

FIELD EVALUATION OF ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL IN THE VICINITY OF SIGNALIZED INTERSECTIONS

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

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May 3, 2016
Blacksburg, VA

Keywords: Eco-driving, Signal Timing, Fuel Consumption, Eco-Cooperative Adaptive Cruise Control, Autonomous Vehicles, Automated Vehicles, Signalized Intersections

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SCHOLARLY ABSTRACT

Traffic signals are used at intersections to manage the flow of vehicles by allocating right-of-way in a timely manner for different users of the intersection. Traffic signals are therefore installed at an intersection to improve overall safety and to decrease vehicular average delay. However, the variation of driving speed in response to these signals causes an increase in fuel consumption and air emission levels. One solution to this problem is Eco-Cooperative Adaptive Cruise Control (Eco-CACC), which attempts to reduce vehicle fuel consumption and emission levels by optimizing driver behavior in the vicinity of a signalized intersection. Various Eco-CACC algorithms have been proposed by researchers to address this issue. With the help of vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication, algorithms are being developed that utilize signal phasing and timing (SPaT) data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections.

The research presented in this thesis constitutes the third phase of a project that entailed developing and evaluating an Eco-CACC system. Its main objective is to evaluate the benefits of the newly developed Eco-CACC algorithm that was proposed by the Center for Sustainable Mobility at the Virginia Tech Transportation Institute. This algorithm uses advanced signal information (SPaT) to compute the fuel-optimal trajectory of vehicles, and, then, send recommended speeds to drivers as an audio message or implement them directly into the subject vehicle. The objective of this study is to quantitatively quantify the fuel-efficiency of the Eco-CACC system in a real field environment. In addition, another goal of this study is to address the implementation issues and challenges with the field application of the Eco-CACC system.

A dataset of 2112 trips were collected as part of this research effort using a 2014 Cadillac SRX equipped with a vehicle onboard unit for (V2V) and (V2I) communication. A total of 32 participants between the ages of 18 and 30 were randomly selected from one age group (18-30) with an equal number of males and females. The controlled experiment was conducted on the Virginia Smart Road facility during daylight hours for dry pavement conditions. The controlled

field experiment included four different scenarios: normal driving, driving with red indication countdown information provided to drivers, driving with recommended speed information computed by the Eco-CACC system and delivered to drivers, and finally automated driving (automated Eco-CACC system). The controlled field experiment was conducted for four values of red indication offsets along an uphill and downhill approach.

The collected data were compared with regard to fuel economy and travel time over a fixed distance upstream and downstream of the intersection (820 ft (250 m) upstream of the intersection to 590 ft (180 m) downstream for a total length of 1410 ft (430 m)). The results demonstrate that the Eco-CACC system is very efficient in reducing fuel consumption levels especially when driving downhill. The field data indicates that the automated scenario could produce fuel and travel time savings of 31% and 9% on average, respectively. In addition, the study demonstrates that driving with a red indication countdown and recommended speed information can produce fuel savings ranging from 4 to 21 percent with decreases in travel times ranging between 1 and 10 percent depending on the value of red indication offset and the direction. Split-split-plot design was used to analyze the data and test significant differences between the four scenarios with regards to fuel consumption and travel time. The analysis shows that the differences between normal driving and driving with either the manual or automated Eco-CACC systems are statistically significant for all the red indication offset values.

FIELD EVALUATION OF ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL IN THE VICINITY OF SIGNALIZED INTERSECTIONS

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GENERAL AUDIENCE ABSTRACT

Signalized intersections have recently drawn attention as researchers realized the significant vehicle fuel consumption increase in their vicinity. When coming close to a signalized intersection, drivers are completely unaware of exactly when the traffic signal will change. Consequently, drivers may have to accelerate/decelerate aggressively to respond to traffic signal changes. This results in non-smooth driving behavior. Non-smooth driving (e.g. hard braking, sudden speed changes) consumes excessive fuel as it follows a non-ideal speed profile. Research efforts have been conducted to generate the fuel-optimal speed profile in the vicinity of signalized intersections. Establishing communication between vehicles and the traffic signal controller is a powerful tool to receive data that otherwise was not available and then use that data to make driver behavior smoother and, therefore, reduce vehicle fuel consumption and emission levels. Various messages can be exchanged wirelessly between the two parties. Among these messages is the Signal Phasing and Timing (SPaT) message that can provide valuable information in advance about upcoming traffic signal timing changes. This information could help drivers make early decisions whether they should proceed or stop safely and smoothly.

Recent research has been trying to address this issue and propose different algorithms that could optimize driver behavior ahead of the intersection and, thereby, reduce pollutions and fuel consumption levels. With the help of vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication, algorithms are being developed that utilize SPaT data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections.

Several algorithms have been introduced to provide an optimal-speed profile for approaching vehicles by optimizing deceleration/acceleration vehicle profiles. However, none explicitly attempted to minimize vehicle fuel consumption. In addition, most of the proposed algorithms have been developed and tested in traffic simulation environment where recommended speeds are enforced and many issues, such as the delay in the system and human-vehicle interaction, are not considered.

This thesis presents the results of a unique controlled field experiment that was designed to evaluate an Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system that was developed by the Center for Sustainable Mobility at the Virginia Tech Transportation Institute. The Eco-CACC system computes and recommends real-time fuel-efficient speeds using V2I communicated data. The computed speeds can be delivered to drivers as an audio message or be implemented directly in the testing vehicle. The objective function of the proposed algorithm is the explicit minimization of the total fuel consumed to travel from some distance upstream of the intersection to a distance downstream of the intersection.

This experiment is considered as the first controlled field experiment of its kind in the world that was conducted in a real environment with real participants using a fully-automated vehicle. The controlled field experiment included four different scenarios, namely: normal driving, driving with countdown (time left from red to green in current signal indication) information provided to drivers, driving with recommended speed information also provided to drivers, and automated driving. Automated driving means that the car can communicate to the traffic light and adjust its speed by itself (i.e. driver only controls the steering wheel).

The controlled field experiment was conducted for four different signal timings and two different directions (uphill and downhill) on the Smart Road test facility. In total, 2112 trips were conducted using 32 different participants between the ages of 18 and 30 with equal number of males and females. Participants drove 32 loops on the smart road passing a signalized intersection continuously, where the data were recorded in the data acquisition system under a researcher's surveillance.

The collected data were compared with regard to fuel economy and travel time over a fixed distance upstream and downstream of the intersection (1410 ft (430m) section). The results demonstrate that the Eco-CACC system is very efficient in reducing fuel consumption levels especially when driving downhill. The analyzed data indicates that the automated scenario has the most fuel consumption savings levels among all tested scenarios and could produce fuel and travel time savings up to 45 and 13 percent, respectively.

In addition, the study demonstrates that driving with countdown and recommended speed information can produce fuel savings ranging between 21 and 4 percent with decreases in travel times ranging between 1 and 10 percent.

Interestingly, post-drive survey results show that 91% of the participants would like to have the automated scenario implemented in their cars if it would save 10 to 15 percent in fuel consumption. In addition, the automated scenario was ranked by the participants as the best scenario for enhancing safety and comfort levels.

DEDICATION

إلى أعلى امرأة في هذا الكون، أمي: هياء عبد الله الناصر

To the most beloved woman to me in this world, my mother: Haya Abdullah Alnasser

When I was a child
You were a doctor for me that I went to when I wasn't well
You were a teacher for me that I used to ask that I didn't know
You were a preacher for me that answered my religious questions
You were a loyal guard protecting me from all potential harm
You were a lawyer defending my rights to my opponents
You were a river of love and compassion that I used to swim in when life got hard
You were! You were! You were!
You were and "are" and "will be" everything in my life!

حينما كنتُ طفلاً
كنتِ لي طبيباً أشكو إليه وجعي
كنتِ معلماً أسأله كل ما يجهلني
كنتِ شيخاً يفتيني في أمر ديني وديني
كنتِ حارساً أميناً لي من كل شر يؤذي
كنتِ محامياً يدافع عن حقي أمام خصمي
كنتِ بجرّاً من الحب والحنان أعمد إليه حينما تدهمني قسوة الحياة!
كنتِ و كنتِ و كنتِ!
كنتِ ولا زلتِ و ستظلين لي كل شيء!

إلى أعلى رجل في هذا الكون، أبي: حمد عثمان المناع

To the most beloved man in this world, my father: Hamad Othman Almannaa

When I was a child
You were a school where I used to learn good manners and politeness
You were light that shone my way in the dark nights
You were a sage that I listened to what I lost my way
You were a guide that showed me the way when my compass was lost
You were a magic key that I looked for when doors were closed
You were! You were! You were!
You were and "are" and "will be" everything in my life!

حينما كنتُ طفلاً
كنتِ لي مدرسةً أتعلّم منها سمو الأخلاق و علو المعالي
كنتِ لي نبراساً أهندي إليه في دجى الليل
كنتِ لي حكماً أستمع إليه ساعةً من نهار حينما أضلّ طريقي
كنتِ مرشداً ألتجأ إليه عندما تنوه بوصلتي
بل كنتِ لي مفتاحاً سحرياً أبحث عنه في كل نازلة!
كنتِ و كنتِ و كنتِ!
كنتِ ولا زلتِ و ستظل لي كل شيء!

والذي :

هذه بذرتكم التي زرعتم و سقيتم، نمت و أينعت! وهذه الرسالة هي أحد ثمارها!

My dear parents:

This is the seed you planted and kept watered many years ago

It has grown and this thesis is one fruit of it!

Your son : Mohammed

5/14/2016

ابنكم : محمد

6 شعبان 1437

ACKNOWLEDGEMENTS

All praise is due to Allah, we thank him, seek his guidance and forgiveness. I would like to express my sincere gratitude to my advisory committee for their outstanding guidance, continuous support, never-ending patience, and friendly advice during the past two years: Dr. Hesham Rakha, Dr. Ihab El-Shawarby, and Dr. Amara Loulizi. I would like to give special thanks to Dr. Hesham Rakha for his encouragement and insightful comments on my research.

My sincere thanks also go to Dr. Hao Chen and the researchers at the center for technology development at the Virginia Tech Transportation Institute: Andy Peterson, Jean Paul, Bill Freeman, Tammy Russell, Greg Brown, and Josh Quesenberry for their support in programming and developing the hardware and software environment.

I would also like to extend my deepest appreciation to the Smart Road staff: Leonore Nadler and her team in helping me reserve the Smart Road and schedule participants. Also, I thank Dr. Suzie Lee and Julie Cook for assisting me in preparing the IRB documents and writing the protocol.

I would also thank my colleagues at the Center for Sustainable Mobility for helping me in testing and conducting the experiment; in particular, Mani Venkat Ala and Karim Fadlhoun. I also would like to offer my sincerest gratitude to Dr. JP Morgan and the researchers at the Lisa Center for their assistance in the statistical part of this research.

During the past two years, I have been blessed with a supportive and cheerful group of colleagues at Virginia Tech; in particular: Dr. Mohammed Elhenawy, Ahmed Elbery, and Abdallah Hassan. I greatly benefited from their excellent expertise in statistics, programming, and even in the life as general. They served as someone more than a friend in the same shoes.

Last but not least, I'm extremely thankful to my family: my parents, my wife (Asmaa), my brothers, and my lovely sisters (Eman and Huda) for their financial and emotional support throughout my undergraduate and graduate career.

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CHAPTER 1: INTRODUCTION

Traffic lights are used at intersections to manage the flow of vehicles by allocating right-of-way in a timely manner for different users of the intersection. Traffic signals are therefore installed at an intersection to improve overall safety and to decrease average travel time. However, the variation of driving speed in response to these signals causes an increase in air emissions and fuel consumption [1]. That happens because of non-optimum speeds created in the vicinity of the signalized intersections [2]. One solution to this problem is eco-driving, which is a strategy that aims to reduce excessive fuel consumption and emissions by optimizing drivers' behaviors (i.e. speed, acceleration, braking. etc) ahead of the intersection [3, 4]. With the help of infrastructure-to-vehicle (I2V) communication, eco-driving could utilize the signal phase and the queue-discharging time information to optimize the speed trajectories for vehicles approaching an intersection [5, 6]. Therefore, optimizing the speed trajectories could help minimizing fuel consumption by providing an optimal-speed profile. The research presented in this thesis evaluates the fuel-efficiency of the newly developed eco-driving algorithm, namely, the Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system that was proposed by Kamalanathsharma [7]. In this thesis, a controlled field experiment around a signalized intersection was conducted to quantify the benefits of the Eco-CACC system. This chapter presents a broad introduction to the study's background, objectives, approach, and finally the organization of this thesis.

1.1 Background

Signalized intersections have been drawn attention recently due to producing excessive fuel consumption usage [1]. On-coming vehicles to a signalized intersection have no clue for when exactly the traffic signal would change. Therefore, drivers may have to accelerate/decelerate aggressively in response to traffic lights. This results in non-smooth driving behavior (e.g. hard barking, sudden speed changes) that consumes excessive fuel as it follows a non-ideal speed profile [2]. Research efforts have been conducted to generate the fuel-optimal speed profile in the vicinity of signalized intersections [5, 8, 9]. Establishing Communication between vehicles and the traffic signal controller is a powerful tool to make the driver behavior smoother and, therefore, less fuel consumption and emission would be achieved. Various messages can be exchanged wirelessly between the two parties. Among these messages is SPaT message that can provide valuable information in advance about upcoming traffic signal timing changes. This

information could help drivers to make early decisions whether they should proceed or stop safely and smoothly.

Recent research has been trying to address this issue and propose different algorithms that could optimize drivers' behaviors ahead of the intersection and, thereby, reduce pollutions and fuel consumption. With the help of vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication, algorithms are being developed that utilize SPaT data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections [8, 10-12]. Therefore, it is possible that vehicles can communicate with the traffic signals, receive SPaT information, and adjust their speeds accordingly.

Several algorithms have been introduced to provide an optimal-speed profile for approaching vehicles by optimizing deceleration/acceleration vehicle profiles. However, none of which attempted to minimize explicitly vehicle fuel consumption. In addition, most of the proposed algorithms have been developed and tested in traffic simulation environments where recommended speeds are enforced and many issues, such as the delay in the system and human-vehicle interaction, are not considered.

In this thesis, the Eco-CACC system was tested in a real field environment. The Eco-CACC system computes and recommends real-time fuel-efficiency speeds using V2V and V2I communicated data. The computed speeds can be delivered to drivers as an audio message or be implemented directly in the testing vehicle. On contrast to most of the previous developed algorithms, the objective function of this algorithm is the explicit minimization of the total fuel consumed to travel from some distance upstream of the intersection to a distance downstream of the intersection.

1.2 Thesis Objectives

The objectives of this research effort are two-fold. First, construct a comprehensive dataset of the drivers' responses at a signalized intersection when they receive advanced signal timing information from the traffic signal controller. Second, evaluate the fuel efficiency effectiveness of the Eco-CACC at a signalized intersection and quantify the other benefits.

In [7], Kamalanathsharma has modeled and tested the Eco-CACC system in a simulated environment. However, the Eco-CACC system has not been utilized for actual implementation. Therefore, this thesis will be a real-implementation study of the ECO-CACC system. It will enable

experimental validation of the Eco-CACC system and compare simulation results with field study results.

1.3 Research Approach

The initial task for this research effort was to design and conduct a field experiment to gather data on reducing fuel consumption and travel times at a signalized intersection using the Eco-CACC system for clear weather and dry roadway conditions. The Eco-CACC system is a type of Cooperative Adaptive Cruise Control that uses vehicle-to-infrastructure (V2I) communication to receive SPaT data from downstream intersections. Subsequently, the Eco-CACC system sends recommended speeds and optimizes the vehicle's trajectory to minimize fuel consumption levels. A moving horizon dynamic programming (DP) approach is used to optimize the vehicle trajectories. To enhance the computational efficiency of the DP, a modified A-star algorithm has been developed.

The Eco-CACC system has been tested in a simulated environment on 30 top-sold vehicles in the United States. Results show that using the Eco-CACC system could provide fuel savings up to 30 percent within the vicinity of signalized intersections [13]. Therefore, there is a need to conduct a field experiment using the Eco-CACC system to validate the simulation results.

In this thesis, the experiment was conducted solely on the Smart Road test facility and only during daylight hours on a dry pavement condition. The experiment was composed of two main phases. The first phase was comprised of the determination of eligibility and the procurement of informed consent from each participant. The second phase, the Smart Road test-track driving portion, required only one session in one day for each participant and took approximately 2-3 hours to complete.

The testing vehicle was equipped with the Eco-CACC system, which contains Dedicated Short-Range Communication (DSRC), Adaptive Cruise Control (ACC) system, and Differential Global Positioning System (DGPS), and a real-time data acquisition system (DAS). In total, 2112 trips were conducted using 32 different participants (16 females and 16 males) between the ages of 18 and 30. Participants drove 32 loops on the smart road passing a signalized intersection continuously, where the data were recorded in the data acquisition system under a researcher's surveillance.

Four different scenarios were tested, namely: normal driving, driving with a red indication countdown information provided to drivers, driving with speed recommendations computed by the Eco-CACC system and provided to drivers, and finally automated driving (automated Eco-CACC system). Vehicle data (fuel consumption, current speed, target speed, and distance to stop line) and SPaT information were calculated every 0.1 second during the test for the four scenarios. Only the data in the range of Eco-CACC system (820 ft (250 m) upstream to 590 ft (180 m) downstream of the intersection) were extracted and analyzed.

The split-split-plot design (SSPD) was used as the factorial treatment structure has three levels (scenarios, red indication offsets, and directions) of experimental units. This design was used with two replications to test the effect of the four scenarios (main treatment), four values of red indication offsets (10, 15, 20, and 25 seconds) (split-plot treatment), and two directions (uphill and downhill) (split-split-plot treatment). The SSPD tested significant differences among all the similar experimental units and helped to analyze this data when applying Analysis of Variance (ANOVA). Conclusion for this study and recommendations for future work are presented at the end of the thesis.

1.4 Thesis Organization

This thesis is organized into five chapters. As well as the research objectives and thesis organization, chapter one briefly presents an overview of the research in testing the Eco-CACC system in the vicinity of a signalized intersection. Chapter two presents a detailed literature review of the previously developed algorithms on eco-driving, along with the implemented field and simulation experiments. A brief summary of the Eco-CACC system is also presented in chapter two. Chapters three and four discuss the experimental design of the study, followed by field data analysis highlighting the benefits of the ECO-CACC system. It should be noted that chapters three and four have the same outlines; however, chapter three discusses the results of normal driving, driving with a red indication countdown, and driving with recommended speed information, while chapter four discusses the results of normal driving, driving with recommended speed information, and automated driving. Finally, chapter five presents the conclusions of the research and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a definition of eco-driving and its benefits along with previous research work. A brief summary of the Eco-CACC system is presented at the end of this chapter.

2.2 What is Eco-Driving?

Eco-driving is a driving style that is considered to be economic and ecologically beneficial. It has been defined by several researchers as the smooth driving resulting from adjustment in driver behavior [3, 4]. Consequently, researchers have suggested tips for drivers [14, 15] that could effectively improve their behavior with the objective of minimizing fuel consumption and emission levels. These tips are:

- Avoid hard braking, sudden acceleration/deceleration, and idling.
- Limit air conditioner use.
- Stop warming engine.
- Shift gear up early.
- Maintain steady speed.
- Look ahead while driving.
- Limit starting speed in the first 5 seconds to 20km/h.

However, recent research shows a vehicle itself could be considered as part of an eco-driving system. Trying to decrease the unnecessary load of the vehicle, maintaining it regularly, and checking tire pressure consistently are effective ways of promoting eco-driving [16]. In addition, there are several advanced devices that could be installed into the vehicle to fulfill the objectives of an eco-driving, such as the eco-indicator [14, 17, 18].

2.3 What Are the Benefits of Eco-Driving?

Eco-driving has shown a significant positive effect on mitigating the environmental impacts of the transportation system. Studies in many countries have revealed a clear improvement in favor of reducing pollution and fuel consumption [5, 19-22]. In Europe, Fonseca et al. [23] studied the impact of driving style on fuel consumption and pollution emissions of five diesel passenger cars

in urban traffic. They took into consideration three different driving styles, namely: normal driving, eco-driving, and aggressive driving. Fonseca et al. found that aggressive driving increased carbon dioxide and fuel consumption by 40%, while eco-driving decreased fuel consumption and carbon dioxide emissions by 14%. In Canada, Michelle et al. [24] studied the impact of engine idling on greenhouse gas (GHG) emissions in the city of Calgary based on eco-driver training. They found that, after decreasing daily idling between 4% and 10% per vehicle per day, carbon dioxide emissions decreased by 3.75 lb (1.7 kg) per vehicle per day and fuel consumption was reduced. In the USA, Barth and Boriboonsomsin [25] found a 10-20% reduction in fuel consumption and carbon dioxide emissions after providing recommended speeds for drivers that help them to drive in a fuel efficient way.

