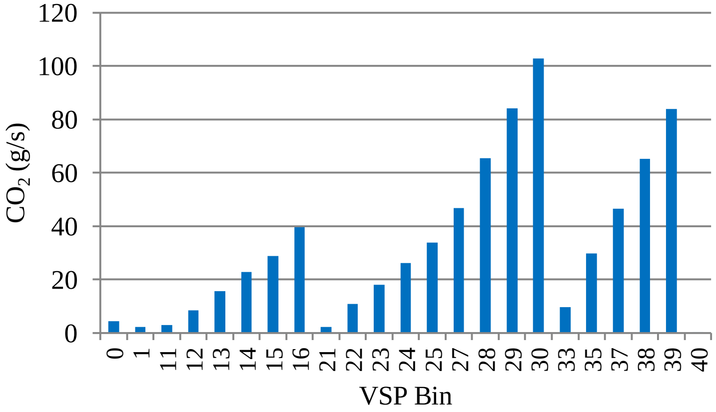
(source: User Guide for MOVES2010a (EPA, 2010b))

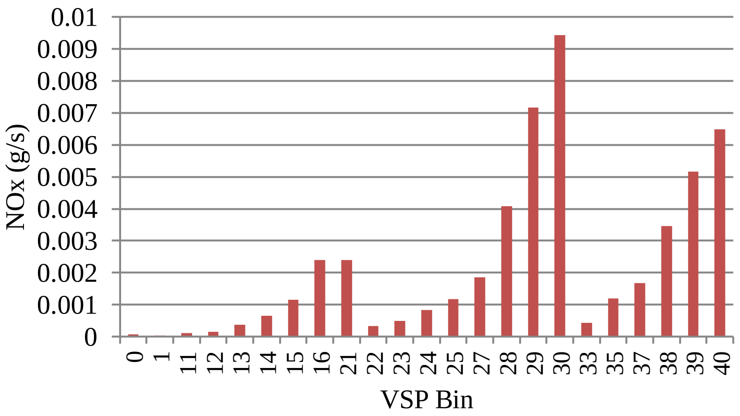
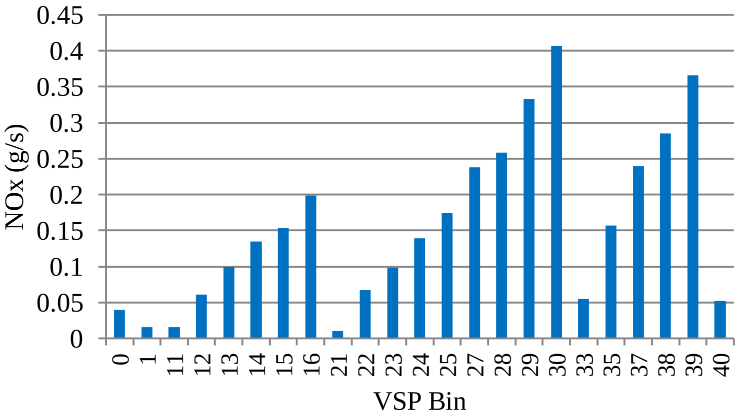
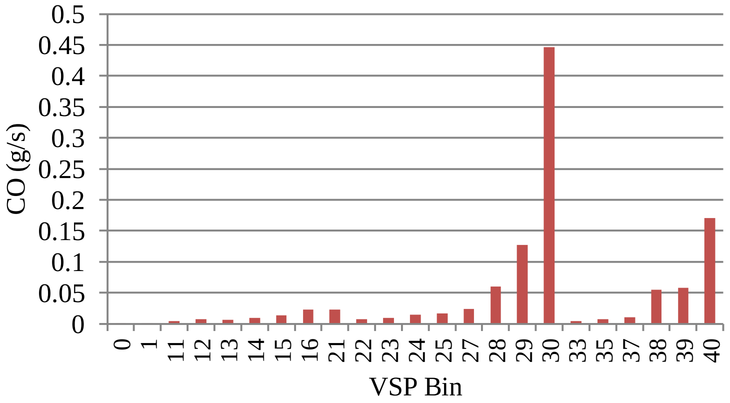
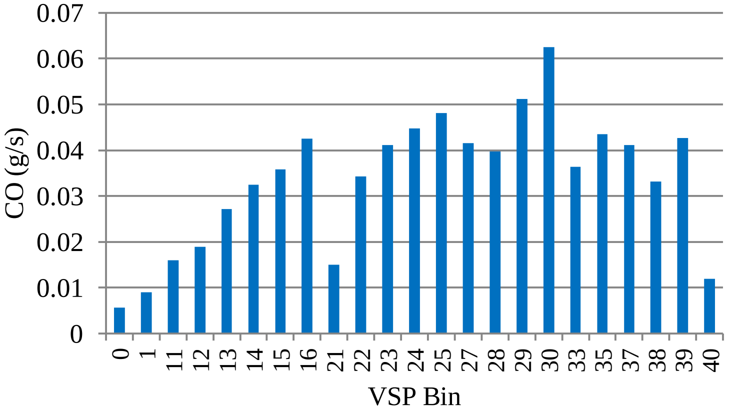
Vehicle Age (year)	Age Fraction	
	PC	HDDT
0	0.0646	0.2
1	0.0602	0.15
2	0.061	0.1
3	0.0624	0.1
4	0.0626	0.1
5	0.0642	0.07
6	0.0597	0.05
7	0.0562	0.05
8	0.0543	0.05
9	0.0596	0.02
10	0.0608	0.02
11	0.0622	0.01
12	0.0549	0.01
13	0.0522	0.01
14	0.0419	0.01
15	0.032	0.01
16	0.0226	0.01
17	0.0155	0.01
18	0.0129	0.01
19	0.0105	0.01
20	0.008	0
21	0.006	0
22	0.0045	0
23	0.0034	0
24	0.0026	0
25	0.0019	0
26	0.0014	0
27	0.0008	0
28	0.0006	0
29	0.0005	0
30	0	0