Moreover, eco-driving could reduce the severity of accidents, thereby decreasing the cost of repairing cars, as it encourages drivers to drive steadily and smoothly. Additionally, previous studies show that eco-driving could be a main reason for reducing physical fatigue of the driver [26]. Yamabe et al. showed that go-and-stop movements at the intersections make the muscle activities of drivers more sensitive and increase physical fatigue.

Finally, safety and user comfort may be considered as indirect goals of eco-driving. The drivers and passengers would experience more comfort when riding with eco-driving, as its' strategies aim at avoiding sudden speed changes and hard braking [27].

2.4 How to Evaluate Eco-Driving?

In order to utilize eco-driving, some research efforts focused on modeling and simulating the driving behavior, while others evaluated eco-driving by conducting real field tests. Therefore, there are three approaches that could evaluate eco-driving, namely: field experiments, driving simulators and traffic simulations.

2.4.1 Field Experiment

The goal of field experiments is to evaluate the improvement of the driver's behavior in real road situations before and after adopting eco-driving strategies. The amount of reduction in GHG emissions and fuel consumption levels varies based on the driver-acceptance of these strategies. Eco-driving in a real environment could be achieved by giving a brief lecture for a couple of hours for drivers, doing practical exercises [24, 28], reading a list of advice [24, 28], or mounting a device in the vehicle [14, 17].

The improvement of the driver's performance is measured by sensors installed on the vehicle. These sensors are able to record the instantaneous speed and measure the fuel consumption and GHG emission levels. However, labor-intensiveness and time-consumption play a role in determining the trustworthiness of the experiments' results [15]. Therefore, the sample size of the experiment should be statistically considerable. Also, the traffic conditions should be the same before and after the comparison. Otherwise, the difference in the results of the comparison will not be noteworthy. This section reviews the research efforts attempting to conduct a real experiment associated with using eco-driving strategies.

In Sweden, Johansson provided training courses to a number of drivers and taught them how to drive ideally. The training courses contained several tips, such as avoiding hard braking and accelerating/decelerating smoothly. Johansson [29] found that fuel consumption decreased by 10.9% after the training course. In France, Andrieu and Pierre [30] conducted two experiments. Each experiment had two scenarios, namely: normal driving and eco-driving. The first experiment was done by giving participants a list of advice, while the other one was done by training the participants. Andrieu and Pierre found that there was a significant difference between the two scenarios in terms of reducing fuel consumption for both of the experiments. In China, Yang et al. [31] studied the effects of eco-driving on fuel consumption. They had two scenarios: normal driving and eco-driving. Eco-driving has four rules: shift the gear in time, maintain steady speed, and slow down appropriately and gently. The study revealed eco-driving could decrease fuel consumption significantly. In Taiwan, Lai [32] used a monetary reward system to encourage bus drivers to follow eco-driving behaviors. He measured the fuel consumption levels per bus driver before and after implementing the reward system. The results demonstrate that there is a reduction of more than 10% in fuel consumption. In Switzerland, Tulusan and Staake [33] used eco-feedback technology (i.e. a smartphone application) to study the impact on the drivers' behavior. The results show an improvement in fuel efficiency by 3.23%.

Table 2-1 summarizes previous field experiments that have been conducted using the eco-driving concept. In general, the results show that eco-driving has a positive effect on drivers' fuel efficiency.

Table 2-1 The results of field tests on eco-driving

Country	Authors	Year	Fuel consumption decreased by
Spain	Fonseca et al.[23]	2010	14 %
Sweden	Johansson [29]	1999	10.9 %
France	Andrieu and Pierre [30]	2012	Significant difference
China	Yang et al. [31]	2012	Positive impact
Belgium	De Vlieger et al. [3]	2000	20-45%
U.K.	Vagg et al. [17]	2013	Up to 12%
Mexico	Rafael et al. [20]	2006	13.4%
Canada	Rutty et al. [24]	2013	Between 4% and 10%
U.S.A	Barth and Boriboonsomsin [25]	2009	Between 10 and 20%
Belgium	Beusen et al. [34]	2009	5.8 %
Netherlands	Vermeulen [35]	2006	Between 7% and 10%
Taiwan	Lai [32]	2015	More than 10%
Switzerland	Tulusan et al. [33]	2012	3.23%
Australia	Symmon and Rose [36]	2009	27%
United States	Boriboonsomsin et al. [37]	2010	6% on city streets and 1% on highways

However, providing training courses and delivering advice to drivers may not be the right way to achieve fuel consumption for long-term periods. All these studies evaluated the short-term impact of eco-driving. Recent research shows that the effects of eco-driving decrease with time over the long-term [34]. Beusen et al. studied the long-term effect of eco-driving for 10 months. They provided training courses for ten drivers, and then they evaluated their behavior during this period by using on-board logging devices. They concluded that there was a decrease in fuel consumption of 5.8% four months after the course was completed. That means some drivers went back to the driving behavior that they practiced prior to taking the course [34]. Moreover, most of these studies used a static advice that does not take into account the real-time traffic sensing and infrastructure information.

In conclusion, the best way to promote eco-driving is using onboard driver assistance systems that utilize real-time traffic information and could keep advising drivers for long-term periods. Subsequently, automated driving should be considered the best way to follow an eco-driving system, given that the system will not depend on the driver's behavior. The automated vehicle will follow exactly the optimal speed profile without being affected by human factors such as PRT, misjudgment, and misunderstanding.

2.4.2 Driving Simulator

A driving simulator is another approach to measure the performance of eco-driving. This approach has three main advantages, namely, it is cheaper, safer and easier to apply the same circumstances for all scenarios. In Japan, Hiraoka et al. [38] have done driving simulator experiments to evaluate fuel consumption. They used three scenarios: normal driving, driving while the fuel consumption meter is presented, and driving with instruction for two types of eco-driving. They found that eco-driving contributed in decreasing fuel consumption by approximately 15%. In Korea, Kim and Kim [39] conducted an eco-driving experiment using a virtual driving system. They proposed three different scenarios, one of which used visual and auditory eco-driving feedback. The feedback delivered to participants were avoiding (sudden acceleration and abrupt braking) and maintaining (efficient speed and optimum gear). The test results show a positive improvement in fuel efficiency. In the U.S.A, Sun et al. [12] endeavored to obtain the optimal fuel/emission efficient speed profile for on-coming vehicles at signalized intersections. Given the upcoming signal information, a dynamic programming approach was used to estimate the optimal speed with regard to fuel efficiency. Subsequently, the authors developed an eco-driving strategy that allows a velocity advisory to be delivered to drivers. Savings of up to 25% in fuel consumption and emissions were found in a driving simulator experiment for 15 drivers.

Table 2-2 provides a sample of previous experiments conducted in a virtual environment using eco-driving concepts. Overall, the results show that eco-driving has a positive influence on fuel efficiency.

Table 2-2 The results of simulator tests on eco-driving

Country	Authors	Year	Fuel consumption decreased by
Japan	Hiraoka et al. [38]	2009	15%
Korea	Kim and Kim [39]	2012	Positive result
Switzerland	Hornung [40]	2004	17%
U.S.A	Sun et al. [12]	2013	25%

However, simulator experiments have three critical issues. First, the accuracy of the simulator is a critical issue, as the result of the experiment would rely on it. Second, some of human factors cannot be taken into account, such as the participants' differences in understanding the simulator. Third, the simulator does not represent the real circumstances in the real field [15].

2.4.3 Traffic Simulation

The simulation approach is essentially related to the model used in an eco-driving system, so the following section will include a brief description of several models and their results.

2.4.3.1 Previous Research on Modeling of Eco-Driving at Signalized Intersections

As mentioned earlier, eco-driving is mainly focused on making the driver behavior smoother in order to save fuel, enhance road safety, reduce traffic congestion, and minimize vehicle emissions. Modeling efforts have been addressing these goals using different approaches. The SPaT message, for instance, is an example of an input for these models. Several studies have used traffic signal status in order to alert drivers approaching signalized intersections so that they could have a smooth acceleration/deceleration maneuver and, therefore, less emission production and more fuel savings. This section reviews the research efforts attempting to develop models associated with the aforementioned concept.

Mandava et al. [8] proposed an algorithm that minimizes acceleration/deceleration rates to increase the probability of having a green light for oncoming vehicles at signalized intersections. Using signal phase and timing information, they delivered dynamic speed advice to drivers when approaching signalized intersections. The results demonstrated that the algorithm could decrease fuel consumption and emissions by 12-14%.

Asadi and Vahidi [10] developed a predictive cruise control system that used constrained optimization to minimize the probability of stopping. Traffic signal information and short range radar were used to change the vehicle's arrival time at the green light. The proposed algorithm did not provide dynamic speed advice to drivers. In addition, the speed profiles provided were not compared with regard to fuel efficiency. The simulation results show a reduction of 47% and 56% in fuel consumption and emissions respectively in an arterial road consisted of nine traffic signals.

Barth et al. [11] developed a dynamic eco-driving velocity planning algorithm along an arterial corridor with traffic signals. The objective function of the proposed algorithm was to minimize the level time spent accelerating and decelerating. The algorithm received signal phase and timing information from a traffic signal and recommended speeds for on-coming vehicles. Up to a 12% reduction in fuel consumption and emissions were reported.

Malakorn and Park [41] have studied the potential benefits of Cooperative Adaptive Cruise Control (CACC) with regard to the environmental impacts and vehicular mobility. The authors integrated CACC with Intelligent Traffic Signals in which CACC produces optimum trajectories to vehicles approaching signalized intersections. Using upcoming signal information, the system minimized acceleration and deceleration distances and idling time. Simulation results indicated a 91 percent and a 75 percent reduction in delay and fuel consumption, respectively. On the other hand, this study did not consider the speed profile downstream of the signalized intersection. In addition, the results were completed using a fixed deceleration distance (100 ft (30.5 m)).

Wu et al. [42] studied the benefits of two types of advanced driving alert systems, namely: stationary Advance Driving Alert System (ADAS) and in-vehicle ADAS. The authors proposed these systems with the objective of helping drivers approaching signalized intersections to achieve smooth driving (i.e. avoid hard braking and hard-deceleration maneuver). Both of these systems alert the drivers of time to red so that they can make a decision in advance to stop safely and thereby smoothly. The simulation results revealed a positive impact on fuel consumption and emissions. However, this study provided drivers information on traffic signal status only when it was red. The authors did not consider informing the drivers of time to green. In addition, they did not consider the downstream intersection in providing a fuel-optimum trajectory.

Tielert et al. [43] studied the effect of Traffic-Light-to-Vehicle Communication on the environmental impacts (i.e. emissions and fuel consumption). In this study, the effect of speed adaptation was tested by using different speeds in the simulation. The authors found that gear choice and the distance from the traffic light have a significant impact on fuel consumption and emissions. The simulation results showed a reduction of 22% for a single vehicle and 8% for multi vehicles.

Sanchez et al. [44] proposed a new driving model called Intelligent-Driver Model Prediction (IDMP). The proposed model uses the information sent from the traffic signal to advise approaching vehicles with the goal of minimizing idling time; thus reducing vehicle fuel consumption levels. The authors made use of this information to compute the recommended speeds that a driver should adopt to achieve the aforementioned goal. In the simulation experiment, they used the Akcelik and Biggs fuel consumption model [45] to compare the results between two

scenarios using the Intelligent-Driver Model (IDM) [46]. The simulation results showed a reduction of 25% in fuel consumption levels in urban areas.

Li et al. [47] introduced an optimized method using an augmented Lagrangian genetic algorithm that provides an optimum speed advisory for on-coming vehicles to intersections with the objective of reducing trip time; thus reducing vehicle fuel consumption levels. The proposed algorithm guarantees that on-coming vehicles do not exceed the maximum permitted speed when passing signalized intersections. The authors used a car following model to handle multi-vehicles. The VT-Micro model [2] was used in the proposed model to calculate the fuel consumption but not in the optimization objective function. In a simulated environment, savings of up to 69.3 percent and 12.1 percent were reported in fuel consumption and trip time, respectively.

Alsabaan et al. [48] developed an optimization model to compute the optimum or close-to-optimum speed in the vicinity of signalized intersections in which driver behavior will be smooth and, thereby, fuel consumption and emissions will be minimized. The authors used traffic-light-signal-to-vehicle (TLS2V) and V2V communication to send SPaT information to approaching vehicles so that drivers can follow the optimum speed. The objective function of this model is minimizing vehicle fuel consumption and emissions using the VT-Micro model [2] for four different scenarios. Heuristic expressions were used to estimate the optimum speed or near-optimum speed.

Jin et al. [49] proposed a mathematical model to optimize vehicle trajectories crossing intersections using six different signal timing configurations. This research effort was intended to reduce the idling time and unnecessary changes in speed in the vicinity of a signalized intersections. The objective function is minimizing acceleration and deceleration distances. Approaching drivers were notified of a suggested speed through a DSRC connection in which SPaT information was sent to drivers. The authors tested different scenarios (e.g. the current signal state is either red or green with different lengths) and optimized the vehicle trajectory for upstream and downstream of the traffic signal. The optimum speed was computed by calculating the emissions and fuel consumption using a vehicle specific power model (VSP). In a simulated environment, average savings in fuel consumption of up to 12.01% and 7.73%, respectively were reported, as well as an increase in travel time.

As has been shown, most of the aforementioned literature have used almost the same concept in which the approaching vehicles are provided with a smooth speed profile in the vicinity of signalized intersections with the goal of minimizing fuel consumption and/or emissions. However, most of these research efforts attempted to minimize vehicle fuel consumption levels by minimizing acceleration/deceleration distances, idling time, and/or travel time, so their objective function was not the explicit minimization of fuel consumption. In addition, all of the proposed algorithms have been developed and tested in traffic simulation environments where recommended speeds are enforced and many issues, such as the delay in the system and human-vehicle interaction, are not considered.

As mentioned earlier, Kamalanathsharma, who was in the same research group at the Virginia Tech Transportation Institute, has proposed an optimization model which explicitly minimizes fuel consumption for any given scenario. The proposed model (i.e. the Eco-CACC system) has been tested in a simulated environment, and the results show a reduction of 30 percent in fuel consumption. Hence, in this thesis, the Eco-CACC system was tested in a real field environment for two cases (will be discussed later on). The following section will present a brief description of this model.

2.5 Algorithm Used For the Experiment[7]

Kamalanathsharma developed an optimization model that provides a speed profile for approaching vehicles, beginning once they enter the designed range and lasting until they leave it. This designed range (DSRC range) allows the vehicle to return to its original speed in the downstream of the traffic signal with the objective of calculating the fuel consumption in the entire maneuver. The entire maneuver is intended to measure the vehicle's fuel consumption from the point where it receives the SPAT information until a certain distance after passing the signalized intersection.

The process of conducting the optimization model involves two main steps. First, compute an estimated time to the signalized intersection given queued vehicle information, lead vehicle, and the upcoming signal change information (Time to Red (TTR) or Time to Green (TTG)). Second, compute a fuel-optimal vehicle trajectory given the computed time to intersection, roadway characteristics, such as grade and curvature, vehicle acceleration/deceleration model, and fuel consumption model.

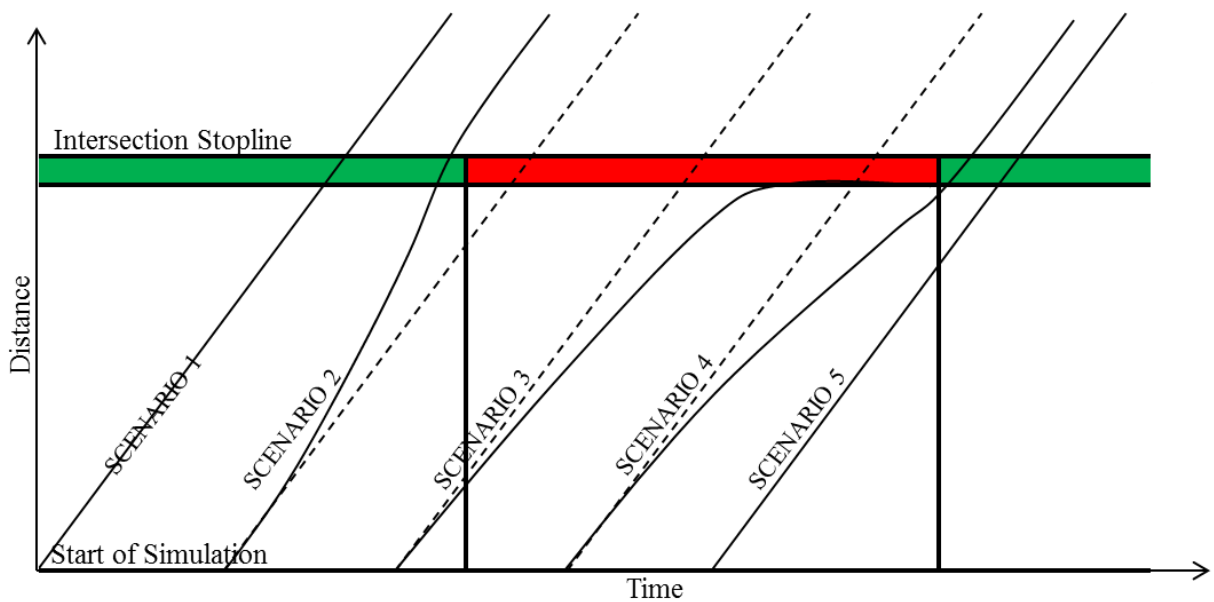


Figure 2-1 Different anticipated scenarios in the vicinity of signalized intersection [7]

When a driver approaches a signalized intersection, there are five anticipated scenarios, as shown in Figure 2-1. The dotted line represents a vehicle without using the Eco-speed algorithm (i.e. the vehicle doesn't receive advanced information with regard to the traffic light status), while the solid line represents a driver using the Eco-Speed algorithm (i.e. the vehicle receives advanced information).

The vehicle approaching the signalized intersection receives upcoming signal change information through V2I communication. With this given information, the distance to intersection (DTI) and the vehicle's current speed, the vehicle will decide whether to accelerate, decelerate, or cruise. The five anticipated scenarios are as follows:

Scenario 1:

The vehicle has ample time to pass the signalized intersection without coming to a complete stop nor decelerating, so it will pass safely without changing its current speed.

Scenario 2:

Based on the received time to red (TTR), the vehicle cannot pass the signalized intersection at its current speed, so it needs to accelerate to the maximum allowed speed. Therefore, the system would ask the vehicle to accelerate to a certain speed and pass the signalized intersection safely.

Scenario 3:

The current traffic light status is green, yet by the time the vehicle arrives at the signalized intersection, it will turn red. In other words, the TTR is not adequate to pass the signalized intersection in any way, even if it accelerates to the maximum allowed speed (i.e. Time to Intersection (TTI) \gg TTR). Accordingly, the vehicle is requested to decelerate smoothly and come to a complete stop.

Scenario 4:

The current traffic light status is red. However, the vehicle is able to pass the signalized intersection without coming to a complete stop if it decelerates properly. The TTI is smaller than the TTG, so the vehicle needs to decelerate to compromise on these two times (i.e. TTI=TTG) (This scenario will be tested in the experiment).

Scenario 5:

The current traffic light status is red, yet the traffic signal will turn green by the time the vehicle arrives (i.e. TTI >TTG). Consequently, the vehicle will be advised to keep the current speed (This scenario will be tested in the experiment).

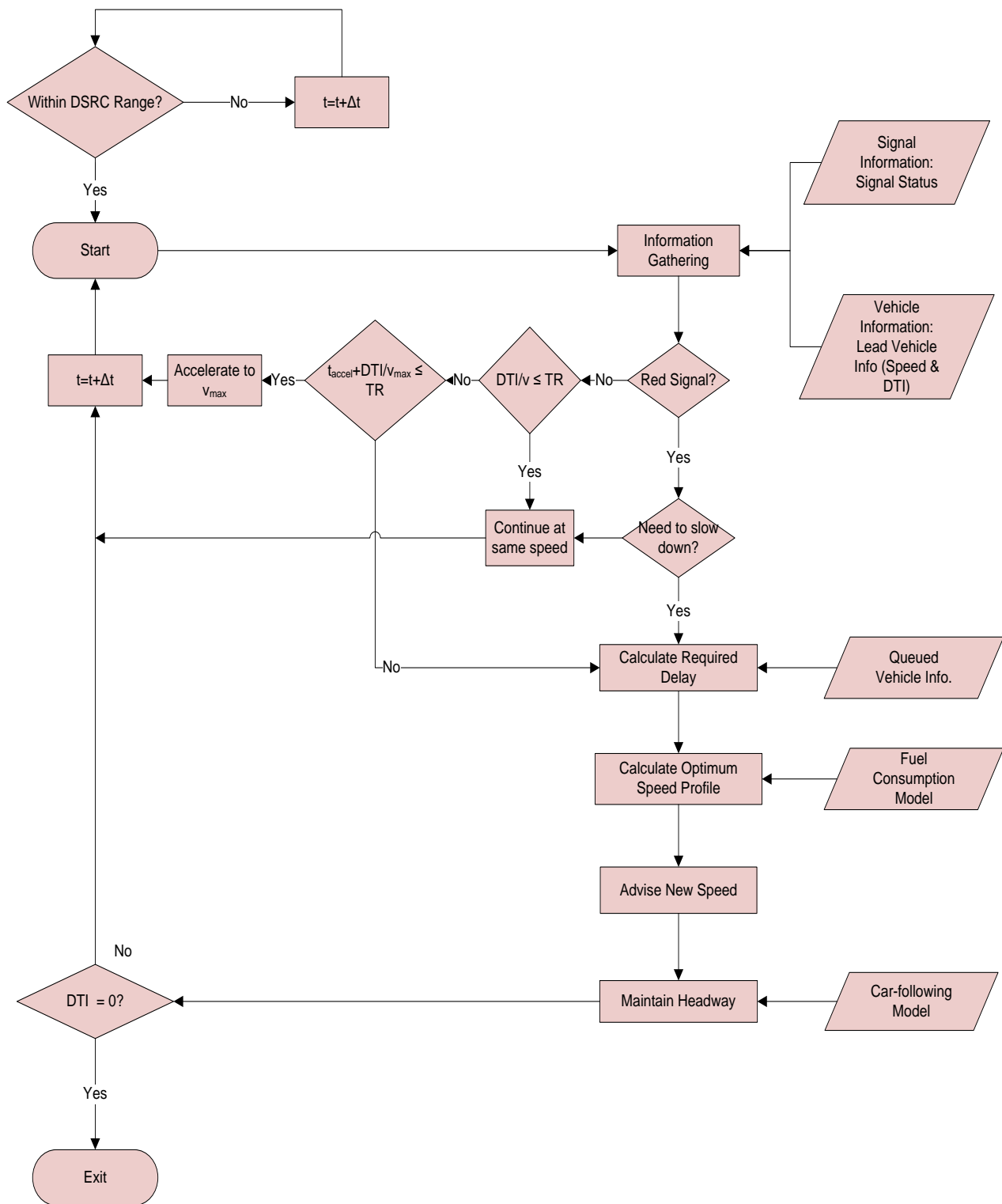


Figure 2-2 Logical diagram for the ECO-CACC system [7]

Figure 2-2 presents the logical steps that the system follows once the vehicle enters DSRC range, in which the system will gather information from the traffic signal and the vehicle. Based on

that, the vehicle will be given an advisory speed recommendation. As the system does not take into consideration the drivers' errors and human-vehicle interaction, the algorithm is recalculated for every time step.

In [7], Kamalanathsharma focused on computing the fuel-optimum vehicle trajectory for scenario 4. An optimization approach was used to compute the lowest-fuel speed profile in the downstream and upstream of the signalized intersection. The constraints of this optimization function are as follows:

1. Distance to intersection (DTI) which is given.
2. Time to Green (TTG), including the time needed to dissipate the queued vehicles.
3. Fixed roadway and vehicle characteristics

As far as scenario 4 is concerned, when a vehicle is approaching a signalized intersection, the time to intersection would be shorter than the time to green. Therefore, the driver needs to decelerate in order to reach the signalized intersection in green phase without having to come to a complete stop. To incorporate this change, the trajectory optimization will consist of three components: deceleration, cruising, and acceleration, as shown in Figure 2-3. The green dotted line represents the fuel-optimum vehicle trajectory upstream of the traffic signal in which the trajectory is divided into two parts: sudden deceleration and cruising. The deceleration will create the desired delay that allows the vehicle to travel at a constant speed (i.e. cruising) passing the signalized intersection without having to stop. The downstream portion of the optimization trajectory will be the acceleration. It ensures that the vehicle will return to its original speed. The vehicle will accelerate gradually until it hits this speed.

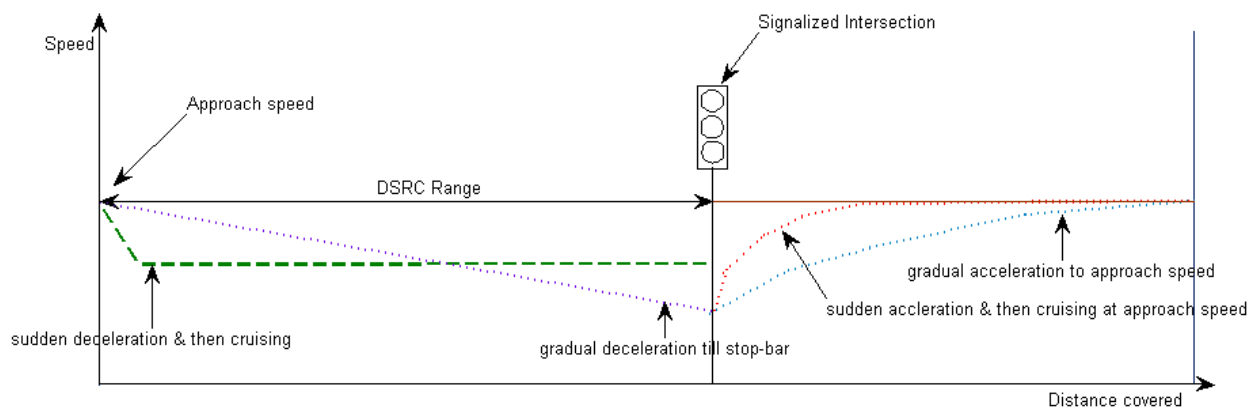


Figure 2-3 Trajectory optimization in the vicinity of signalized intersection [7]

It should be noted that the cruise speed is calculated based on the initial deceleration. The lower the vehicle decelerates, the higher the cruise speed will be. That leads to a shorter acceleration maneuver, and, therefore, more fuel consumption.

2.5.1 Upstream Portion of the Traffic Signal

As mentioned earlier, SPaT information (i.e. TTG) will be received by an approaching eco-vehicle at distance x and, therefore, the speed profile of the eco-vehicle will be changed accordingly. The time needed for the eco-vehicle to reach the stop line at its current speed v_a is TTI (denote t), which is shorter than TTG (denote $t+\Delta t$). The vehicle needs to decelerate from the approach speed $v_a = x/t$ to the new speed $v_s = x/(t+\Delta t)$. The new speed v_s is calculated based on the deceleration level, d . The lowest value of the deceleration level d_{min} is the value that allows the vehicle to decelerate until reaching the stop line. Any value greater than d_{min} has an associated cruise speed v_s that allows the vehicle to pass the intersection in $t+\Delta t$. As shown in Figure 2-4, the solid line represents a vehicle decelerating with d_{min} , while the dotted line represents a vehicle decelerating with d_{max} . (maximum decelerate rate). These two cases represent the boundaries of the optimization trajectory. There is an infinite number of speed profiles between these boundaries (i.e. d_{min} and d_{max}).

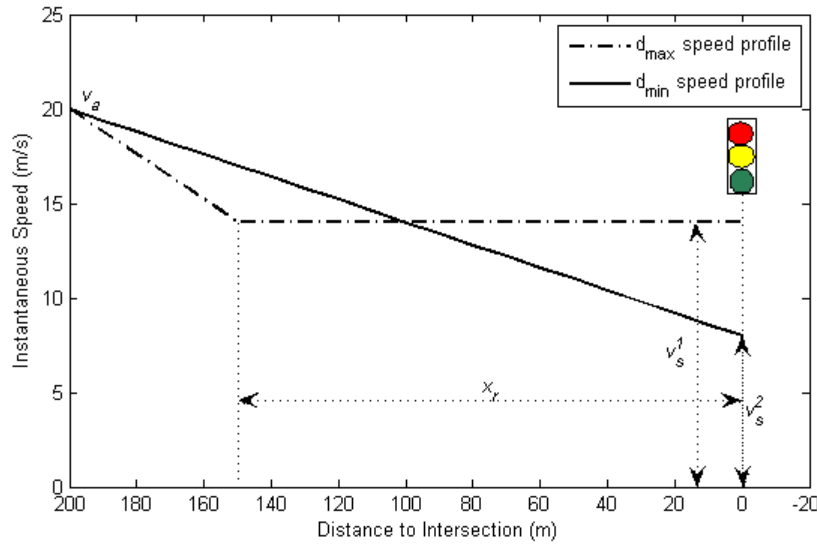


Figure 2-4 Speed profile in upstream [7]

The value of d_{min} can be calculated using the following Equation:

$$d_{min} = \frac{v_a - v_s}{t + \Delta t} \quad (2-1)$$

The cruising speed can be calculated as follows:

$$v_s = \frac{2x}{t + \Delta t} - v_a \quad (2-2)$$

In case of the value of d greater than the minimum deceleration (d_{min}), the following Equation can be used to calculate the cruise speed v_s :

$$v_s = v_a - (d \pm Gg)(t + \Delta t) + \sqrt{(d \pm Gg)((d \pm Gg)(t + \Delta t)^2 - 2v_a(t + \Delta t) + 2x)} \quad (2-3)$$

Where G is the roadway grade and g is the gravitational acceleration (9.81 m/s²)

The upstream cruising distance can be calculated using the following Equation:

$$x_r = x - \frac{v_a^2 - v_s^2}{2(d \pm Gg)} \quad (2-4)$$

The previous equation can calculate the upstream cruising distance for various speed profiles between the maximum and minimum deceleration levels.

2.5.2 Downstream Portion of the Traffic Signal

After passing the intersection, the vehicle needs to accelerate back to its original speed within a predetermined distance. A vehicle dynamic model for light-duty acceleration is used to generate the downstream speed profile [50]. It should be noted here the downstream speed profile is a non-linear speed profile unlike the upstream portion. Accelerating from the cruising speed to the original speed requires a specific throttle level, and each throttle level is associated with a different speed profile. Therefore, optimization approach is used to determine the fuel-efficient speed profile and the associated throttle level. The downstream speed profile is consisted of two sections: acceleration and cruising sections. However, if the car accelerates at a low throttle level, the cruising section will be zero. The following equation calculates the fuel consumed in downstream of the intersection:

$$FC_i(ds) = FC_i(v_s \rightarrow v_a) + FC_{cruise}(v_a) \times (x_{max} - x_{i-acc}) \quad (2-5)$$

where $FC_i(ds)$ is the fuel consumed in downstream of the intersection for case i , $FC_i(v_s \rightarrow v_a)$ is the fuel consumption when accelerating from the cruise speed (v_s) to the original speed (v_a) for case i , $FC_{cruise}(v_a)$ is the fuel consumption per meter when cruising at v_a , x_{max} is the maximum

distance when a vehicle accelerates from v_s to v_a in any case, and x_{i-acc} is the distance covered when a vehicle accelerates in the case i .

2.6 Developing the Eco-Cooperative Adaptive Cruise Control [60]

Given that both upstream and downstream vehicle speed profiles are considered in the Eco-CACC algorithm, a control region in the vicinity of signalized intersections should be defined. Considering the communication range of DSRC, the Eco-CACC algorithm is activated at a distance of d_{up} upstream of the intersection to a distance of d_{down} downstream of the intersection. It has to be noted here that the distance is calculated from the vehicle location to the intersection stop line. The value of d_{down} is defined to ensure that the vehicle has enough downstream distance to accelerate from a complete stop to the limit speed at a low throttle level (e.g. 0.3). This ensures that all computations are made along a fixed distance of travel.

The Eco-CACC algorithm described in this thesis computes the optimum vehicle speed profile starting from upstream to downstream of a signalized intersection, by incorporating vehicle dynamics and fuel consumption models. The proposed Eco-CACC algorithm is implemented in the test vehicle to develop an Eco-CACC system. It should be noted that the impacts from neighboring vehicles such as car-following and/or lane-changing behavior are not considered in this field experiment given that we only have one test vehicle. However, the impacts of these factors on the proposed Eco-CACC system were tested in a traffic simulation environment [7, 51-55].

When a vehicle is approaching a signalized intersection, the vehicle may accelerate, decelerate, or cruise (keep its current speed) depending on its speed, distance to the intersection, signal timing, etc. Considering that the vehicle may or may not need to decelerate when approaching the traffic signal, two cases are considered to develop the Eco-CACC strategies:

- Case 1: vehicle is able to pass the intersection during the green indication without decelerating (either maintaining a constant speed, or accelerating to a higher speed and then maintaining that speed).
- Case 2: vehicle needs to decelerate to a lower speed, and then maintains that speed to proceed through the intersection during the green indication.

The above two cases describe the vehicle's optimum trajectory in order to minimize its fuel consumption while traversing the intersection. After the vehicle passes the stop line, the

vehicle attempts to reach the speed limit downstream of the intersection. More details of optimum speed profiles for various situations have been discussed in [7, 56]. Figure 2-5 demonstrates the optimum speed profile when a vehicle proceeds through a signalized intersection, and the Eco-CACC algorithm helps to find the best acceleration and deceleration levels. The sample speed profiles (initial speed u_1 and u_2) for case 1 are highlighted in blue, and the sample speed profile (initial speed u_3) for case 2 is represented in maroon. The road speed limit is denoted as u_f . Note that the samples of case 1 and 2 in Figure 2-5 happens at the red phase when vehicle passes the upstream distance d_{up} . The same classification of case 1 and 2 also exist for the situation of green phase. Considering the simplicity to explain the proposed Eco-CACC algorithm, the initial red phase is assumed for the following sections.

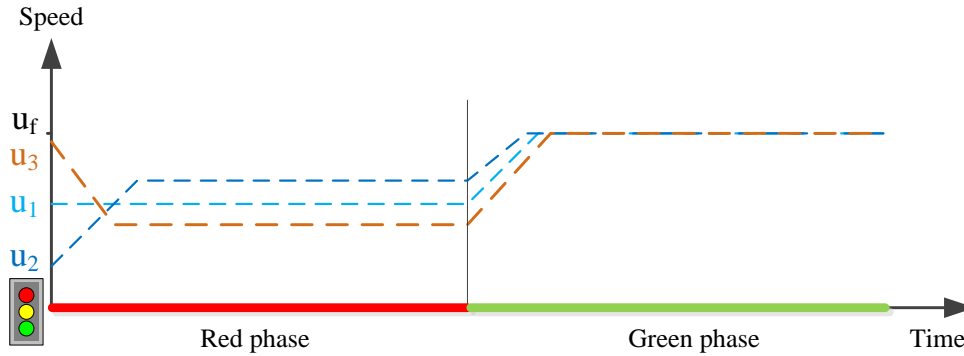


Figure 2-5 Samples of optimum speed profile when vehicle approaches the signalized intersection

In the proposed Eco-CACC algorithm, the deceleration is assumed constant for case 2. In case 1, the vehicle acceleration follows the vehicle dynamics model developed in [57]. In this model, the acceleration value depends on vehicle speed and throttle level. Given that the throttle level is typically around 0.6 as obtained from field studies [7], a constant throttle level of 0.6 is assumed in the vehicle dynamics model to simplify the calculations in the algorithm for case 1. In case 2, the throttle level ranges between 0.4 to 0.8, and the optimum throttle level is computed to minimize the fuel consumption level. The vehicle dynamics model is summarized by Equations (2-6) to (2-8).

$$v(t + Dt) = v(t) + 3.6 \frac{F(t) - R(t)}{m} Dt \quad (2-6)$$

$$F = \min \left\{ 3600 f_p \beta h_d \frac{P}{v}, m_{ta} g \frac{\ddot{v}}{g} \right\} \quad (2-7)$$

$$R = \frac{r}{25.92} C_d C_h A_f v^2 + m g \frac{c_{r0}}{1000} (c_{r1} v + c_{r2}) + m g G \quad (2-8)$$

Where F is the vehicle tractive effort; R represents the resultant of the resistance forces, including aerodynamic, rolling and grade resistance forces; f_p is the driver throttle input [0,1] (unitless); β is the gear reduction factor (unitless), and this factor is set to 1.0 for light-duty vehicles; η_d is the driveline efficiency (unitless); P is the vehicle power (kW); m_{ta} is the mass of the vehicle on the tractive axle (lb/kg); g is the gravitational acceleration (32 ft/s² (9.8067 m/s²)); μ is the coefficient of road adhesion (unitless); ρ is the air density at sea level and a temperature of 15°C (0.0765 lb/ft³ (1.2256 kg/m³)); C_d is the vehicle drag coefficient (unitless), typically 0.30; C_h is the altitude correction factor (unitless); A_f is the vehicle frontal area (ft²/m²); c_{r0} is rolling resistance constant (unitless); c_{r1} is the rolling resistance constant (h/km (h/ft)); c_{r2} is the rolling resistance constant (unitless); m is the total vehicle mass (lb/kg); and G is the roadway grade at instant time t (unitless).

A fuel consumption model is needed in the Eco-CACC algorithm to calculate fuel consumption using vehicle speed data. The VT-CPFM-1 was selected due to its simplicity, accuracy and ease of calibration [58]. The selected fuel model utilizes instantaneous power as an input variable and can be easily calibrated using publicly available fuel economy data (e.g., Environmental Protection Agency [EPA]-published city and highway gas mileage). Thus, the calibration of model parameters does not require gathering any vehicle-specific data. The VT-CPFM-1 is formulated as presented by Equations (2-9) and (2-10).

$$FC(t) = \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2; & P(t) \geq 0 \\ a_0; & P(t) < 0 \end{cases} \quad (2-9)$$

$$P(t) = \left(\frac{R(t) + 1.04 m a(t)}{3600 \eta_d} \right) v(t) \quad (2-10)$$

Where α_0 , α_1 and α_2 are the model parameters that can be calibrated for a particular vehicle, and the details of calibration steps can be found in [58]; $P(t)$ is the instantaneous total power (kW); $a(t)$ is the acceleration at instant t , which can be calculated by consecutive time speed values; $v(t)$

is the velocity at instant t ; and $R(t)$ is the resistance force on the vehicle as given by Equation ((2-8).

2.6.1 Eco-Cooperative Adaptive Cruise Control Algorithm

Given that vehicles behave differently for the two cases described above, the Eco-CACC algorithms are developed separately for cases 1 and 2.

Case 1:

The vehicle can pass the intersection during a green indication without decelerating. In order to have the maximum average speed to save fuel consumption, the cruise speed during red phase is defined as shown by Equation (2-11). If u_c is equal to vehicle's initial speed $u(t_0)$, then the vehicle can proceed at a constant speed upstream of the intersection. Otherwise, the vehicle should accelerate to u_c by following the vehicle dynamics model presented by Equations (2-6) to (2-8). Thereafter, when the signal turns green, the vehicle needs to follow the vehicle dynamics model and accelerate from cruise speed u_c to the speed limit u_f until the vehicle travels a distance d_{down} downstream of the intersection. Thus, the optimum speed profile is the profile that minimizes the fuel consumption from upstream d_{up} to downstream d_{down} .

$$u_c = \min \left(\frac{d_{up}}{t_r}, u_f \right) \quad (2-11)$$

Case 2:

Upstream of the intersection, the vehicle needs to slow down with a deceleration level a , then cruises at a speed u_c to pass the intersection when the signal just turns into green. Downstream of the intersection, the vehicle should accelerate from u_c to u_f , and then cruises at u_f . Since the deceleration level a upstream of the intersection and the throttle level f_p downstream of the intersection are the only unknown variables for this case, the optimum speed profile can be calculated by solving the optimization problem described below. The vehicle's speed profile for case 2, is illustrated in Figure 2-6.