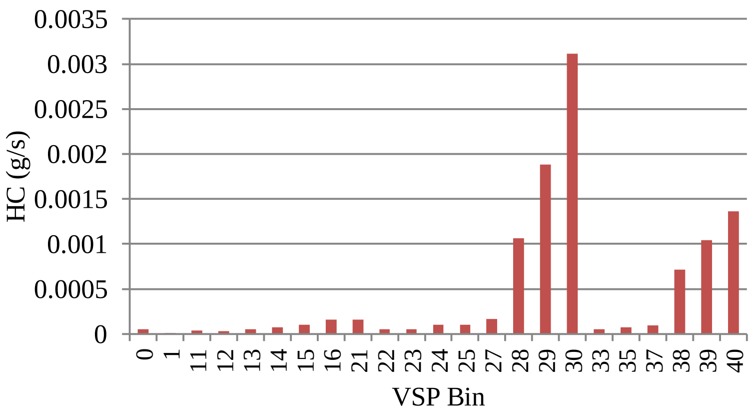
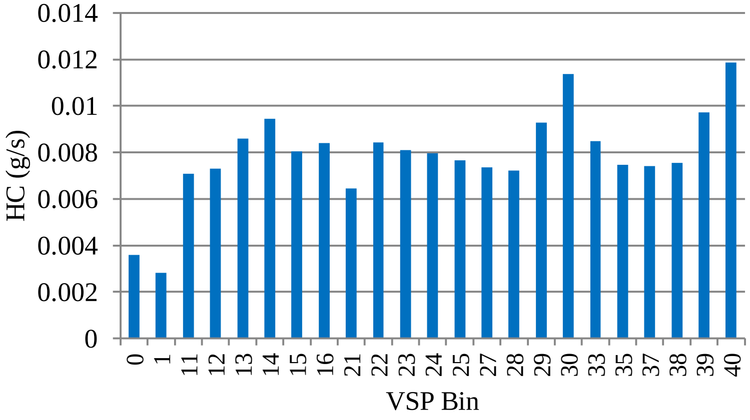
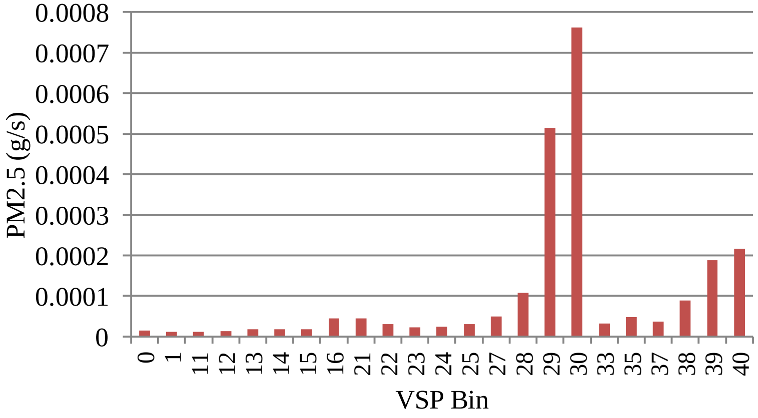
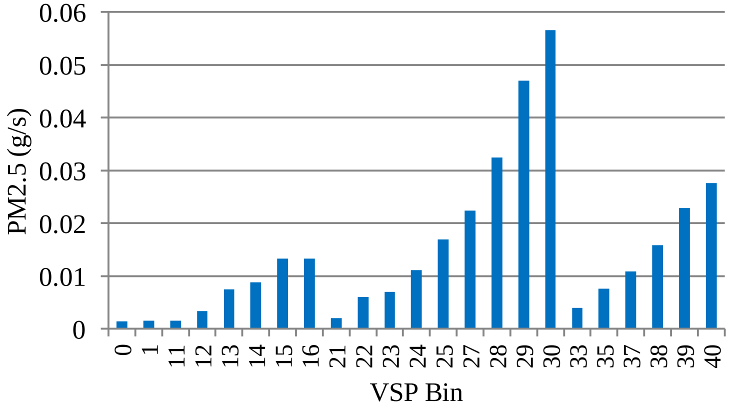
APPENDIX H