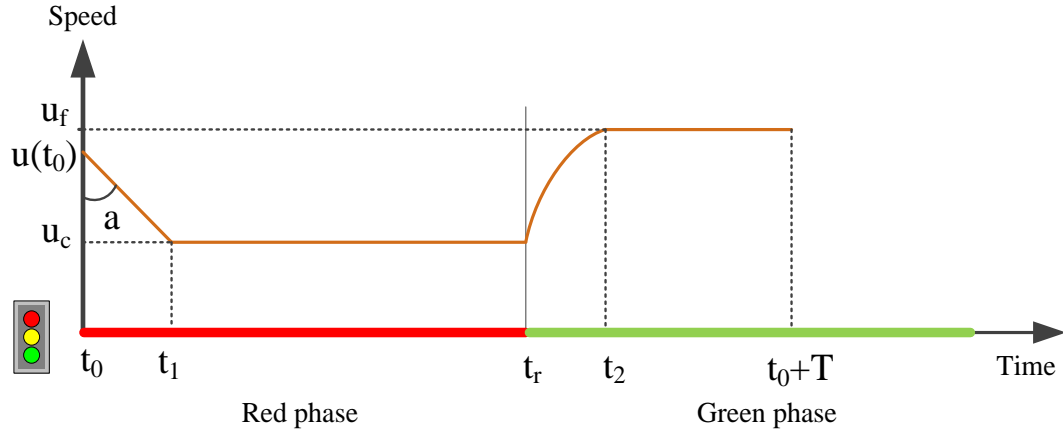


Figure 2-6 Optimum speed profile in case 2

Assume a vehicle arrives d_{up} at time t_0 and passes d_{down} at time t_0+T , the cruise speed during red phase is u_c , and the objection function is the total fuel consumption level given in Equation (2-12):

$$\min \int_{t_0}^{t_0+T} FC(u(t)) \cdot dt \quad (2-12)$$

Where $FC(*)$ denotes the calculated fuel consumption at instant t (Equations (2-9)) with vehicle speed $u(t)$. The constraints can be constructed by the relationships between speed, acceleration, deceleration, and distance as shown in Equation (2-13) and (2-14):

s.t.

$$u(t) : \begin{cases} u(t) = u(t_0) - at; & t_0 \leq t \leq t_1 \\ u(t) = u_c; & t_1 < t \leq t_r \\ u(t + \Delta t) = u(t) + 3.6 \frac{F(f_p) - R(u(t))}{m} \Delta t; & t_r < t \leq t_2 \\ u(t) = u_f; & t_2 < t \leq t_0 + T \end{cases} \quad (2-13)$$

$$\begin{aligned}
u^*(t_0) - \frac{1}{2}at^2 + u_c(t_r - t_1) &= d_{up} \\
u_c &= u(t_0) - a(t_1 - t_0) \\
\int_{t_r}^{t_2} u(t) dt + u_f(t_0 + T - t_2) &= d_{down} \\
u(t_2) &= u_f \\
0 < a &\leq 5.9 \\
0.4 \leq f_p &\leq 0.8 \\
u_c &> 0
\end{aligned} \tag{2-14}$$

In Equation (2-13) and (2-14), the functions $F(*)$ and $R(*)$ represent the vehicle tractive effort and resistance force as computed by Equations ((2-7) and ((2-8), and respectively. According to the relationships in Equation (2-13) and (2-14), the deceleration a and throttle level f_p are the only unknown variables. It should be noted that the maximum deceleration level is limited to 19.35 ft/s² (5.9 m/s²)(comfortable deceleration threshold felt by a driver). In addition, the throttle level is set to range from 0.4 to 0.8, given that the optimum throttle level is usually around 0.6 [7]. Dynamic programming (DP) is used to solve the problem by listing all the combinations of deceleration and throttle values and calculating the corresponding fuel consumption levels; the minimum calculated fuel gives the optimum parameters [7, 59].

Theoretically, the Eco-CACC algorithm provides a “fuel optimized” speed profile at any instant time t , when vehicle is driving within the range of Eco-CACC (from d_{up} to d_{down}). The speed profile include all the speed values at each time interval Δt , which covers vehicle’s target speeds from its current location to the downstream location d_{down} . Practically, the driver can only follow one target speed value at instant time t , and then follow another target speed after a certain time interval Δt^* . The value of Δt^* was set equal to be 2 seconds during the field test described in this experiment.

2.7 Summary and Proposed Research

As has been shown, several previously conducted eco-driving experiments have shown a positive impact with regard to fuel consumption and emissions. However, most of these studies were conducted either by providing a training course for drivers before driving and measuring

before-after differences or by delivering “static” advice during traveling. Very few have used real-time traffic sensing and SPaT information to deliver “dynamic” advice during driving. Moreover, many research efforts have been trying to develop models delivering “dynamic” advice (i.e. recommended speeds) in the vicinity of signalized intersections with the goal of minimizing fuel consumption. However, most of these algorithms have been developed and tested in traffic simulation environments where recommended speeds are enforced and many issues, such as the delay in the system and human-vehicle interaction, are not considered.

The research presented in this thesis is aiming to evaluate the benefits of an Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system in a real field environment. The Eco-CACC system attempts to minimize explicitly the fuel consumption using advanced signal information (SPaT). The Eco-CACC system forecasts the fuel-optimal trajectory for vehicles, and, then, send recommended speeds to drivers as an audio message or implement them directly into the testing vehicle.

CHAPTER 3: FIELD EVALUATION OF ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL IN THE VICINITY OF SIGNALIZED INTERSECTIONS

3.1 Abstract

Signalized intersections can produce significant increases in vehicle fuel consumption levels. With the help of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, algorithms are being developed that utilize SPaT data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections. This chapter presents the results of a unique controlled field experiment designed to evaluate an Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system that was developed by the Center for Sustainable Mobility at the Virginia Tech Transportation Institute. The Eco-CACC system computes and recommends real-time fuel-efficient speeds using V2I communicated data that can be delivered to drivers as an audio message. The controlled field experiment included three different scenarios, namely: normal driving, driving with count down information provided to drivers, and driving with recommended speed information also provided to drivers (Eco-CACC system). The controlled field experiment was conducted for four red indication offset values to drivers traveling along an uphill and downhill approach on the Smart Road test facility. In total, 1536 trips were conducted by 32 different participants (16 females and 16 males) between the ages of 18 and 30. The collected data were compared with regard to fuel economy and travel time over a fixed distance starting upstream and ending downstream of the intersection (from 820 ft (250 m) upstream of the intersection to 590 ft (180 m) downstream for a total length of 1410 ft (430 m)). The results demonstrate that the developed Eco-CACC system is very efficient in reducing fuel consumption levels, especially when driving downhill. Specifically, the results indicate that following the recommended speeds could produce fuel and travel time savings of up to 18.9 and 10.1 percent, respectively. In addition, the study demonstrates that driving with the provision of countdown information can achieve average fuel and travel time savings of 11.2 and 2.8 percent on average, respectively.

3.2 Introduction

The transportation sector is the second main reason for the increase in fuel consumption and emission levels in the United States [16]. The increase in vehicle travel miles and, thereby, traffic congestion contributes significantly to produce excessive fuel consumption and global pollution. The eco-driving concept has been proposed and studied widely as a key solution to mitigate the environmental impacts of transportation [5, 19-22].

Eco-driving is a driving style that is considered to be economic and ecologically beneficial. It has been defined by several researchers as the smooth driving resulting from adjustment in driver behavior [3, 4]. Consequently, researchers have suggested tips for drivers [14, 15] that could effectively improve their behavior with the objective of minimizing fuel consumption and emission levels. These tips are:

- Avoid hard braking, sudden acceleration/deceleration, and idling.
- Limit air conditioner use.
- Stop warming engine.
- Shift gear up early.
- Maintain steady speed.
- Look ahead while driving.
- Limit starting speed in the first 5 seconds to 12.4 mph (20km/h).

However, recent research has shown how a vehicle could help drivers achieve the aforementioned steps. Onboard driver assistance systems can be installed into the vehicle to fulfill the objectives of eco-driving [14, 17, 18]. These devices can deliver “static” advice to drivers such as “accelerate slowly,” “avoid hard braking,” and “reduce high speed.” However, the impact of the static advice on fuel consumption and emission levels is limited.

By taking advantage of real-time traffic sensing and infrastructure information, onboard driver assistance systems can deliver “dynamic” advice to drivers that can help them to drive smoothly and efficiently. In particular, establishing communication between the vehicle and the traffic signal controller is a powerful tool to make the driver behavior smoother; thus reducing vehicle fuel consumption levels. Various messages can be exchanged between the two parties to provide better advice to drivers. Among these messages is a SPaT message that can provide

approaching vehicles with valuable advance information about upcoming traffic signal timing changes. This information could help drivers to make early decisions whether they should proceed or stop safely and smoothly.

With the help of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, algorithms are being developed that utilize SPaT data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections [8, 10-12]. Therefore, it is possible that vehicles can communicate with the traffic signals, receive SPaT information, and adjust their speeds accordingly.

Several Eco-Speed control (ESC) algorithms have been introduced to provide an optimal trajectory through signalized intersections. However, very few explicitly attempted to minimize vehicle fuel consumption levels. In addition, most of the proposed algorithms have been developed and tested in traffic simulation environments where recommended speeds are enforced and many issues, such as the delay in the system and human-vehicle interaction, are not considered.

In [7], Kamalanathsharma developed a new ESC algorithm named Eco-Cooperative Adaptive Cruise Control (Eco-CACC). The Eco-CACC system computes and recommends real-time fuel-efficient speeds using V2V and V2I communicated data within the vicinity of the traffic signalized intersection. The objective function of the Eco-CACC system is the explicit minimization of the total fuel consumed to travel from some distance upstream of the intersection to a distance downstream of the intersection. The Eco-CACC system was tested and evaluated in a simulation environment. A reduction in fuel consumption of over 30 percent reduction was achieved.

In [60], we addressed the implementation issues and challenges of the field application of the Eco-CACC system by conducting a preliminary field test. We have shown that the Eco-CACC system is applicable and very promising in terms of fuel consumption and travel time savings.

In this thesis, we extend our work by conducting an extensive field experiment using 32 participants on the Smart Road test facility at the Virginia Tech Transportation Institute with the goal of evaluating the Eco-CACC system with regard to fuel consumption and travel time savings. Three different scenarios were considered: normal driving, driving with red indication countdown information provided to drivers, and driving with recommended speed information

also provided to drivers (Eco-CACC system). Previous studies showed that visual messages are less efficient and more distracting for drivers compared to audio messages [61-63]. Consequently, the computed speeds in this presented work were delivered to drivers as audio messages.

The chapter is divided into several sections, as follows: the literature review, which highlights the uniqueness and importance of contributed work; a brief description of the algorithm used; the experimental design used in gathering the data; the field data analysis and findings; and, finally, the conclusion and recommendations for future work.

3.3 Background

Signalized intersections have recently drawn attention as researchers have realized the significant increase of vehicles' fuel consumption levels in their vicinity [1]. When coming close to a signalized intersection, drivers are completely unaware of exactly when the traffic signal indication will change. Consequently, drivers may have to accelerate/decelerate aggressively to respond to these changes. This results in non-smooth driving behavior. Non-smooth driving (e.g. hard braking, sudden speed changes) consumes excessive fuel as it follows a non-ideal speed profile [2]. Research efforts have attempted to generate the fuel-optimal speed profile in the vicinity of signalized intersections [5, 8, 9]. This section reviews those research efforts attempting to develop models associated with the aforementioned concept.

Mandava et al. [8] proposed an algorithm that minimizes acceleration/deceleration rates to increase the probability of having a green light for oncoming vehicles at signalized intersections. Using signal phase and timing information, they delivered dynamic speed advice to drivers when approaching signalized intersections. The results demonstrated that the algorithm could decrease fuel consumption and emissions by 12-14%.

Asadi and Vahidi [10] developed a predictive cruise control system that used constrained optimization to minimize the probability of stopping. Traffic signal information and short range radar were used to change the vehicle's arrival time at the green light. The proposed algorithm did not provide dynamic speed advice to drivers. In addition, the speed profiles provided were not compared with regard to fuel efficiency. The simulation results show a reduction of 47% and 56% in fuel consumption and emissions respectively in an arterial road consisted of nine traffic signals.

Barth et al. [11] developed a dynamic eco-driving velocity planning algorithm along an arterial corridor with traffic signals. The objective function of the proposed algorithm was to minimize the level time spent accelerating and decelerating. The algorithm received signal phase and timing information from a traffic signal and recommended speeds for on-coming vehicles. Up to a 12% reduction in fuel consumption and emissions were reported.

Sun et al. [12] endeavored to obtain the optimal fuel/emission efficient speed profile for on-coming vehicles at signalized intersections. Given the upcoming signal information, a dynamic programming approach was used to estimate the optimal speed with regard to fuel efficiency. Subsequently, the authors developed an eco-driving strategy that allows a velocity advisory to be delivered to drivers. Savings of up to 25% in fuel consumption and emissions were found in a driving simulator experiment for 15 drivers.

Malakorn and Park [41] have studied the potential benefits of Cooperative Adaptive Cruise Control (CACC) with regard to the environmental impacts and vehicular mobility. The authors integrated CACC with Intelligent Traffic Signals in which CACC produces optimum trajectories to vehicles approaching signalized intersections. Using upcoming signal information, the system minimized acceleration and deceleration distances and idling time. Simulation results indicated a 91 percent and a 75 percent reduction in delay and fuel consumption, respectively. On the other hand, this study did not consider the speed profile downstream of the signalized intersection. In addition, the results were completed using a fixed deceleration distance (100 ft (30.5 m)).

Wu et al. [42] studied the benefits of two types of advanced driving alert systems, namely: stationary ADAS and in-vehicle ADAS. The authors proposed these systems with the objective of helping drivers approaching signalized intersections to achieve smooth driving (i.e. avoid hard braking and hard-deceleration maneuver). Both of these systems alert the drivers of time to red so that they can make a decision in advance to stop safely and thereby smoothly. The simulation results revealed a positive impact on fuel consumption and emissions. However, this study provided drivers information on traffic signal status only when it was red. The authors did not consider informing the drivers of time to green. In addition, they did not consider the downstream intersection in providing a fuel-optimum trajectory.

Tielert et al. [43] studied the effect of Traffic-Light-to-Vehicle Communication on the environmental impacts (i.e. emissions and fuel consumption). In this study, the effect of speed

adaptation was tested by using different speeds in the simulation. The authors found that gear choice and the distance from the traffic light have a significant impact on fuel consumption and emissions. The simulation results showed a reduction of 22% for a single vehicle and 8% for multi vehicles.

Sanchez et al. [44] proposed a new driving model called Intelligent-Driver Model Prediction (IDMP). The proposed model uses the information sent from the traffic signal to advise approaching vehicles with the goal of minimizing idling time; thus reducing vehicle fuel consumption levels. The authors made use of this information to compute the recommended speeds that a driver should adopt to achieve the aforementioned goal. In the simulation experiment, they used the Akcelik and Biggs fuel consumption model [45] to compare the results between two scenarios using the Intelligent-Driver Model (IDM) [46]. The simulation results showed a reduction of 25% in fuel consumption levels in urban areas.

Li et al. [47] introduced an optimized method using an augmented Lagrangian genetic algorithm that provides an optimum speed advisory for on-coming vehicles to intersections with the objective of reducing trip time; thus reducing vehicle fuel consumption levels. The proposed algorithm guarantees that on-coming vehicles do not exceed the maximum permitted speed when passing signalized intersections. The authors used a car following model to handle multi-vehicles. The VT-Micro model [2] was used in the proposed model to calculate the fuel consumption but not in the optimization objective function. In a simulated environment, savings of up to 69.3 percent and 12.1 percent were reported in fuel consumption and trip time, respectively.

Alsabaan et al. [48] developed an optimization model to compute the optimum or close-to-optimum speed in the vicinity of signalized intersections in which driver behavior will be smooth and, thereby, fuel consumption and emissions will be minimized. The authors used traffic-light-signal-to-vehicle (TLS2V) and V2V communication to send SPaT information to approaching vehicles so that drivers can follow the optimum speed. The objective function of this model is minimizing vehicle fuel consumption and emissions using the VT-Micro model [2] for four different scenarios. Heuristic expressions were used to estimate the optimum speed or near-optimum speed.

Jin et al. [49] proposed a mathematical model to optimize vehicle trajectories crossing intersections using six different signal timing configurations. This research effort was intended to

reduce the idling time and unnecessary changes in speed in the vicinity of a signalized intersections. The objective function is minimizing acceleration and deceleration distances. Approaching drivers were notified of a suggested speed through a DSRC connection in which SPaT information was sent to drivers. The authors tested different scenarios (e.g. the current signal state is either red or green with different lengths) and optimized the vehicle trajectory for upstream and downstream of the traffic signal. The optimum speed was computed by calculating the emissions and fuel consumption using a vehicle specific power model (VSP). In a simulated environment, average savings in fuel consumption of up to 12.01% and 7.73%, respectively were reported, as well as an increase in travel time.

As has been shown, most of the aforementioned literature have used almost the same concept in which the approaching vehicles are provided with a smooth speed profile in the vicinity of signalized intersections with the goal of minimizing fuel consumption and/or emissions. However, most of these research efforts attempted to minimize vehicle fuel consumption levels by minimizing acceleration/deceleration distances, idling time, and/or travel time, so their objective function was not the explicit minimization of fuel consumption.

Several previously conducted eco-driving experiments have shown a positive impact with regard to fuel consumption and emissions [3, 17, 20, 23, 24, 28, 29, 31-37]. However, all these studies were conducted either by providing a training course for drivers before driving and measuring before-after differences or by delivering “static” advice while traveling. None have used real-time traffic sensing and SPaT information to deliver “dynamic” advice while driving. A few field experiments were conducted by delivering “dynamic” advice to drivers [25, 64]; however, none of them explicitly considered vehicle fuel consumption as the objective function.

This field experiment was conducted using an Eco-CACC system that explicitly attempts to minimize vehicle fuel consumption levels. In the Eco-CACC system scenario, participants received a dynamic speed recommendation using V2I communication and were asked to adjust their speeds accordingly. Results were compared to normal driving with regard to fuel consumption and travel time savings. The analyzed data indicates that the proposed Eco-CACC system scenario results in the best fuel consumption saving levels among all tested scenarios and can produce fuel and travel time savings of up to 18.9 and 10.1 percent, respectively. In addition, the study demonstrates that driving with a red indication countdown can achieve fuel consumption and travel time savings of 11.2% and 4% on average, respectively.

3.4 Methodology

3.4.1 Test Facility

The Virginia Department of Transportation's (VDOT) Virginia Smart Road at the Virginia Tech Transportation Institute (VTTI) was the site of the field test. Located in the southwestern region of Virginia, the Smart Road serves as a distinctive, state-of-the-art, closed test-bed research facility. The Smart Road is a 2.2 mile (3.5 km) two-lane road (one-lane for each direction) with one four-way signalized intersection (Figure 3-1). The 1.6 mile (2.5 km) section used for the data collection includes only the section between two turnarounds with the four-way signalized intersection, as shown in Figure 3-2. The first end (T1) is a high-speed banked turnaround and the second end (T2) is a low-speed flat turnaround. Although there is some insignificant horizontal curvature, the test section's horizontal layout is generally straight. However, this curvature does not affect road speeds. The vertical layout of the test section has a grade of 3 percent (uphill and downhill). Due to the fact that study participants turned around at the conclusion of each trip, half the trips occurred on a 3 percent upgrade while the others were on a 3 percent downgrade. In this experiment, the speed limit of the testing facility was 40 mph (64 km/h).

The Eco-CACC system is activated when the testing vehicle is at 820 ft (250 meters) upstream of the stop line (denoted by d_{up}) and is deactivated when the testing vehicle is at 590 ft (180 meters) downstream of the stop line (denoted by d_{down}). This can be seen in Figure 3-2, in which the two maroon lines indicate the distance where the Eco-CACC is activated, while the two red lines represent the stop lines for each direction. It must be mentioned that these values (i.e. d_{up} and d_{down}) were chosen based on the geographical constraints of the testing site.



Figure 3-1 Signalized intersection in the VA Smart Road Test facility

3.4.2 Experimental Equipment

A VTTI automated vehicle (2014 Cadillac SRX) was used in the experiment. It is equipped with an onboard vehicle unit for V2V and V2I communication, a Differential Global Positioning System (DGPS), a real-time data acquisition system (DAS), and a laptop with installed VTTI proprietary programs to control the trips and road scenarios. The DAS is capable of data collection of up to 0.1-second precision. All data recorded were stored in a hard drive located in the truck, as shown in Figure 3-2.