MOVES RESULTS IN JEFFERSON COUNTY, WASHINGTON (SINGLE-VEHICLE AGE)

Operating Mode #	Passenger Car						Heavy Duty Truck					
	$PM_{2.5}$	FC	CO2	NO_x	CO	HC	$PM_{2.5}$	FC	CO2	NO_x	CO	HC
0	1.42E-05	1.06E-04	0.98	6.92E-05	1.29E-03	5.39E-05	1.43E-03	4.41E-04	4.43	3.98E-02	5.69E-03	3.60E-03
1	1.23E-05	9.76E-05	0.90	2.93E-05	2.23E-04	1.31E-05	1.55E-03	2.17E-04	2.18	1.57E-02	8.95E-03	2.81E-03
11	1.22E-05	1.54E-04	1.42	1.03E-04	4.43E-03	3.68E-05	1.58E-03	2.91E-04	2.93	1.57E-02	1.60E-02	7.07E-03
12	1.29E-05	2.12E-04	1.96	1.57E-04	7.24E-03	2.82E-05	3.35E-03	8.47E-04	8.52	6.11E-02	1.89E-02	7.30E-03
13	1.83E-05	2.95E-04	2.73	3.67E-04	6.67E-03	5.32E-05	7.49E-03	1.55E-03	15.61	9.91E-02	2.72E-02	8.59E-03
14	1.82E-05	3.72E-04	3.44	6.47E-04	9.58E-03	7.24E-05	8.82E-03	2.26E-03	22.78	1.35E-01	3.25E-02	9.46E-03
15	1.76E-05	4.44E-04	4.11	1.15E-03	1.39E-02	1.01E-04	1.33E-02	2.86E-03	28.80	1.53E-01	3.58E-02	8.04E-03
16	4.53E-05	5.36E-04	4.96	2.39E-03	2.34E-02	1.61E-04	1.33E-02	3.94E-03	39.62	1.99E-01	4.26E-02	8.39E-03
21	4.53E-05	5.36E-04	4.96	2.39E-03	2.34E-02	1.61E-04	2.09E-03	2.35E-04	2.36	1.00E-02	1.50E-02	6.45E-03
22	3.10E-05	2.38E-04	2.20	3.30E-04	7.66E-03	5.05E-05	5.99E-03	1.09E-03	10.95	6.75E-02	3.42E-02	8.44E-03
23	2.25E-05	2.90E-04	2.68	4.98E-04	9.85E-03	5.45E-05	7.07E-03	1.81E-03	18.16	9.87E-02	4.11E-02	8.10E-03
24	2.49E-05	3.71E-04	3.44	8.40E-04	1.44E-02	1.04E-04	1.12E-02	2.61E-03	26.29	1.40E-01	4.47E-02	7.97E-03
25	3.10E-05	4.96E-04	4.59	1.18E-03	1.63E-02	1.04E-04	1.69E-02	3.36E-03	33.81	1.75E-01	4.81E-02	7.65E-03
27	4.95E-05	6.54E-04	6.05	1.85E-03	2.45E-02	1.64E-04	2.24E-02	4.64E-03	46.70	2.38E-01	4.16E-02	7.37E-03
28	1.08E-04	8.81E-04	8.15	4.08E-03	6.00E-02	1.06E-03	3.24E-02	6.50E-03	65.38	2.59E-01	3.98E-02	7.23E-03
29	5.14E-04	1.21E-03	11.17	7.16E-03	1.27E-01	1.89E-03	4.70E-02	8.36E-03	84.06	3.33E-01	5.11E-02	9.29E-03
30	7.62E-04	1.52E-03	14.02	9.42E-03	4.46E-01	3.11E-03	5.66E-02	1.02E-02	102.73	4.07E-01	6.25E-02	1.14E-02
33	3.21E-05	2.98E-04	2.75	4.32E-04	4.34E-03	5.29E-05	4.00E-03	9.69E-04	9.74	5.46E-02	3.63E-02	8.48E-03
35	4.76E-05	4.77E-04	4.42	1.19E-03	7.41E-03	7.34E-05	7.59E-03	2.96E-03	29.80	1.57E-01	4.36E-02	7.47E-03
37	3.68E-05	6.22E-04	5.75	1.67E-03	1.09E-02	9.41E-05	1.10E-02	4.64E-03	46.64	2.40E-01	4.12E-02	7.41E-03
38	8.93E-05	8.10E-04	7.50	3.46E-03	5.50E-02	7.17E-04	1.58E-02	6.49E-03	65.29	2.85E-01	3.31E-02	7.55E-03
39	1.87E-04	1.08E-03	9.99	5.16E-03	5.80E-02	1.04E-03	2.29E-02	8.35E-03	83.94	3.66E-01	4.26E-02	9.71E-03
40	2.17E-04	1.38E-03	12.73	6.49E-03	1.70E-01	1.36E-03	2.76E-02	1.08E-02	0.45	5.21E-02	1.19E-02	1.19E-02

<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">Fuel Consumption</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">CO_2</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

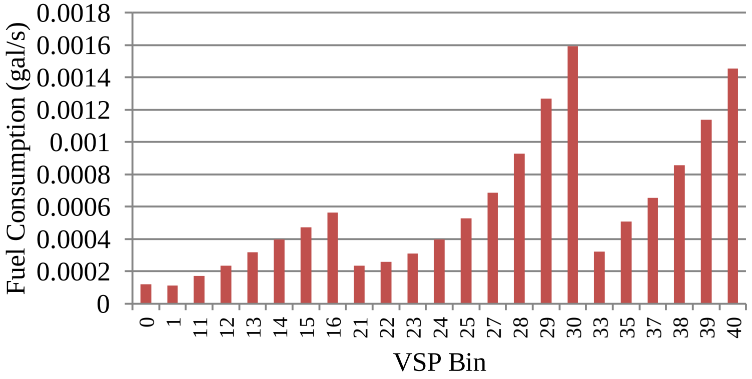
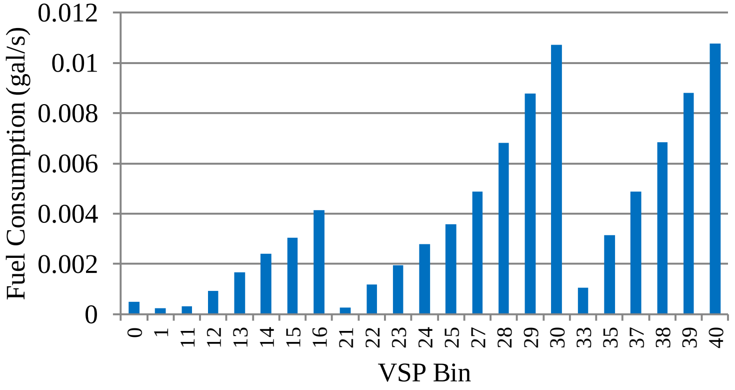
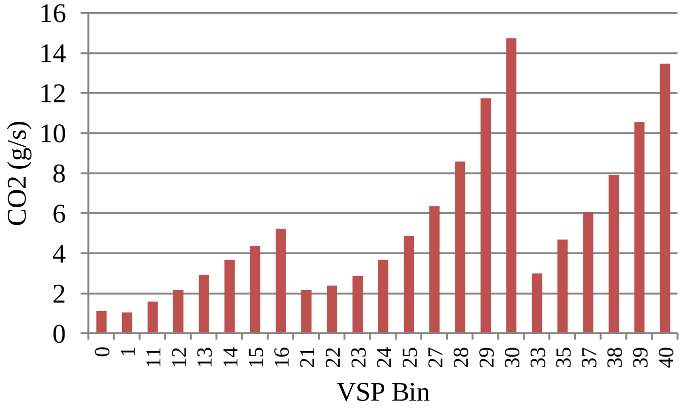
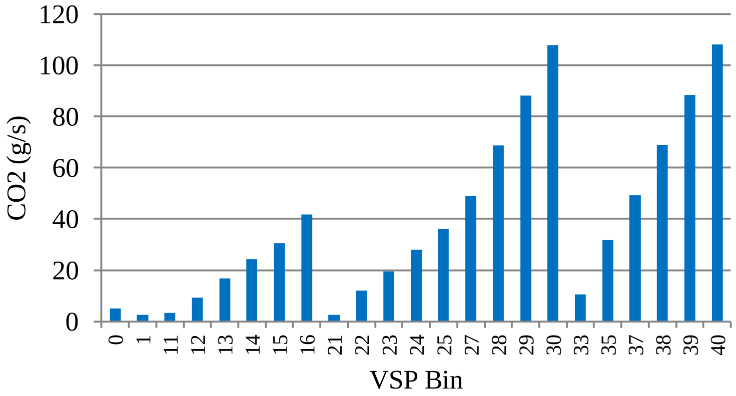
<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">NO$_x$</td></tr>
<tr><td> </td><td> </td></tr>
<tr><td colspan="2">CO</td></tr>
<tr><td> </td><td> </td></tr>
</table>