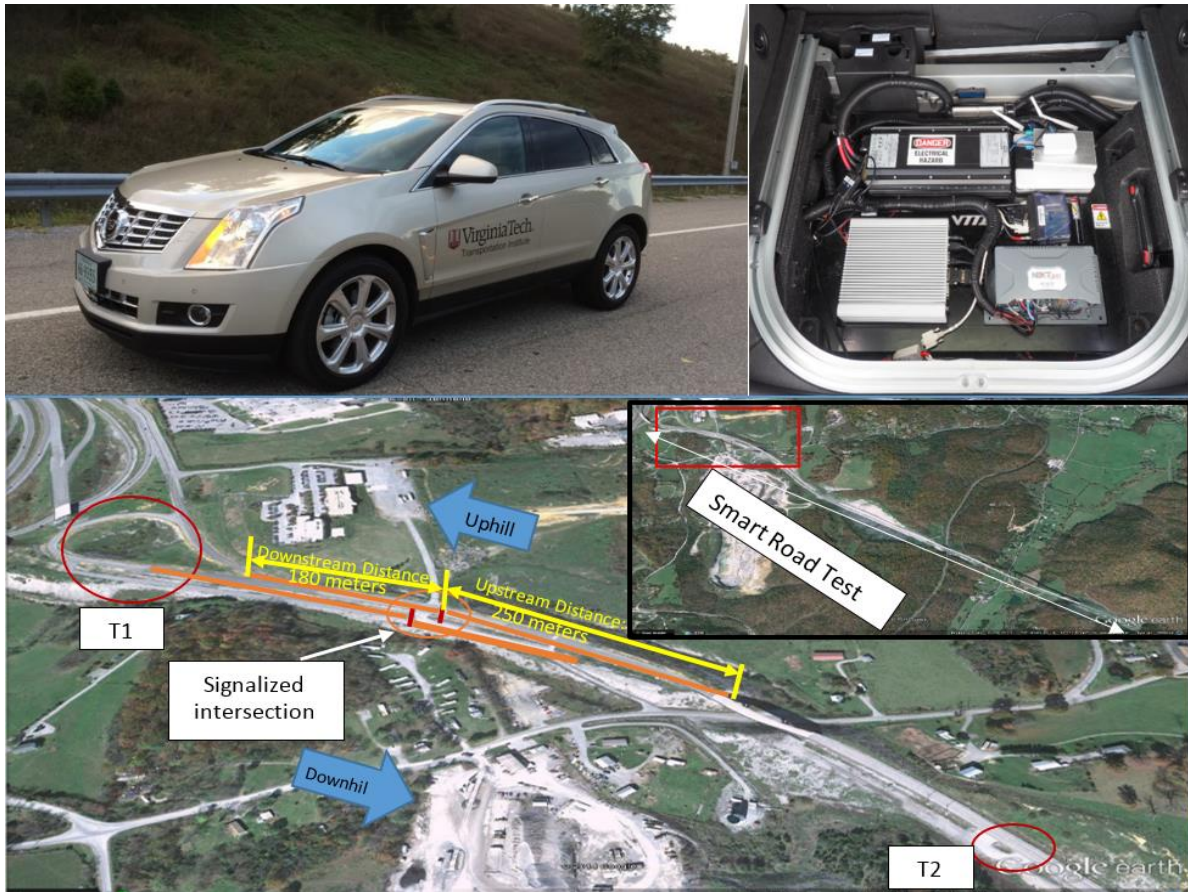


Figure 3-2 Instrumented vehicle and field test site

With the help of the V2I communication, the testing vehicle received upcoming signal changes (i.e. time from red to green). In the Eco-CACC system scenario, the optimum speed profile and target speed were calculated by the algorithm every deci-second, but the recommended speeds were delivered to participants at a 2-second interval through an in-car sound system and within the range of algorithm parameters.

3.4.3 Participants

IRB approval was obtained in November 2015 from the Institutional Review Board (IRB #15-1092) at Virginia Tech before starting recruiting the subjects. Participants were licensed drivers recruited from the VTTI internal participant database, flyers, ads in the local Blacksburg, VA newspaper, and/or word-of-mouth. Participants were screened through a verbal questionnaire over the phone (Appendix D) to determine if they were licensed drivers and if they had any health concerns that would exclude them from participating in the study. Any participant with more than two driving violations or responsible for an injurious accident was excluded. A total of

32 participants between the ages of 18 to 30 were recruited. An equal number of males and females was assigned to this group. Participants were paid \$30 per hour for a 2 –3 hour session.

In order to have a representative sample for the local community and avoid newly licensed drivers, participating drivers were required to have U.S. driving experience of at least two years. Therefore, their driver's licenses were checked to verify this condition upon arrival at VTTL.

3.4.4 Procedure

The experiment was conducted solely on the Smart Road test facility and only during daylight hours in a dry pavement condition. The experiment was composed of two main phases. The first phase was comprised of the determination of eligibility and the procurement of informed consent from each participant. The second phase, the Smart Road test-track driving portion, required only one session in one day for each participant and took approximately 2-3 hours to complete. Each participant was assigned to three different scenarios with 16 trips each. The following are the three scenarios:

- ✓ **Scenario 1:** The participant was asked to drive freely, following the signal as he/she would on a real signalized road.
- ✓ **Scenario 2:** The participant was given a countdown to the next signal change via an audio message at two-second intervals using an in-vehicle device, and he/she was allowed to use this information to adjust his/her driving following the signal rules.
- ✓ **Scenario.3 (Eco-CACC scenario):** The participant was given a recommended speed in an audio message at two-second intervals using an in-vehicle device and he/she was asked to follow that recommended speed following the signal rules.

Participants drove loops on the Smart Road, crossing a four-way signalized intersection between two turnarounds (Figure 3-2) where the data were collected. Exclusive of practice trips, each participant drove a total of 48 trips (16 trips for each scenario), where a trip consists of one approach to the intersection. Each participant was tested individually, using the same vehicle. These trips were split equally into four values of red indication offset, namely: 10, 15, 20, and 25 seconds. Each red indication offset was repeated two times for each direction. In each scenario, these trips were in a predetermined randomized order.

The red indication offset refers to the number of seconds when the traffic light turns from red to green. The values of red indication offset were chosen based on the fact that a vehicle traveling at 40 mph (64 km/h) over 820 ft (250 meters) (d_{up}) needs approximately 14 seconds to reach the stop line. Therefore, a baseline of 15 seconds was used, with one value before and two values after with a 5-unit interval.

The red indication offset is triggered when the testing vehicle approaches the signalized intersection and reaches the range of Eco-CACC (820 ft/250 meters). From the available values of red indication offset (10, 15, 20, and 25 seconds), one value will be randomly assigned to the traffic signal for each trip. In other words, when the testing vehicle reaches 820 ft (250 meters), the red indication offset will be either 10, 15, 20, or 25 seconds. It should be noted that the green phase was always set at 25 seconds in order to give the vehicle enough time to pass the range of Eco-CACC at a downstream distance of 590 ft (180 meters).

On test day:

Each participant reviewed and signed an informed consent form (appendix C) after arriving at VTTI. The experiment was explained in detail. Then, a Snellen vision test was administered to ensure that vision acuity was within the legal driving limit (at least corrected to 20/40). Following completion of the test, the participant was taken to the testing vehicle (SRX 2014). The participants familiarized themselves with the test vehicle (e.g., adjusting mirrors and seat, fastening seat belt), and then proceeded to the Smart Road with an in-vehicle experimenter. The experimenter was present in the testing vehicle at all times during the study to offer guidance to the participant, operation of the computer system and control scenarios, supervision of the experiment, and responses to any questions. Before the first official trip, the participant drove three practice trials (intersection passes) to become familiar with the vehicle and the Smart Road. Participants were informed of the 40 mph (64 km/h) speed limit and asked to follow all normal traffic rules and obey all traffic laws.

All participants performed the three scenarios in order. Each started the test uphill, made a U-turn at the end of the road (T1), and went back, approaching the signalized intersection in the downhill direction toward the other U-turn (T2). The participant continuously drove the testing vehicle until all the trips (uphill and downhill) for all three scenarios were completed.

In order to calculate the vehicle fuel consumption of the entire maneuver near the signalized intersection and have fair comparison, participants were asked to drive at 40 mph (64

km/h) once they entered the Eco-CACC range of the intersection (820 ft /250 meters) and once they leave this range (590 ft/180 meters) (Figure 3-2). Four cones were put on the boundaries of the Eco-CACC range to inform the participants when the speed needed to be at 40 mph (64 km/h). Therefore, the entry and exit speed were the same for all trips. If a participant drove more than 3 mph above or below the instructed speed (40 mph/64 km/h), the trip was repeated. In addition, the participant was reminded of the instructed speed and the speed limit at turnaround T2. On completion of the experiment, the participant was asked to leave the Smart Road and fill out a questionnaire (Appendix G).

3.5 Field Data Analysis

The vehicle trip information (e.g. the current and recommended speed, distance to stop line, time, and SPaT information) were recorded each deci-second. Only the data in the range of Eco-CACC (820 ft (250 m) upstream and 590 ft (180 m) downstream) were extracted and analyzed. In total, 1536 trips were recorded for 32 participants. All the entry and exit speeds for each participant were checked to ensure they were in the allowable range of 37 to 43 mph (59.5 km/h to 69.2 km/h). Due to the fact that some participants found it difficult to follow the recommended speed at 2-second intervals in the Eco-CACC scenario, 10 % of the trips were found to be outliers. However, these trips were included in the analysis as they represent a variant in behavior of some drivers.

Several statistical designs have been considered for this experiment. One of which is a three-way factorial design in which the response is either the fuel consumption or travel time with three independent variables or factors: scenario, direction, and red indication offset. However, this model assumes that the three factors are randomized, which is not the case in this experiment. The scenario factor cannot be randomized, as that may affect the participant's performance. To be specific, if a participant had tried driving with recommended speed information before driving normally, his/her behavior would be affected in the normal driving scenario. Additionally, the direction factor was found to be excessively time-consuming if randomized. Therefore, a split-split-plot design (SSPD) was chosen to analyze the data, given its power in accommodating the factors that were difficult to change [65]. SSPD is an extension of the split-plot design that was invented by Fisher in 1925.

The split-split-plot design is a blocked experiment with three levels of experimental units. The first level of the experimental units is the whole plot (scenario); the second level is the

experimental units within the whole plot, called the split-plot (direction of travel in our case); and the third level is the experimental units within the split-plot, called the split-split plot (red indication offset in our case). The red indication offset factor was the only randomized factor in the experiment, as shown in

Figure 3-3.

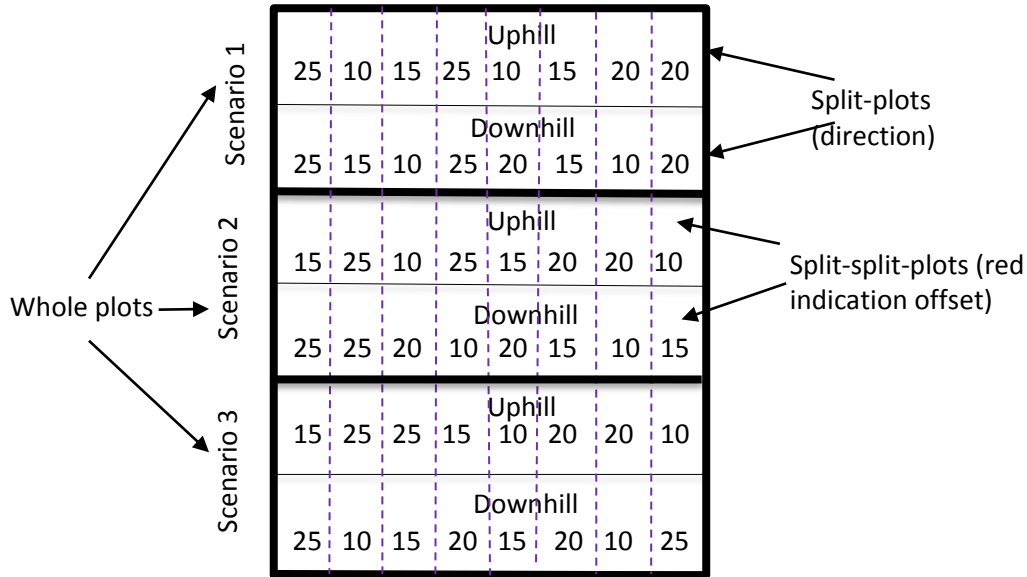


Figure 3-3 Experimental design

Figure 3-3, each participant had a complete set of all treatment combinations (24 treatments), and each treatment combination replicated twice. In addition to the three aforementioned factors, gender and participant effects were added to the model. Given that there is a variation among drivers owing to their behaviors, the participant effect was considered as a random effect and, thereby, was blocked, while the gender effect was treated as a fixed effect and tested.

The linear statistical model used for the split-split-plot design is as follows:

$$\begin{aligned}
 y_{kijl} &= \mu + \rho_k + \eta_k + \alpha_i + \varepsilon_{kih} && \text{(Whole plot)} \\
 &+ \gamma_j + (\alpha\gamma)_{ij} + \varepsilon_{kijh} && \text{(Split-plot)} \\
 &+ \beta_k + (\alpha\beta)_{il} + (\gamma\beta)_{jl} + (\alpha\gamma\beta)_{ijl} + \varepsilon_{kijlh} && \text{(Split-split-plot)}
 \end{aligned} \tag{3-1}$$

Where y_{kijlh} is the fuel consumed or travel time by the k th participant in the i th scenario, the j th direction and the l th red indication offset for the h th replicate in which $k = 1, \dots, 32$, $i = 1, 2, 3$, $j = 1, 2$, $l = 1, 2, 3, 4$, and $h = 1, 2$; μ is the grand mean; ρ_k is the random effect of the k th participant (blocking); η_k is the fixed effect of gender for the k th participant; α_i is the fixed effect of the i th scenario; ε_i is the whole-plot error representing unexplained variations among the three scenarios; γ_j is the fixed effect of the j th direction; $(\alpha\gamma)_{ij}$ is the interaction effect between the i th scenario and the j th direction; ε_{ij} is the split-plot error representing unexplained variations between each run in each direction; β_k is the fixed effect of the l th red indication offset; $(\alpha\beta)_{il}$ is the interaction effect between the i th scenario and the l th red indication offset; $(\gamma\beta)_{jl}$ is the interaction effect between the j th direction and the l th red indication offset; $(\alpha\gamma\beta)_{ijl}$ is the interaction effect between the i th scenario, the j th direction, and the l th red indication offset; and ε_{ijl} is the split-split-plot error representing unexplained variations between each run in each red indication offset.

Split-split-plot design assumes that the residuals are independent and normally distributed with common variances. These assumptions have been checked, and it has been found that the normality condition is the only assumption that has not been met for fuel consumption. Therefore, the Box-Cox transformation, a well-known parametric power transformation developed by Box & Cox in 1964, was used to transform the fuel consumption to meet the normality condition [66].

After applying SSPD, Tukey's Honest Significance Test (HSD) at a 5-percent significance level ($\alpha = 0.05$) was used to analyze all pairwise comparisons between the three scenarios to determine which, if any, are significantly different from each other [67].

The in-field data results show that fuel consumption measurements are not reliable as they don't capture the sudden changes in speeds and, also, give a value of zero when the vehicle is decelerating as shown in Figure 3-4. Consequently, the Virginia Tech Comprehensive Power-based Fuel Model, Type 1 (VT-CPFM-1) was used to estimate the fuel consumption rate because of its simplicity, accuracy, and ease of calibration [58]. VT-CPFM-1 uses instantaneous power to estimate the fuel consumption rates as given in Equations (2-9) and (2-10).

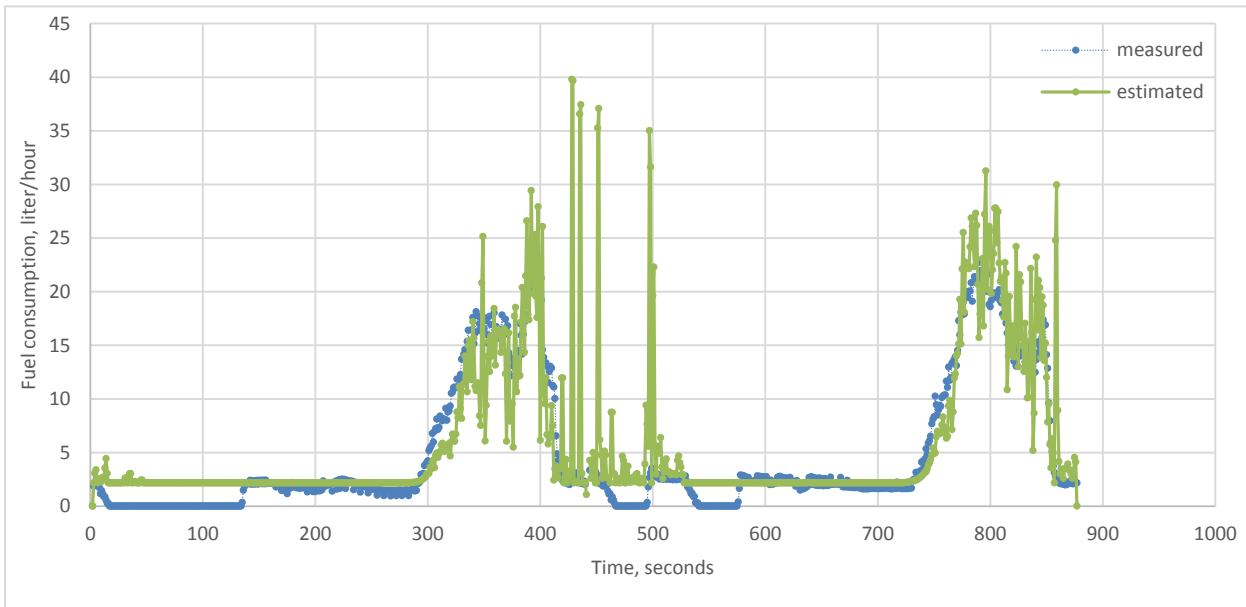
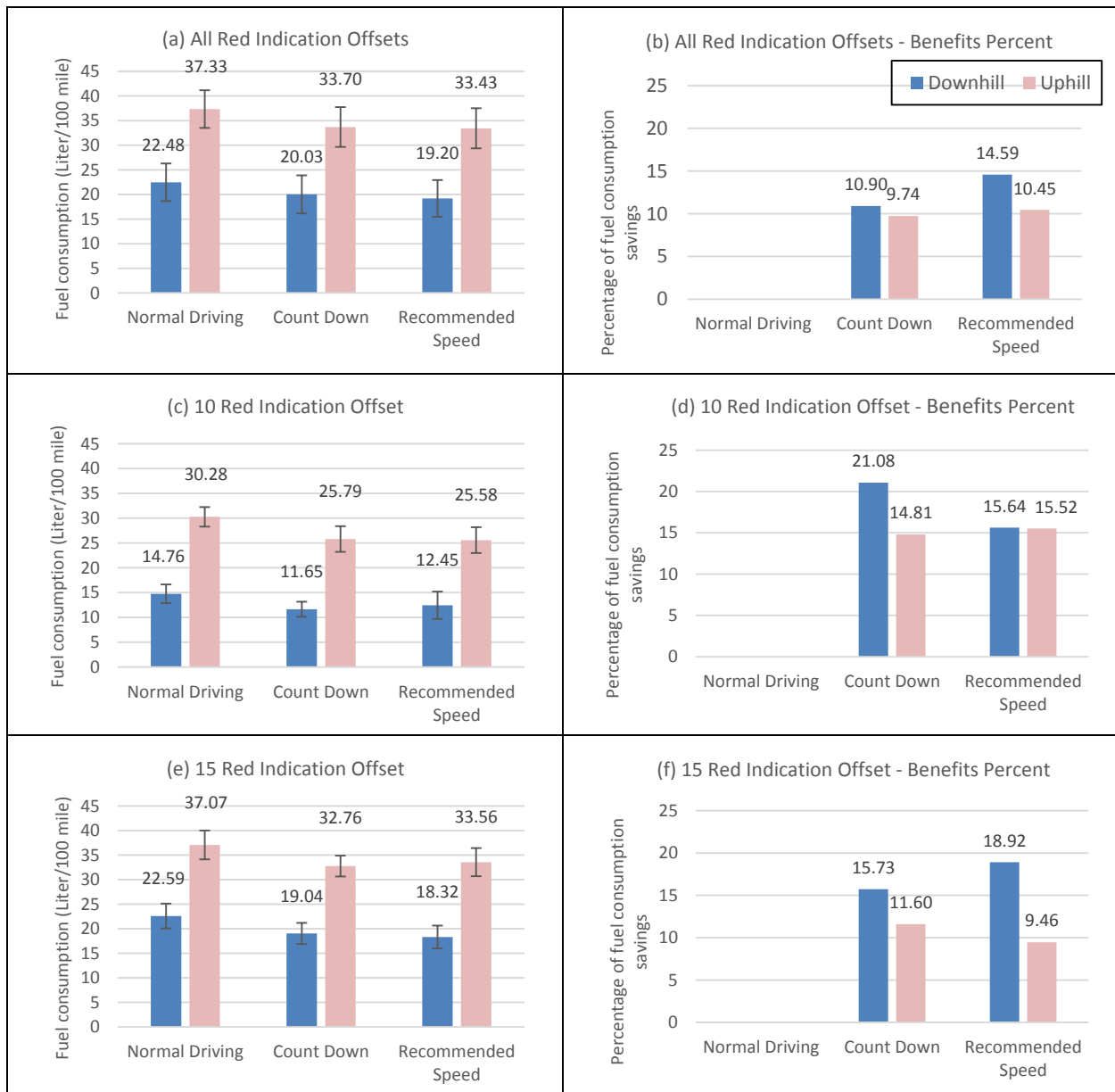


Figure 3-4 Fuel consumption comparison

3.5.1 Fuel Consumption

The field test results clearly demonstrate that a vehicle equipped either with countdown or recommended speed information always results in a fuel economy enhancement for every treatment combination of trip direction and red indication offset value. Remarkably, these benefits were generally found to be slightly larger in the downhill direction than the uphill direction for each red indication offset value, which is in compliance with previous research that showed using conventional cruise control always produced a better result in the downhill direction than the uphill direction [68]. Additionally, driving at the speed recommended by the Eco-CACC system results in a better fuel economy than driving with the countdown for most of the values of red indication offsets. In particular, it provides higher fuel consumption saving levels, especially in the downhill direction, for all the values of red indication offsets, with the exception of the red indication offset value of 10 seconds downhill and 15 seconds uphill.

Figure 3-5 presents a comparison of fuel consumption levels between all three scenarios for 10, 15, 20, and 25 second red indication offset values. Figure 3-5 (a) illustrates that, for all red indication offset values, the average fuel consumption levels for driving with a countdown and driving at the recommended speed are smaller than those for normal driving. The analysis shows that driving at the recommended speed reduces fuel consumption levels in both the downhill and uphill directions by 14.59% and 10.45%, respectively when compared to normal driving. As for driving with the countdown is concerned, the reductions in fuel consumption in both the downhill and uphill directions are 10.9% and 9.74%, respectively.



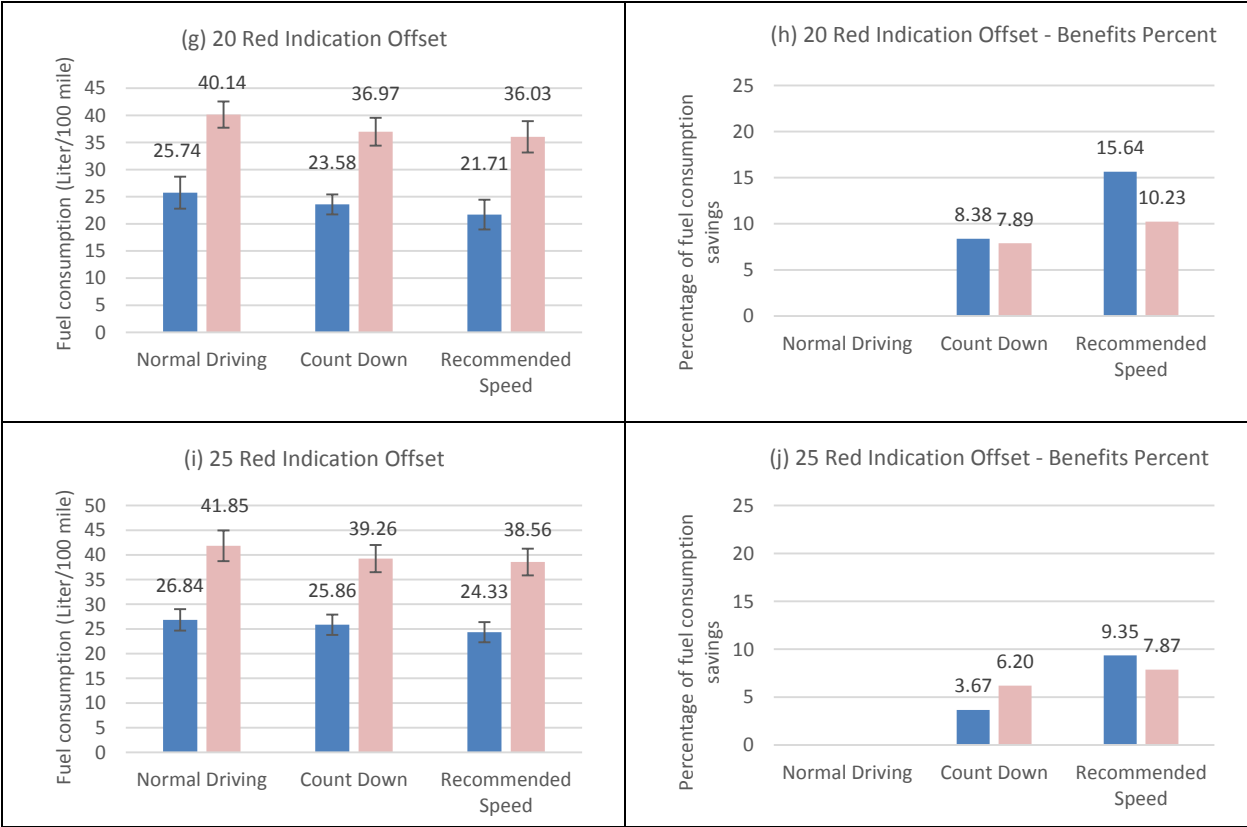


Figure 3-5 Fuel consumption comparison between all the three scenarios with standard deviation

The maximum fuel consumption savings levels for driving at the recommended speed is 15.52% in the uphill direction for a red indication offset value of 10 seconds (Figure 3-5 (d)), yet it is 18.9% in the downhill direction for a 15 second red indication offset value (Figure 3-5 (f)). When driving with a countdown, the maximum fuel consumption savings in the downhill and uphill direction are 21.1% and 14.8% respectively, and this occurs for a red indication offset value of 10 seconds (Figure 3-5 (d)). It must be noted that a red indication offset value of 10 seconds means drivers can continue driving at their current speed (i.e. entry speed of 40 mph (64 km/h)) without any deceleration, while the 15 second red indication offset value requires a slight deceleration (i.e. decelerating from 40 to 35 mph (56 to 64 km/h)). This explains why the maximum fuel consumption saving levels occur under 10 and 15 second red indication offsets.

When compared to normal driving, most of the drivers had unnecessary deceleration or hard deceleration events for a red indication offset value of 10 and 15 seconds. While moving at the recommended speed, drivers with a 10 or 15 second red indication offset found it easy to maintain their current speed or to decelerate slightly, but they failed with large red indication offset values of 20 and 25 seconds. Similarly, drivers with a countdown of 10 or 15 seconds

realized that they can maintain their current speeds without any deceleration or with a little deceleration, but failed with larger red indication offset values and came to a complete stop. Consequently, the maximum fuel consumption saving levels for either driving with a countdown or at the recommended speed occur at a 10 and 15 second red indication offset.

It can be concluded that driving at the recommended speed or with countdown information is very efficient in reducing fuel consumption levels at shorter red indication offsets. That can also be easily observed in Figure 3-6, in which the percentage of fuel consumption savings levels for most cases generally decreases as the value of red indication offset increases, both when driving with a countdown and recommended speed information.

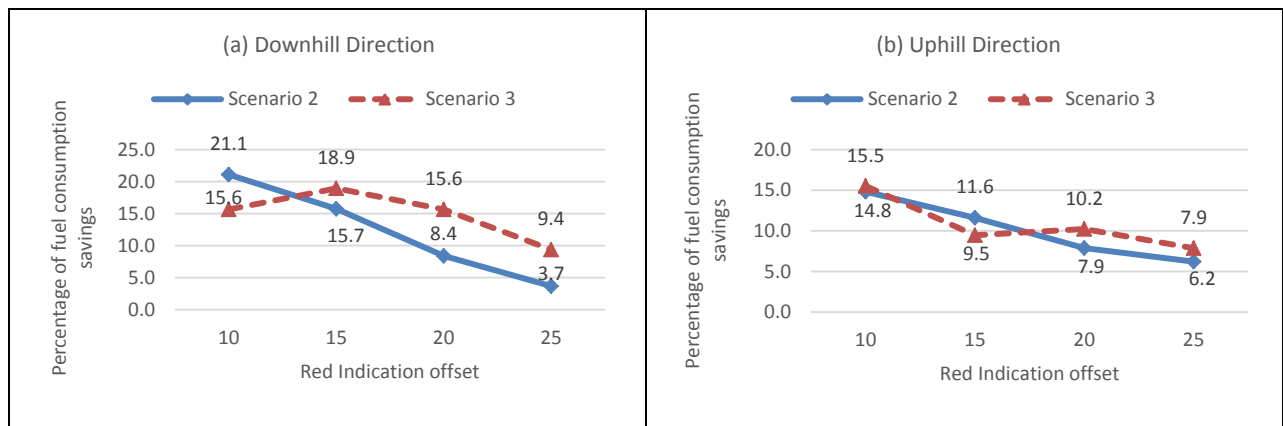


Figure 3-6 The trend of the percentage of fuel consumption savings across all the values of red indication offsets

Table 3-1 provides a summary of the observations of average fuel consumption levels with the percentage reductions compared to normal driving for different combinations of trip direction and red indication offset values.

Table 3-1 Average fuel consumption (FC) levels

Direction	Red Indication Offset (sec)	Scenario 1	Scenario 2		Scenario 3	
		FC (liter/100 mile)	FC (liter/100 mile)	Reduction (%)	FC (liter/100 mile)	Reduction (%)
Downhill	10	14.8	11.6	21.1	12.5	15.6
	15	22.6	19.0	15.7	18.3	18.9
	20	25.7	23.6	8.4	21.7	15.6
	25	26.8	25.9	3.7	24.3	9.4
Uphill	10	30.3	25.8	14.8	25.6	15.5
	15	37.1	32.8	11.6	33.6	9.5
	20	40.1	37.0	7.9	36.0	10.2
	25	41.9	39.3	6.2	38.6	7.9
Average (downhill)		22.5	20.0	12.2	19.2	14.9
Average (uphill)		37.3	33.7	10.1	33.4	10.8
Total Average		29.9	26.9	11.2	26.3	12.8

The analysis of SSPD at a 5-percent significance level was conducted and the results are presented in Table 3-2 where DF and DFDen indicate the degrees of freedom in the numerator and denominator respectively. The model was able to explain approximately 90 % of the variations in fuel consumption levels. Given the presence of significant interactions in the model, the main effects (scenario, direction, and red indication offset) cannot be examined individually. Consequently, the significant interactions (scenario-red indication offset and red indication offset-direction) were studied and drawn in Figure 3-7. It is observable that both of these interactions are co-directional, which means that each scenario/red indication offset has the same pattern across the values of red indication offset/direction with a slight change in slope. Consequently, the main effects can be tested separately.

Table 3-2 Results of fixed effects of the split-split-plot ANOVA using the fuel consumption as the dependent variable for scenario, direction, and red indication offset.

Source	DF	DFDen	F Ratio	Prob > F
scenario	2	158	98.6247	<.0001
red indication offset	3	1134	1267.443	<.0001
direction	1	189	7948.735	<.0001
scenario*direction	2	189	1.7589	0.175
scenario*red indication offset	6	1134	6.4503	<.0001
red indication offset*direction	3	1134	41.4121	<.0001
scenario*red indication offset*direction	6	1134	1.8518	0.0861
gender	1	30	1.6958	0.2027

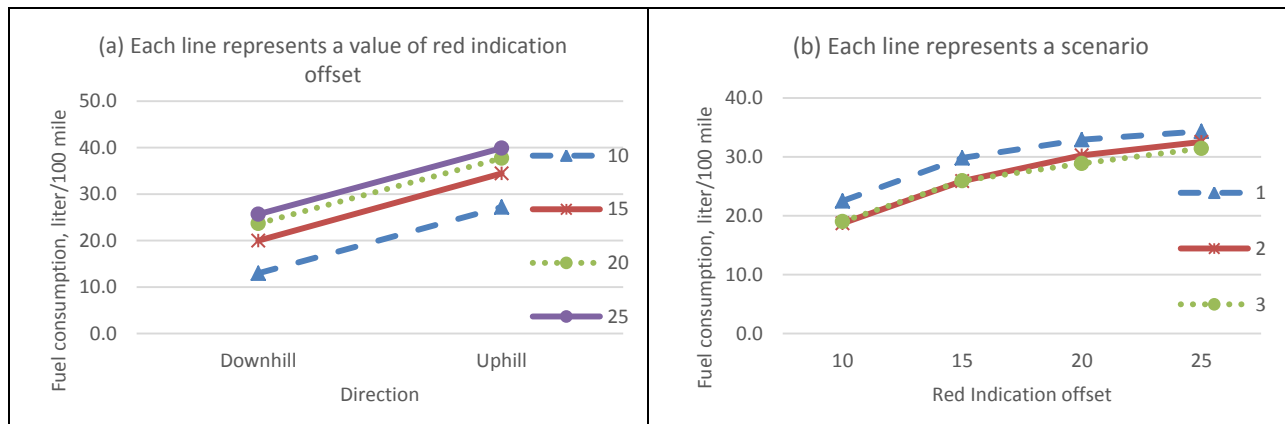


Figure 3-7 Fuel consumption comparison

The effect of the scenario was found to be significant with a p-value of less than 0.0001. Subsequently, a multiple comparison using Tukey’s HSD was carried out to analyze the differences in fuel consumption among all the similar treatment combinations. The analysis shows that the differences between normal driving and recommended speed scenarios were statistically significant for all the values of red indication offset. Moreover, Tukey’s HSD test indicates that a normal driving scenario differs significantly from a scenario of driving with countdown information under all the values of red indication offset except 20 seconds downhill and 25 seconds for both directions. Unexpectedly, there was no significant difference between driving with a countdown and driving with recommended speed information for all the values of red indication offset. Interestingly, females tend to consume more gas than males under all the values of red indication offset, but that was found statistically insignificant.

3.5.2 Travel Time

Compared to normal driving, driving with either countdown or recommended speed information decreases the average travel time for all the values of red indication offset and directions. In

particular, driving with recommended speed information produces dramatic travel time savings when compared to driving with countdown information for each treatment combination of red indication offset and direction. In some cases, the benefits in travel time savings when driving with recommended speed information are as much as 4 times the benefits of driving with countdown information. Figure 3-8 gives a comparison of travel times between all three scenarios for all the values of red indication offset. The average travel time savings for all red indication offset values when using recommended speed information both downhill and uphill are 7.3% and 7.93 % respectively, while they are only 2.57% and 2.66% when driving with countdown information (Figure 3-8 (b)). In contrast to fuel consumption savings levels, for most treatment combinations, traveling uphill has a higher benefit in travel time savings than traveling downhill. This can be explained by the fact that drivers were more aggressive when approaching the signalized intersection going uphill than going downhill.



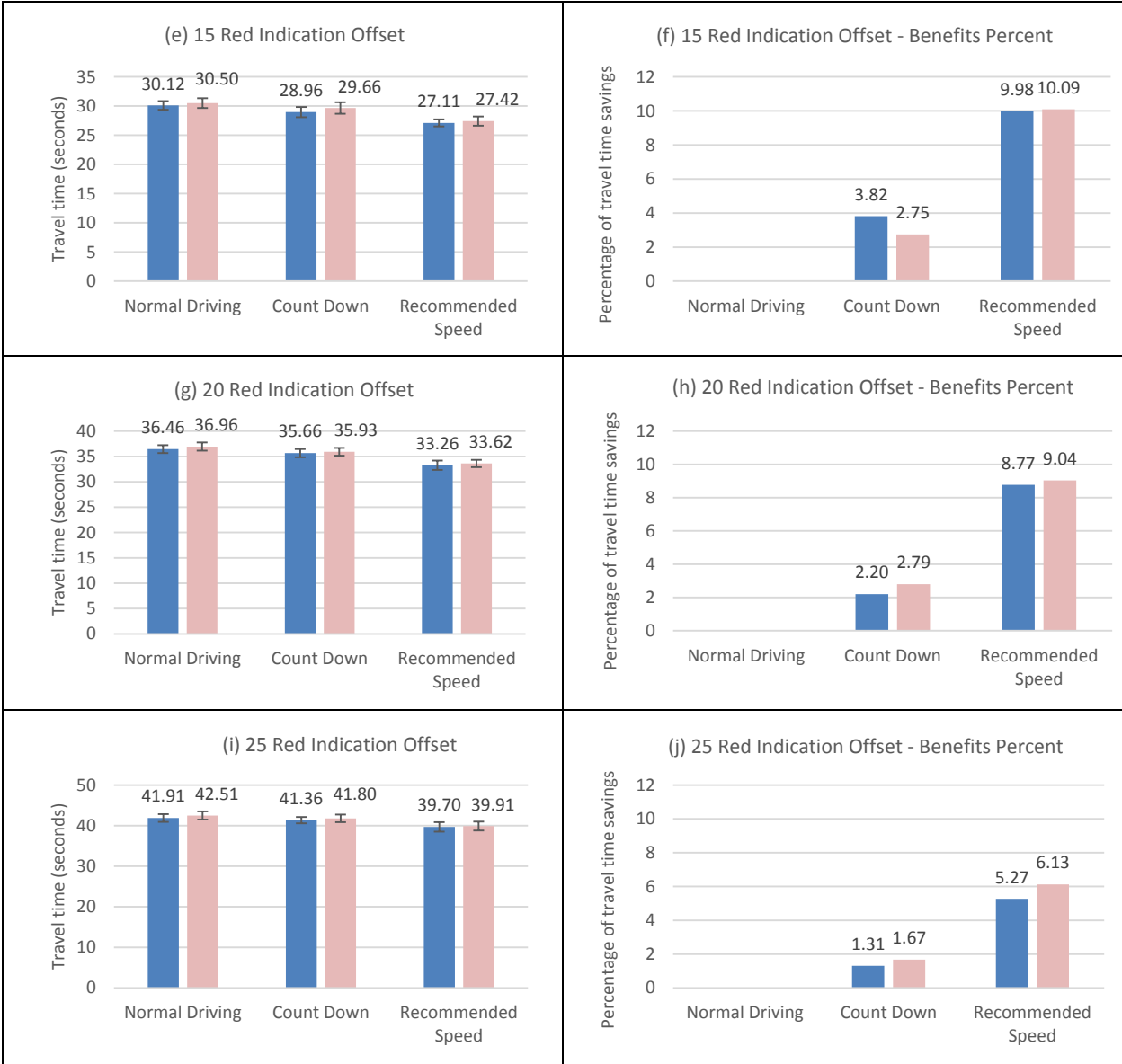


Figure 3-8 Travel time comparison between all the three scenarios for all the values of red indication offsets with standard deviation

The trend of the percentage of travel time savings within the values of red indication offset for both of these scenarios is shown in Figure 3-9. As for driving with recommended speed information, the reduction in travel time increases for both directions when the value of red indication offset increases from 10 to 15 seconds, then decreases from 15 to 25 seconds. It can be seen that the maximum travel time savings for driving downhill and uphill with recommended speed information under a 15 second red indication offset value are 10% and 10.1%, respectively. Driving with countdown information has a different pattern for each direction. The percentage of travel time savings in the downhill direction is the same as driving with

recommended speed information, while, in the uphill direction, the percentage decreases when the value of red indication offset changes from 10 to 15 seconds. It then remains constant from 15 to 20 seconds and decreases at 25 seconds. Consequently, the maximum travel time savings for driving with a countdown are 3.7 % and 4% for a 10 second red indication offset for downhill and uphill directions, respectively.

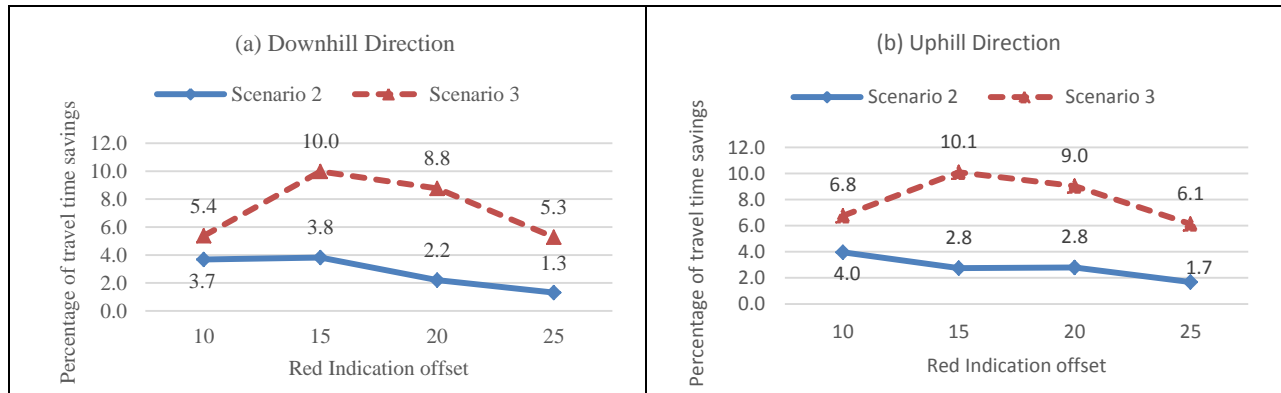


Figure 3-9 The trend of the percentage of travel time savings across all the values of red indication offsets

A summary of the average time with the percentage of reduction for each scenario under different circumstances is presented in Table 3-3.