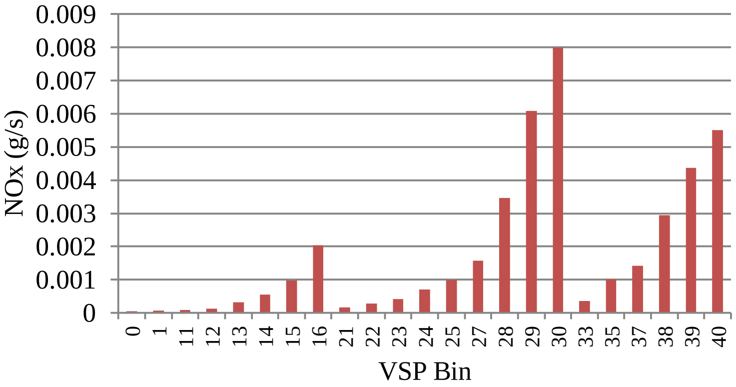
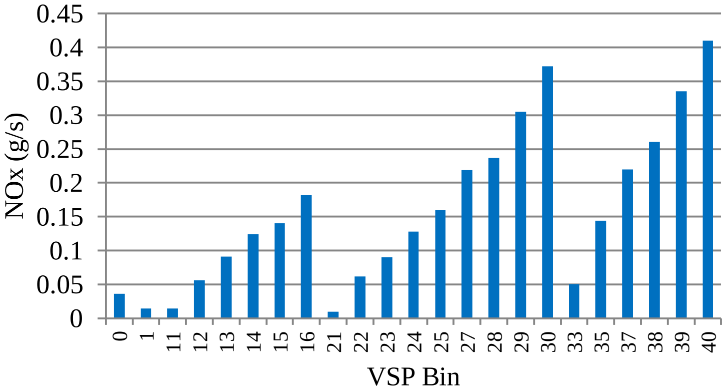
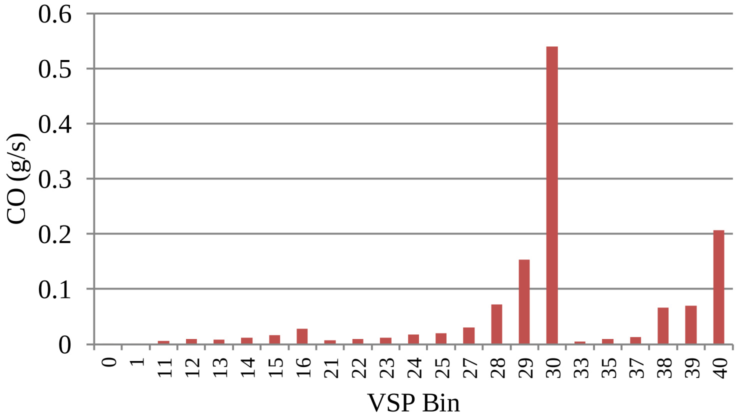
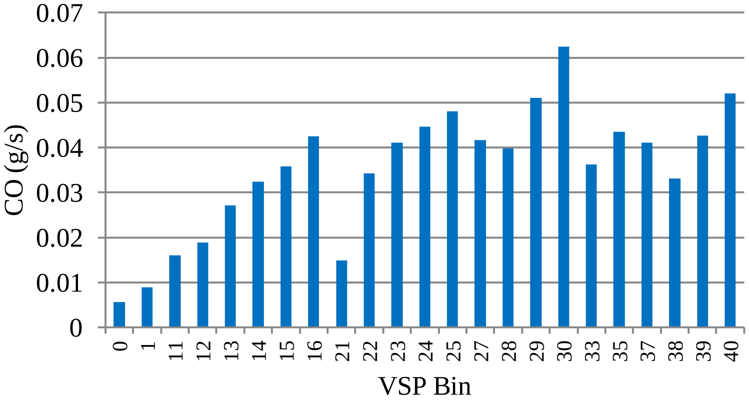
<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">HC</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">PM$_{2.5}$</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