Table 3-3 Average travel times (TT)

Direction	Red indication offset (sec)	Scenario 1	Scenario 2		Scenario 3	
		TT (sec)	TT (sec)	Reduction (%)	TT (sec)	Reduction (%)
Downhill	10	25.6	24.6	3.7	24.2	5.4
	15	30.1	29.0	3.8	27.1	10.0
	20	36.5	35.7	2.2	33.3	8.8
	25	41.9	41.4	1.3	39.7	5.3
Uphill	10	26.0	25.0	4.0	24.3	6.8
	15	30.5	29.7	2.8	27.4	10.1
	20	37.0	35.9	2.8	33.6	9.0
	25	42.5	41.8	1.7	39.9	6.1
Average (downhill)		33.5	32.7	2.8	31.1	7.3
Average (uphill)		34.0	33.1	2.8	31.3	8.0
Total Average		33.8	32.9	2.8	31.2	7.7

The SSPD Analysis-of-Variance was conducted, as shown in Table 3-4. The model used captures approximately 99 % of the variation in the response (i.e. travel time) given the three effects (i.e. scenario, red indication offset, and direction) with their interactions. Scenario-direction and scenario-red indication offset interactions were found significant, and thus further investigated.

Table 3-4 Results of fixed effects of the split-split-plot ANOVA using travel time as the dependent variable for scenario, direction, and red indication offset

Source	DF	DFDen	F Ratio	Prob > F
scenario	2	158	709.9287	<.0001
red indication offset	3	1134	38431.48	<.0001
direction	1	189	149.1616	<.0001
scenario*direction	2	189	5.8171	0.0035
scenario*red indication offset	6	1134	50.6643	<.0001
red indication offset*direction	3	1134	0.8162	0.4849
scenario*red indication offset*direction	6	1134	1.3416	0.2355
gender	1	30	0.2442	0.6248

Based on Figure 3-10, it can be concluded that these interactions are additive interactions. Each value of red indication offset/direction acts on travel time via the same or a similar mechanism. Therefore, the main effects can be tested individually.

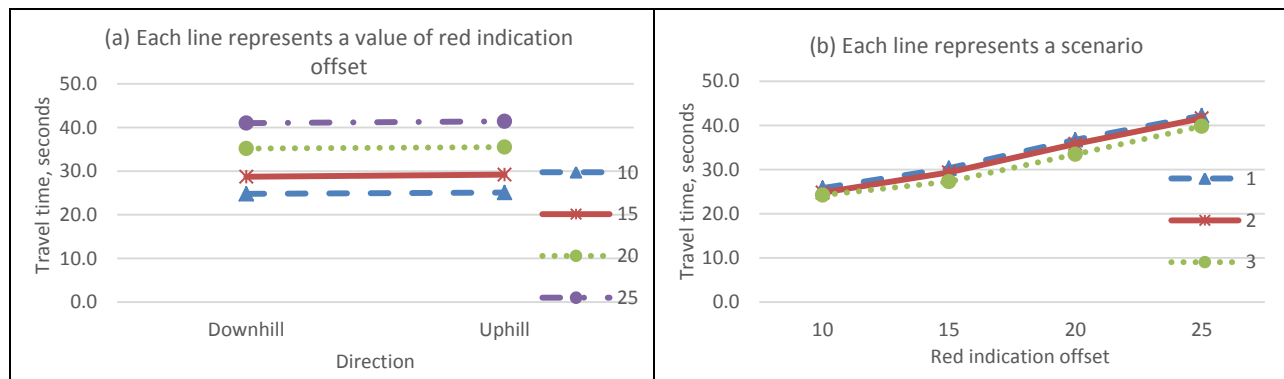


Figure 3-10 Travel time comparison

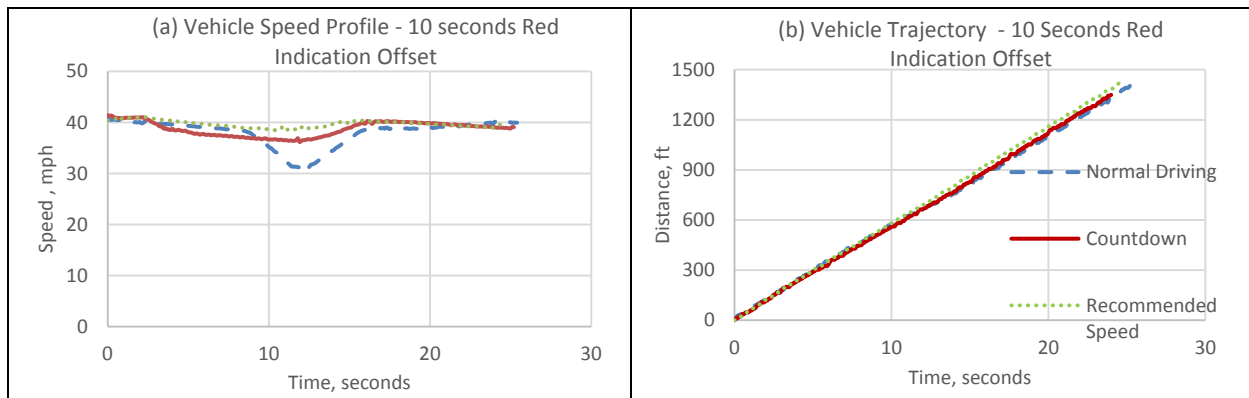
The scenario effect was found to be statistically significant and, thereby, Tukey’s HSD was conducted to assess the differences in travel time between each treatment combination. Results show that the differences between normal driving and driving with either countdown or recommended speed information are statistically different under all the values of red indication offset for both directions. Unlike fuel consumption response, driving with recommended speed information is significantly different from driving with countdown information under all the values of red indication offset except 10 seconds downhill. Furthermore, females tend to spend more time traveling for most values of red indication offset, but that was found insignificant.

3.6 Findings

As has been shown previously, driving with either recommended speed or countdown information is very efficient in producing fuel economy enhancement in the downhill direction and reducing average travel time in the uphill direction. This demonstrates that driving uphill

efficiently with recommended speed or countdown information is difficult, yet it incurs a greater reduction in travel time.

Additionally, the results show that driving with recommended speed information improved the drivers' behavior for all of the treatment combinations. It decreases acceleration and deceleration maneuver distances and provides a smooth speed profile. This can be seen in Figure 3-11 and Figure 3-12, in which an example of vehicle speed profile and a trajectory comparison for the three scenarios for each value of red indication offset is presented. It has to be noted that at $t=0$, the vehicle enters the range of Eco-CACC system. In Figure 3-11 (g) and (h), in the base scenario (normal driving), the driver came to a complete stop at the intersection with a long deceleration maneuver distance and waited for 10 seconds. Similarly, in the second scenario (driving with countdown information), the driver stopped and waited for 5 seconds at the intersection with a long deceleration maneuver distance. However, in the third scenario (recommended speed information), the driver tried to follow the recommended speed by decelerating initially and then cruising at around 17 mph (27.3 km/h) until he/she passed the intersection without having to come to a complete stop. It should be mentioned that driving with countdown information improved the driver's behavior slightly, especially under 10 or 15 second red indication offset values, but with less impact than driving with recommended speed information.



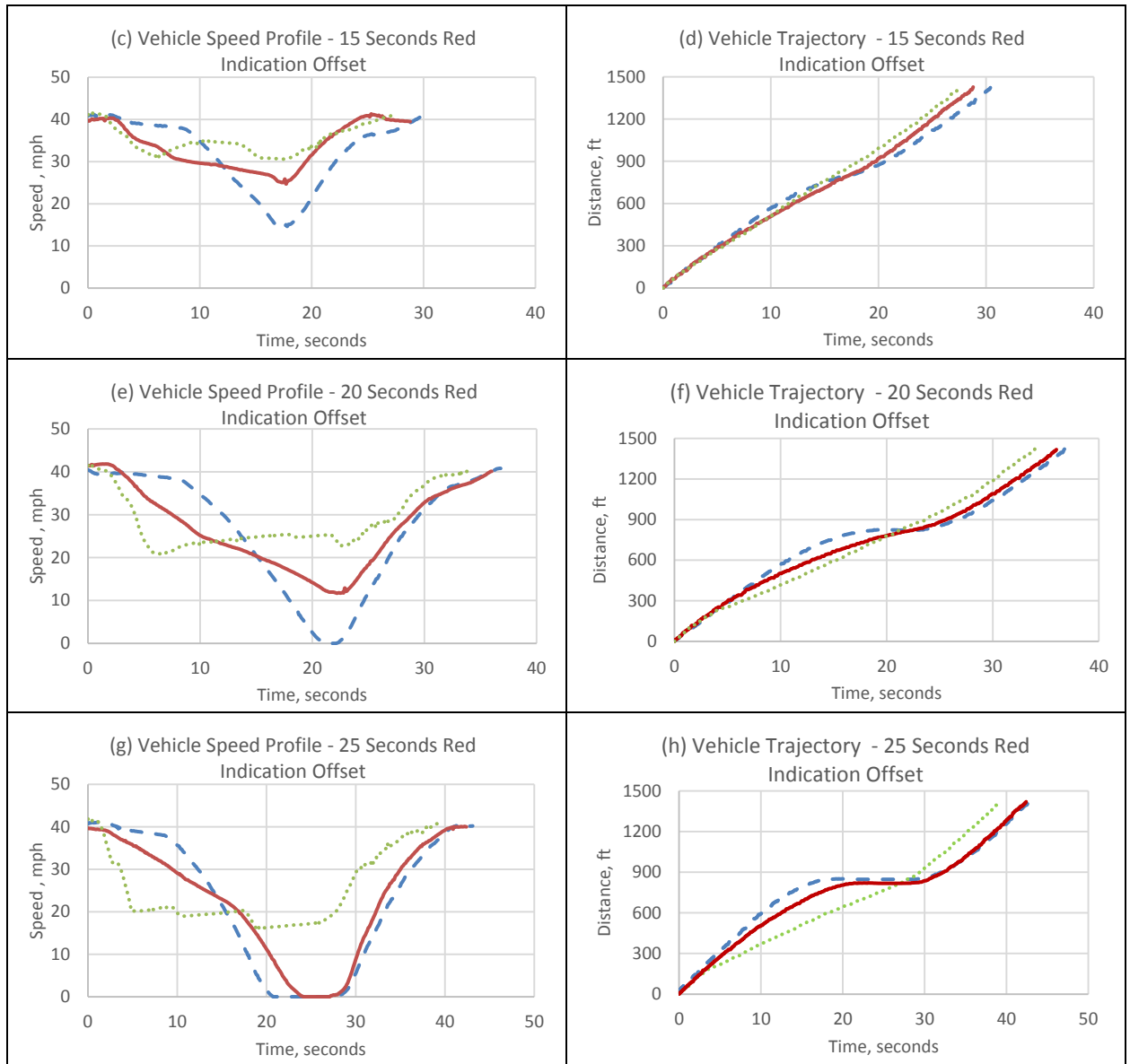
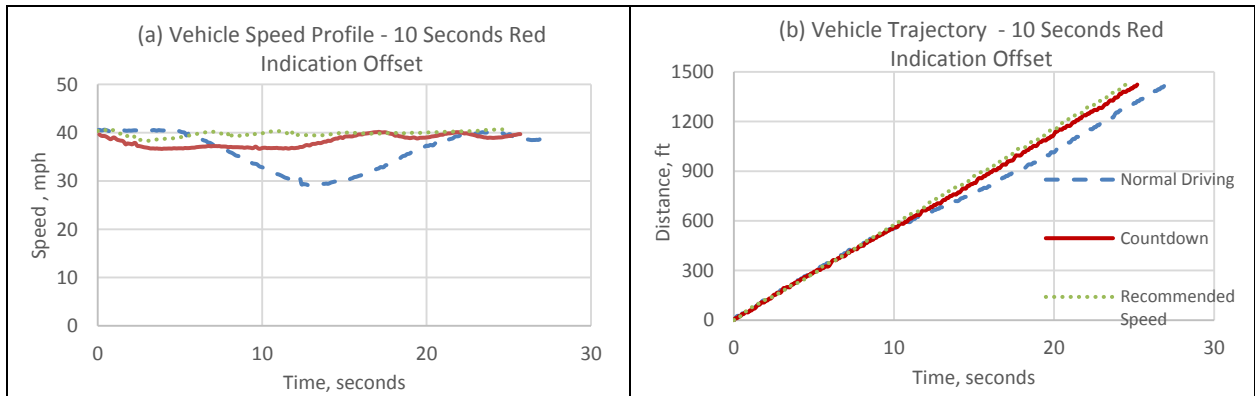


Figure 3-11 Example vehicle speed profile and trajectory, downhill direction



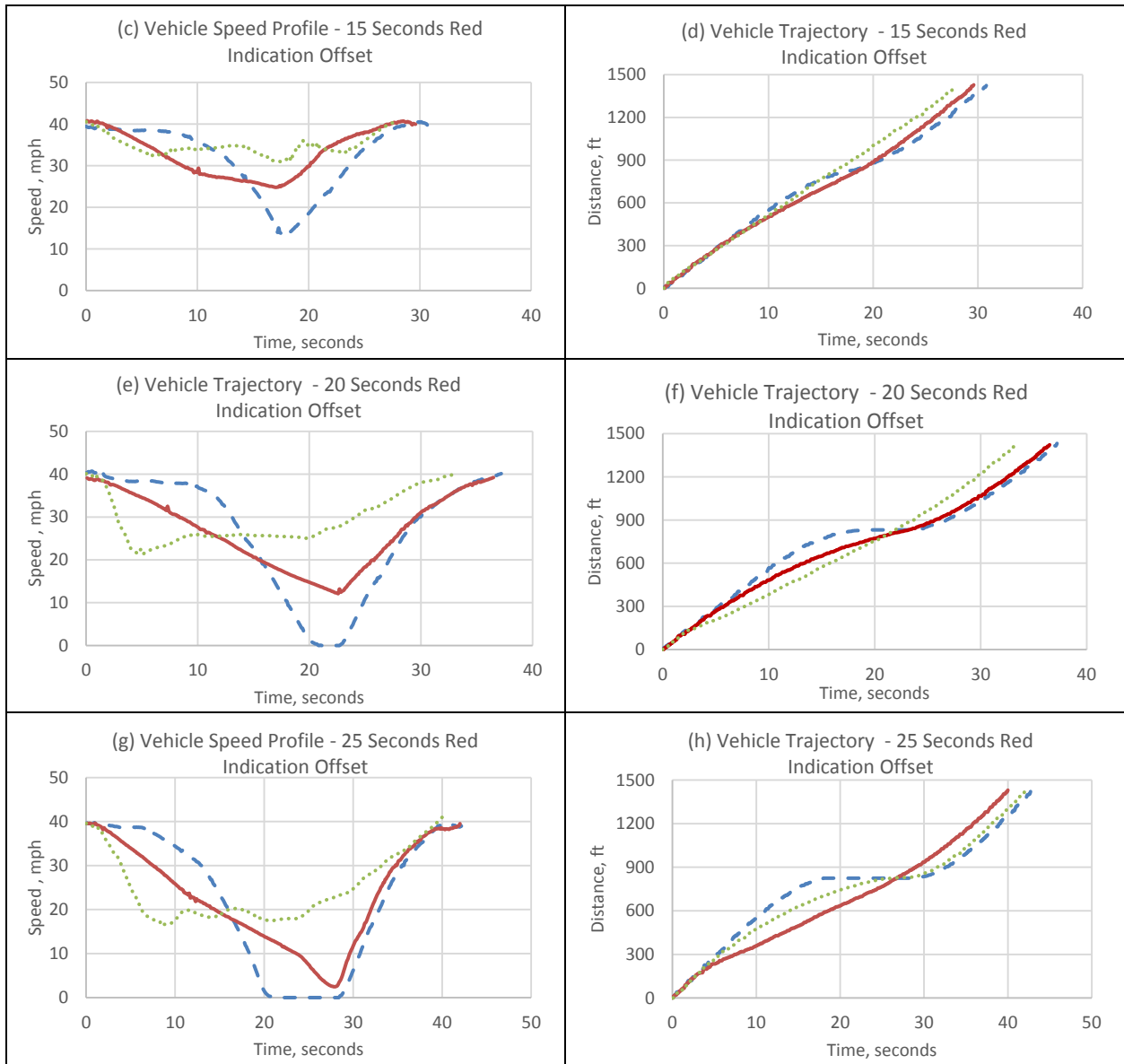
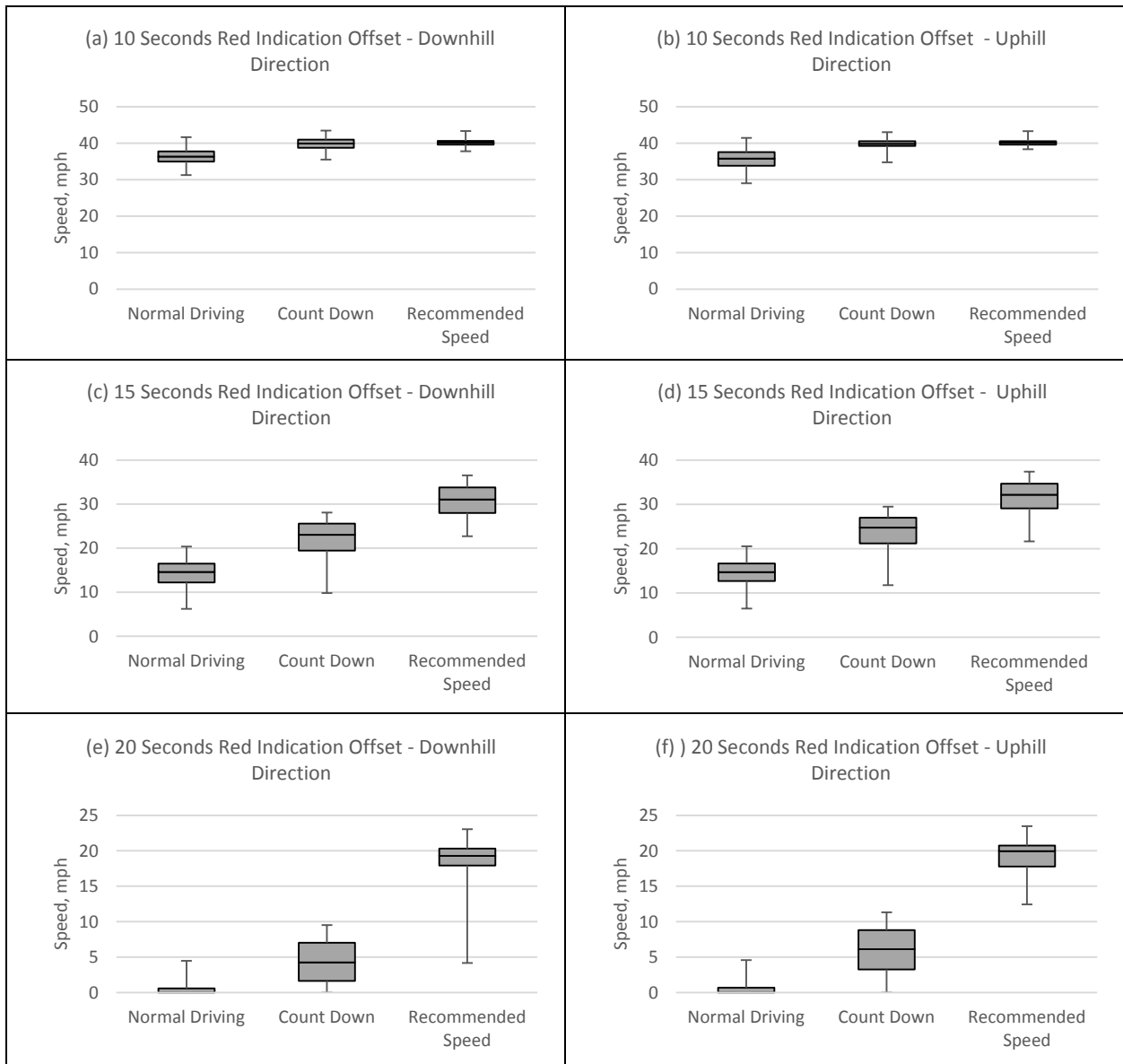


Figure 3-12 Example vehicle speed profile and trajectory, uphill direction

Figure 3-13 illustrates the box plot of the instantaneous speed when passing the intersection for all the participants. Instantaneous speed increases from scenario 1 to 3 are observable, and generally driving with recommended speed information had the highest speed under all the values of red indication offset. It should be noted that the variance of the instantaneous speed in the third scenario (recommended speed information) under 20 and 25 seconds red indication offset is longer than the other two scenarios (Figure 3-13 (e),(f),(g), and (h)). This suggests that there are different levels in driver acceptance and behavioral adaption of the provided recommended speeds. Some participants came to a slower speed than they were supposed to because they were unable to follow the recommended speed.