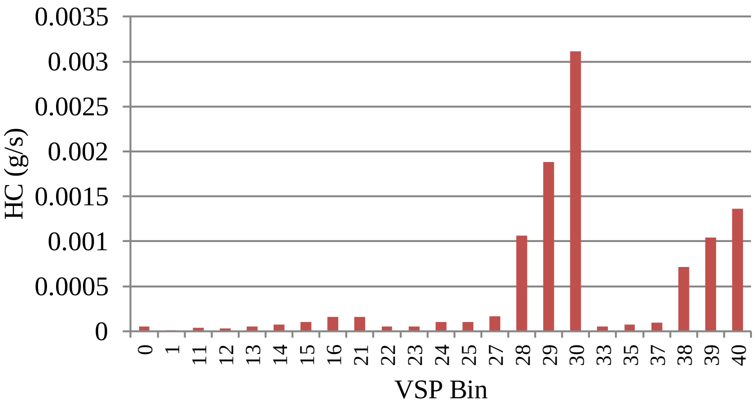
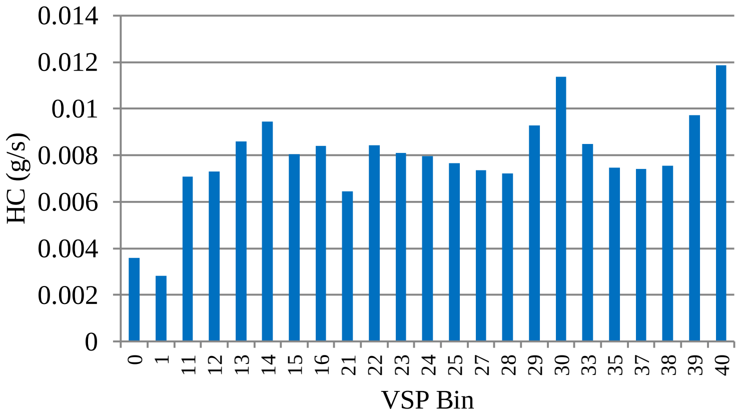
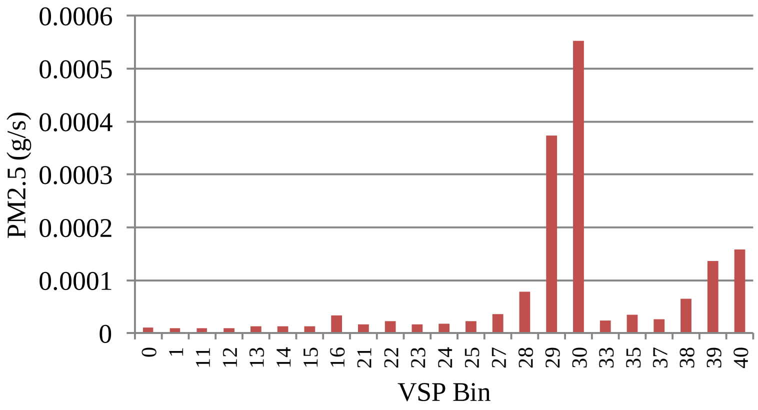
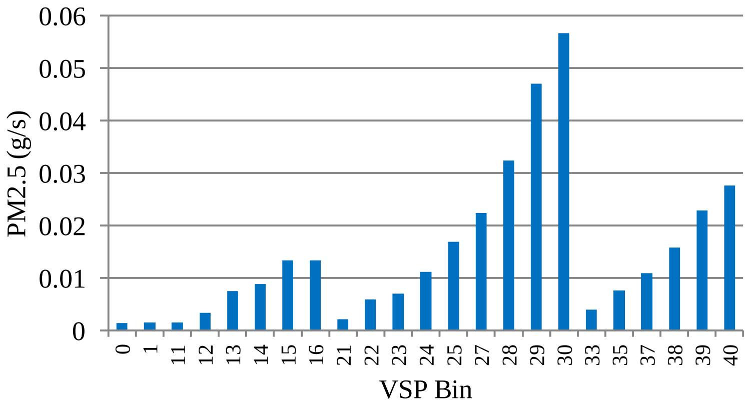
APPENDIX I

MOVES RESULTS IN JEFFERSON COUNTY, WASHINGTON (MULTI-VEHICLE AGE)

Operating Mode #	Passenger Car						Heavy Duty Truck					
	$PM_{2.5}$	FC	CO2	NO_x	CO	HC	$PM_{2.5}$	FC	CO2	NO_x	CO	HC
0	1.46E-05	1.29E-04	1.12	3.63E-04	5.14E-03	5.95E-04	6.90E-04	5.00E-04	5.03	2.27E-02	5.42E-03	2.03E-03
1	1.15E-05	1.18E-04	1.03	1.03E-03	5.47E-03	4.56E-04	7.49E-04	2.48E-04	2.50	1.34E-02	4.81E-03	1.72E-03
11	1.30E-05	1.80E-04	1.57	6.64E-04	1.06E-02	4.84E-04	8.28E-04	3.27E-04	3.29	1.24E-02	1.14E-02	3.42E-03
12	1.57E-05	2.40E-04	2.09	1.33E-03	1.77E-02	6.08E-04	1.71E-03	9.32E-04	9.38	4.46E-02	1.27E-02	3.58E-03
13	2.47E-05	3.35E-04	2.92	2.77E-03	2.43E-02	8.19E-04	3.92E-03	1.67E-03	16.76	7.21E-02	2.16E-02	4.39E-03
14	3.00E-05	4.25E-04	3.70	4.86E-03	3.51E-02	1.04E-03	4.71E-03	2.41E-03	24.27	9.60E-02	2.71E-02	4.84E-03
15	3.81E-05	5.11E-04	4.45	7.21E-03	4.27E-02	1.26E-03	6.87E-03	3.04E-03	30.56	1.12E-01	3.31E-02	4.44E-03
16	1.10E-04	6.23E-04	5.43	1.07E-02	5.52E-02	1.58E-03	6.89E-03	4.14E-03	41.62	1.53E-01	4.23E-02	4.43E-03
21	2.32E-05	2.36E-04	2.06	1.63E-03	1.77E-02	6.95E-04	1.03E-03	2.62E-04	2.64	8.35E-03	1.15E-02	3.35E-03
22	2.52E-05	2.69E-04	2.35	1.94E-03	2.00E-02	6.63E-04	2.96E-03	1.18E-03	11.92	5.17E-02	1.98E-02	4.19E-03
23	2.51E-05	3.31E-04	2.89	2.97E-03	2.59E-02	7.85E-04	3.67E-03	1.94E-03	19.50	7.93E-02	2.36E-02	4.12E-03
24	2.97E-05	4.25E-04	3.71	5.07E-03	3.83E-02	1.05E-03	5.87E-03	2.79E-03	28.02	1.12E-01	2.92E-02	4.25E-03
25	3.85E-05	5.55E-04	4.84	7.14E-03	4.26E-02	1.18E-03	8.83E-03	3.57E-03	35.91	1.39E-01	3.35E-02	4.21E-03
27	6.59E-05	7.22E-04	6.30	1.17E-02	7.01E-02	1.76E-03	1.20E-02	4.88E-03	49.03	1.95E-01	3.87E-02	4.27E-03
28	2.98E-04	9.73E-04	8.48	1.75E-02	1.21E-01	2.99E-03	1.82E-02	6.83E-03	68.65	2.33E-01	4.24E-02	4.27E-03
29	1.03E-03	1.33E-03	11.62	2.49E-02	2.44E-01	4.87E-03	2.78E-02	8.78E-03	88.26	2.89E-01	5.45E-02	5.49E-03
30	2.54E-03	1.67E-03	14.56	3.27E-02	6.99E-01	8.32E-03	3.46E-02	1.07E-02	107.87	3.54E-01	6.66E-02	6.71E-03
33	6.19E-05	3.38E-04	2.95	2.23E-03	1.54E-02	7.06E-04	2.08E-03	1.05E-03	10.53	3.80E-02	2.28E-02	4.97E-03
35	6.46E-05	5.30E-04	4.62	6.51E-03	2.84E-02	9.84E-04	3.93E-03	3.14E-03	31.63	1.39E-01	2.88E-02	4.68E-03
37	7.00E-05	6.85E-04	5.97	9.51E-03	3.87E-02	1.20E-03	5.86E-03	4.89E-03	49.16	2.06E-01	3.96E-02	5.02E-03
38	1.28E-04	8.93E-04	7.78	1.44E-02	1.03E-01	2.33E-03	8.81E-03	6.84E-03	68.83	2.57E-01	3.32E-02	6.31E-03
39	3.04E-04	1.19E-03	10.36	2.05E-02	1.43E-01	3.36E-03	1.34E-02	8.80E-03	88.49	3.21E-01	4.27E-02	8.12E-03
40	3.53E-04	1.51E-03	13.20	2.56E-02	3.80E-01	4.52E-03	1.65E-02	1.08E-02	108.16	3.92E-01	5.22E-02	9.92E-03

<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">Fuel Consumption</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">CO_2</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">NO$_x$</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">CO</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

<table>
<tr><th>Passenger Car</th><th>Heavy Duty Diesel Truck</th></tr>
<tr><td colspan="2">HC</td></tr>
<tr><td> </td><td> </td></tr>
<tr><td colspan="2">PM$_{2.5}$</td></tr>
<tr><td> </td><td> </td></tr>
</table>

APPENDIX J

ESTIMATION ON RATIOS OF BENEFITS TO COST ON VERTICAL CREST CURVES

Case	Benefit-Cost Ratios											
	5%[1]			10%[2]			15%[3]			20%[4]		
	10-Year	20-Year	30-Year	10-Year	20-Year	30-Year	10-Year	20-Year	30-Year	10-Year	20-Year	30-Year
1	0.22	0.56	1.16	0.40	1.02	2.13	0.59	1.48	3.10	0.77	1.94	4.07
2	0.20	0.50	1.04	0.19	0.47	0.98	0.18	0.45	0.93	0.17	0.42	0.88
3	8.74	23.29	50.15	16.18	43.32	93.50	23.62	63.36	136.85	31.06	83.39	180.20
4	0.98	2.47	5.15	1.05	2.64	5.52	1.12	2.82	5.88	1.19	2.99	6.25

NOTE: [1] 5 percent truck volume and 95 percent passenger car volume of total traffic volume; [2] 10 percent truck and 90 percent passenger car volumes; [3] 15 percent truck and 85 percent passenger car volumes; [4] 20 percent truck and 80 percent passenger car volumes.

APPENDIX K

ESTIMATION ON BENEFIT-COST RATIOS ON HORIZONTAL CURVES

Case	Benefit-Cost Ratios											
	5%			10%			15%			20%		
	10-Year	20-Year	30-Year	10-Year	20-Year	30-Year	10-Year	20-Year	30-Year	10-Year	20-Year	30-Year
1	3.59	7.47	11.59	3.80	7.85	12.22	4.01	8.22	12.85	4.22	8.60	13.49
2	1.36	3.34	5.42	1.46	3.53	5.73	1.56	3.71	6.04	1.66	3.89	6.35
3	1.40	3.42	5.50	1.30	3.24	5.24	1.20	3.05	4.97	1.10	2.87	4.70
4	0.54	1.82	3.14	0.58	1.90	3.27	0.62	1.97	3.40	0.66	2.04	3.53
5	8.50	16.57	25.16	8.80	17.10	26.07	9.09	17.63	26.99	9.38	18.16	27.90
6	0.89	2.45	4.08	1.06	2.76	4.58	1.23	3.07	5.09	1.40	3.38	5.59

NOTE: [1] 5 percent truck volume and 95 percent passenger car volume of total traffic volume; [2] 10 percent truck and 90 percent passenger car volumes; [3] 15 percent truck and 85 percent passenger car volumes; [4] 20 percent truck and 80 percent passenger car volumes.

VITA

Name: Myung-Hoon Ko

Address: Zachry Department of Civil Engineering, Texas A&M University,
College Station, TX 77843-3136

Email Address: kmh114@gmail.com

Education: B.S., Aeronautical & Mechanical Engineering,
Korea Aerospace University, 1996
Ph.D., Civil Engineering, Texas A&M University, 2011

Academic Interests:

– Environmentally and safety conscious highway geometric design
– Sustainable Transportation
– Transportation Safety Analysis & Evaluation
– Urban Transportation Modeling in Planning & Operations

Experience:

– Graduate Research Assistant, Texas Transportation Institute (TTI), September 2008 ~ December 2011
  ▪ Participated in several research regarding traffic safety analysis and sustainable transportation
– Airport Safety Inspector, Ministry of Land, Transport, and Maritime Affairs, December 2002 ~ August 2006
  ▪ Evaluated the operational procedures and programs to ensure safe operation in the airport
– Production Engineer, Korea Aerospace Industries Ltd., April 2000 ~ December 2002
  ▪ Programmed a Numerical Control (NC) code
  ▪ Designed the 3D models for several airplane parts
– Instructor, Korea Aviation College, March 1999 ~ December 1999
  ▪ Instructed undergraduate level courses (Airplane Structure, Dynamics, and Power Plants) for aviation maintenance technicians