It should also be noted that driving with countdown information slightly increased the instantaneous speed at the intersection when compared to normal driving, but it failed under 20 and 25 second red indication offsets as most of the drivers came to a complete stop. This confirms the aforementioned fact that driving with countdown information improved the driver's behavior and helped them to avoid a complete stop under smaller values of red indication offset but not with larger values.



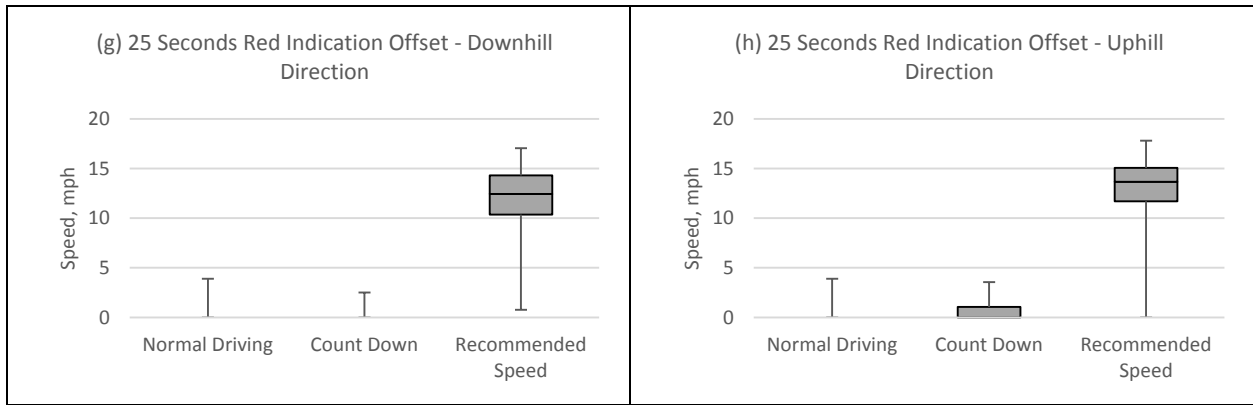


Figure 3-13 Box plot of the instantaneous speed at the intersection

Additionally, drivers with recommended speed information rarely stopped at the intersection. As can be seen in Figure 3-14, the percentage of time idling at the intersection continually reduces from scenario 1 to 3, and becomes almost zero at the third scenario under all the values of red indication offset.

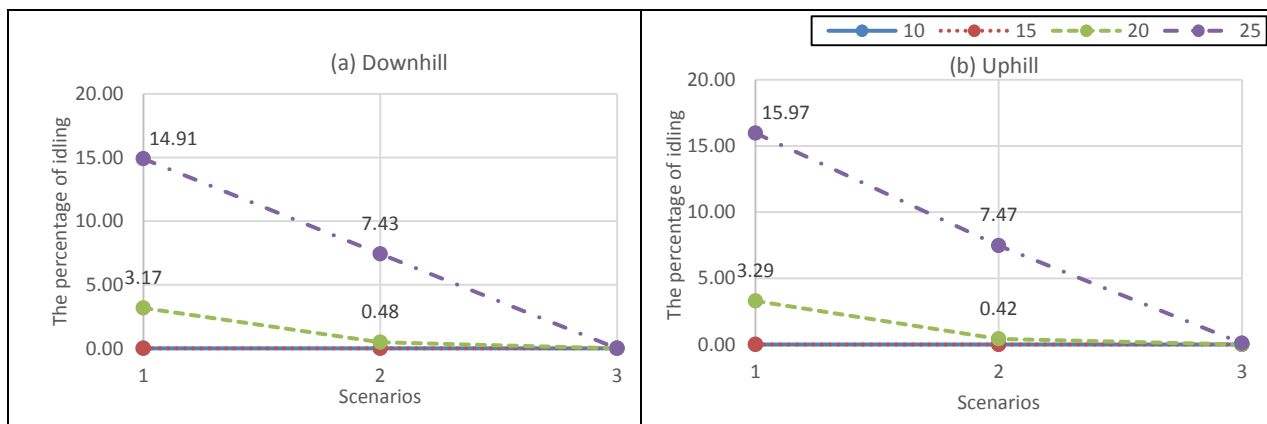


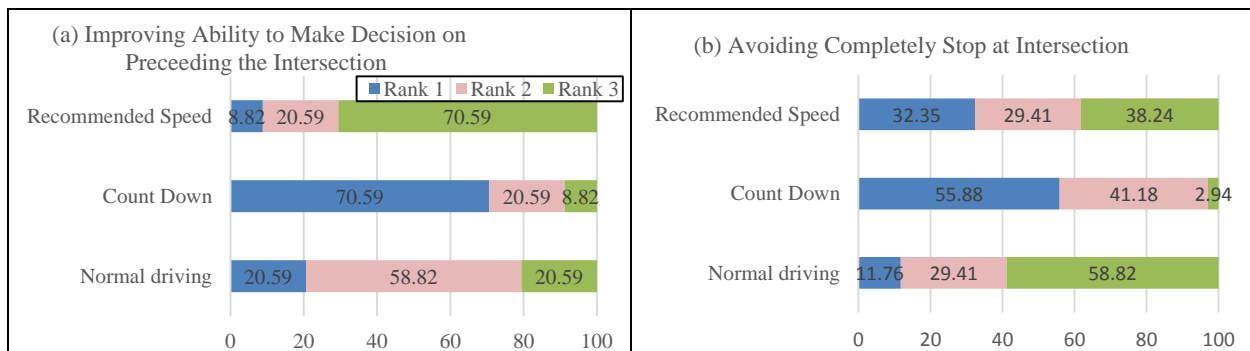
Figure 3-14 The percentage of time idling under different values of red indication offset for each scenario

A post-driving survey (appendix G) was conducted to evaluate drivers' perceptions of the three scenarios in terms of enhancing safety, comfort, fuel efficiency, and improving drivers' decisions in the vicinity of the intersection. The participants were asked to rank the three scenarios that would best improve their ability to make a better decision when proceeding to the intersection, avoiding a complete stop, saving fuel consumption levels, making driving more comfortable, and enhancing safety, and the results are given in Figure 3-15. Unexpectedly, driving with countdown information was found to be the most preferred scenario among the three, while driving with recommended speed information was nearly the least preferred scenario.

Although driving with recommended speed information produces higher fuel consumption saving levels than the other scenarios, participants believed it was the least fuel-efficient scenario. It had lowest ranking, with 50 percent of respondents making it as the least favorite scenario (worse than the normal driving scenario), while driving with countdown information was ranked at the top by over 70 percent of respondents (Figure 3-15 (c)). It can be concluded that participants are not aware of how to drive in a fuel-efficient way. Furthermore, giving them countdown information would not always help them to drive smoothly and efficiently.

Additionally, participants ranked driving with recommended speed information as the lowest in terms of enhancing comfort and safety, with over 80 and 70 percent of respondents respectively. This may be explained by the fact that the frequency of the recommended speed information is very high (2-second interval) and difficult for the participants to follow. Therefore, participants found it distracting and dangerous to both pay attention to the road and adjust their speed every 2 seconds. In addition, some of the participants expressed their concern that driving with recommended speed information induces them to pass at the onset of a green indication which they consider to be an unsafe situation.

Moreover, participants were asked to rank which of the three scenarios they would want in their cars. Driving with countdown information was ranked at the top by nearly 80 percent, followed by normal driving, as shown in Figure 3-15 (f). This implies that the majority of the participants prefer not to have recommended speed technology in their cars due to the aforementioned concerns.



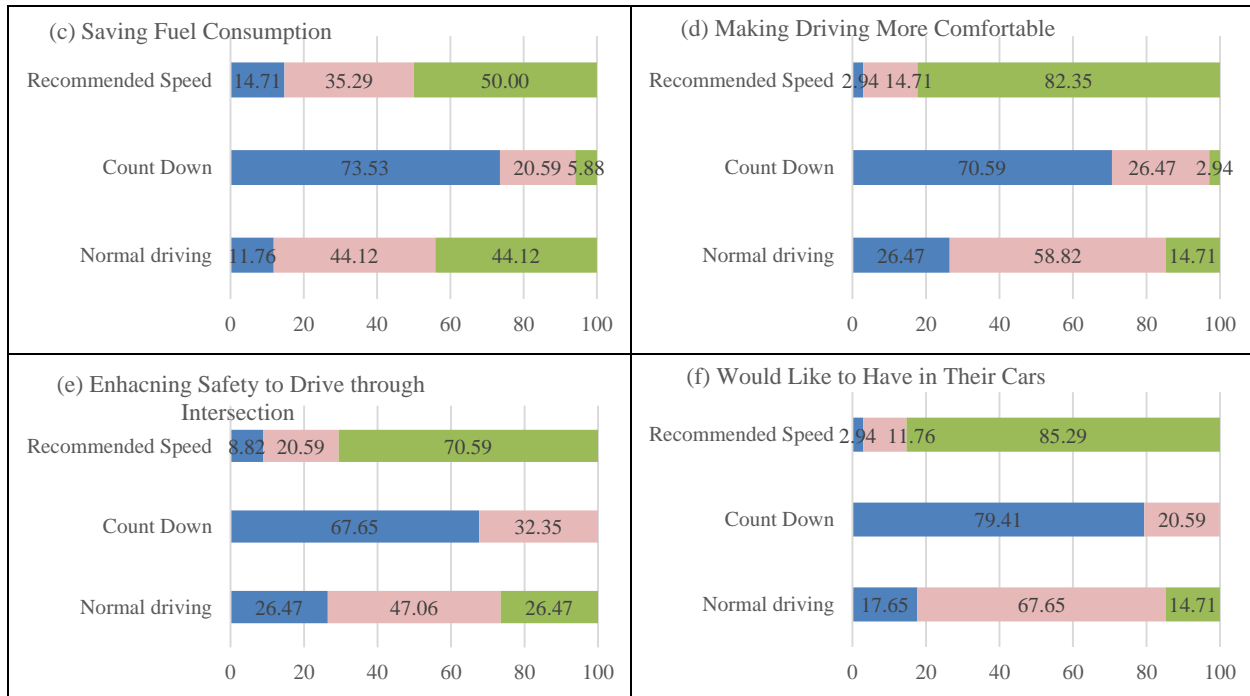


Figure 3-15 Respondent ranking of the three scenarios

3.7 Conclusions and Recommendations for Future Research

The research presented in this chapter investigated the benefit of an Eco-CACC system that computes the fuel-optimal velocity of a vehicle using SPaT information within the vicinity of a traffic signalized intersection. A controlled field experiment of 32 participants was conducted on the Smart Road test facility at VTTI. The experiment included three scenarios, namely: normal driving, driving with countdown information, and driving with recommended speed information. Each scenario had four different red indication offset values (10, 15, 20, and 25 seconds) with downhill and uphill directions. In total, 1536 trips were recorded and compared in terms of fuel consumption and travel time in the vicinity of the signalized intersection (430 meter). The study found that the developed Eco-CACC system always increases fuel consumption saving levels and reduces travel time significantly, at different percentages depending on the value of red indication offset and the direction of travel. In particular, the developed Eco-CACC is very effective in producing fuel economy enchantment when traveling downhill and reducing travel time when traveling uphill. Compared to normal driving, the Eco-CACC system reduced fuel consumption levels and travel time, on average, by nearly 13 and 8 percent respectively. In addition, it was found that, on average, driving with countdown information reduces fuel consumption levels and travel time but with a lower percentage than the Eco-CAC system.

Another finding of this study showed that the Eco-CACC system reduced the percentage of time idling to nearly zero and provided a smooth speed profile at the intersection. Likewise, driving with countdown information partially helped the participants to drive smoothly without having to come a complete stop for 10 and 15 second red indication offset values, but failed with larger values.

The post-driving survey showed that driving with recommended speed information is the least favorite scenario among those presented due to the high frequency of the recommended speed information update and other safety concerns that the participants raised.

In order to continue the work presented in this chapter with further improvements, the authors recommend conducting the same experiment with a level 3 automated Eco-CACC system added to the experiment as a fourth scenario in which the vehicle adjusts its speed automatically without human-vehicle interaction. This can produce valuable results that will be comparable with the manual Eco-CACC (recommended speed information) and will identify the impact of human error/delay on the benefits gained from the Eco-CACC system. Moreover, the following research precautions should be considered:

1. Increase the range of the Eco-CACC (the control length) from 820 and 590 ft (250 and 180 meters) upstream and downstream of the intersection to the ideal control length of 1640 ft (500 meters), which provides the greatest fuel consumption saving levels [69].
2. Examine the impact of multiple conditions of roadway grades (including a zero grade), road-weather, and travel-speeds on the benefits of the Eco-CACC system and driver's response to the provided information.
3. Investigate the impact of different frequencies of the recommended speed information on the benefits of the Eco-CACC system and the driver's response to the provided information.
4. Investigate the age effect on driver-acceptance of the advisory speeds using different age groups.
5. Investigate the impact of the presence of Eco-CACC non-equipped vehicles on Eco-CACC ones at single-lane and two-lane intersections.

3.8 Acknowledgments

This research effort was jointly funded by the Connected Vehicle Initiative University Transportation Center (CVI-UTC), the TranLIVE University Transportation Center, and NPRP Grant # 5-1272-1-214 from the Qatar National Research Fund (a member of The Qatar Foundation). The authors acknowledge the help of researchers from the hardware group at VTTI for their assistance in developing the hardware and software environment.

CHAPTER 4: FIELD EVALUATION OF AN AUTOMATED ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL SYSTEM IN THE VICINITY OF SIGNALIZED INTERSECTIONS

4.1 Abstract

Signalized intersections can produce significant increases in vehicle fuel consumption levels. With the help of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, algorithms are being developed that utilize SPaT data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections. This chapter presents the results of a unique controlled field experiment designed to evaluate an Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system that was developed by the Center for Sustainable Mobility at the Virginia Tech Transportation Institute. The Eco-CACC system computes and recommends real-time fuel-efficiency speeds using V2I communicated data that can be delivered to drivers as an audio message or be implemented directly in the testing vehicle. The controlled field experiment included three different scenarios, namely: normal driving, driving with recommended speed information provided to drivers (manual Eco-CACC system), and finally automated driving (automated Eco-CACC system). The controlled field experiment was conducted for four red indication offset values to drivers traveling along an uphill and downhill approach on the Smart Road test facility. In total 1536 trips were conducted by 32 different participants between the ages of 18 and 30 with an equal number of males and females. The collected data were compared with regard to fuel economy and travel time over a fixed distance starting upstream and ending downstream of the intersection (from 820 ft (250 m) upstream of the intersection to 590 ft (180 m) downstream for a total length of 1410 ft (430 m)). The results demonstrate that the Eco-CACC system is very efficient in reducing fuel consumption levels especially when driving downhill. Specifically, the analyzed data indicates that the automated scenario could achieve fuel and travel time savings of 31% and 9% on average, respectively.

4.2 Introduction

The transportation sector is the second main reason for the increase in fuel consumption and emission levels in the United States [16]. The increase in vehicle travel miles and, thereby, traffic congestion contributes significantly to produce excessive fuel consumption and global pollution. The eco-driving concept has been proposed and studied widely as a key solution to mitigate the environmental impacts of transportation [5, 19-22].

Eco-driving is a driving style that is considered to be economic and ecologically beneficial. It has been defined by several researchers as the smooth driving resulting from adjustment in driver behavior [3, 4]. Consequently, researchers have suggested tips for drivers [14, 15] that could effectively improve their behavior with the objective of minimizing fuel consumption and emission levels. These tips are:

- Avoid hard braking, sudden acceleration/deceleration, and idling.
- Limit air conditioner use.
- Stop warming engine.
- Shift gear up early.
- Maintain steady speed.
- Look ahead while driving.
- Limit starting speed in the first 5 seconds to 12.4 mph (20km/h).

However, recent research has shown how a vehicle could help drivers achieve the aforementioned steps. Onboard driver assistance systems can be installed into the vehicle to fulfill the objectives of eco-driving [14, 17, 18]. These devices can deliver “static” advice to drivers such as “accelerate slowly,” “avoid hard braking,” and “reduce high speed.” However, the impact of the static advice on fuel consumption and emission levels is limited.

By taking advantage of real-time traffic sensing and infrastructure information, onboard driver assistance systems can deliver “dynamic” advice to drivers that can help them to drive smoothly and efficiently. In particular, establishing communication between the vehicle and the traffic signal controller is a powerful tool to make the driver behavior smoother; thus reducing vehicle fuel consumption levels. Various messages can be exchanged between the two parties to provide better advice to drivers. Among these messages is a SPaT message that can provide approaching vehicles with valuable advance information about upcoming traffic signal timing

changes. This information could help drivers to make early decisions whether they should proceed or stop safely and smoothly.

With the help of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, algorithms are being developed that utilize SPaT data together with queue information to optimize vehicle trajectories in the vicinity of signalized intersections [8, 10-12]. Therefore, it is possible that vehicles can communicate with the traffic signals, receive SPaT information, and adjust their speeds accordingly and automatically.

Several Eco-Speed control (ESC) algorithms have been introduced to provide an optimal trajectory through signalized intersections. However, none explicitly attempted to minimize vehicle fuel consumption levels. In addition, most of the proposed algorithms have been developed and tested in traffic simulation environments where recommended speeds are enforced and many issues, such as the delay in the system and human-vehicle interaction, are not considered.

In [7], Kamalanathsharma developed a new ESC algorithm named Eco-Cooperative Adaptive Cruise Control (Eco-CACC). The Eco-CACC system computes and recommends real-time fuel-efficient speeds using V2V and V2I communicated data within the vicinity of the traffic signalized intersection. The objective function of the Eco-CACC system is the explicit minimization of the total fuel consumed to travel from some distance upstream of the intersection to a distance downstream of the intersection. The Eco-CACC system was tested and evaluated in a simulation environment. A reduction in fuel consumption of over 30 percent reduction was achieved.

In [60], we addressed the implementation issues and challenges of the field application of the Eco-CACC system by conducting a preliminary field test. We have shown that the Eco-CACC system is applicable and very promising in terms of fuel consumption and travel time savings.

In this thesis, we extend our work and conducted an extensive field experiment using 32 participants on the Smart Road test facility of the Virginia Tech Transportation Institute with the goal of evaluating the Eco-CACC system with regard to fuel consumption and travel time savings. Three different scenarios were considered, namely: normal driving, driving with recommended speed information provided to drivers (a manual Eco-CACC system), and finally automated driving (an automated Eco-CACC system). Previous studies showed that visual

messages are less efficient and more distracting for drivers compared to audio messages [61-63]. Consequently, the computed speeds in the manual Eco-CACC system were delivered to drivers as audio messages.

As far as the chapter layout is concerned, the following sections deal with literature review, which highlights the uniqueness and importance of contributed work, a brief description of the algorithm used, the experimental design used in gathering the data, field data analysis and findings, and finally the conclusion and recommendations for future work.

4.3 Background

Signalized intersections have recently drawn attention as researchers have realized the significant increase of vehicles' fuel consumption levels in their vicinity [1]. When coming close to a signalized intersection, drivers are completely unaware of exactly when the traffic signal indication will change. Consequently, drivers may have to accelerate/decelerate aggressively to respond to these changes. This results in non-smooth driving behavior. Non-smooth driving (e.g. hard braking, sudden speed changes) consumes excessive fuel as it follows a non-ideal speed profile [2]. Research efforts have attempted to generate the fuel-optimal speed profile in the vicinity of signalized intersections [5, 8, 9]. This section reviews those research efforts attempting to develop models associated with the aforementioned concept.

Mandava et al. [8] proposed an algorithm that minimizes acceleration/deceleration rates to increase the probability of having a green light for oncoming vehicles at signalized intersections. Using signal phase and timing information, they delivered dynamic speed advice to drivers when approaching signalized intersections. The results demonstrated that the algorithm could decrease fuel consumption and emissions by 12-14%.

Asadi and Vahidi [10] developed a predictive cruise control system that used constrained optimization to minimize the probability of stopping. Traffic signal information and short range radar were used to change the vehicle's arrival time at the green light. The proposed algorithm did not provide dynamic speed advice to drivers. In addition, the speed profiles provided were not compared with regard to fuel efficiency. The simulation results show a reduction of 47% and 56% in fuel consumption and emissions respectively in an arterial road consisted of nine traffic signals.

Barth et al. [11] developed a dynamic eco-driving velocity planning algorithm along an arterial corridor with traffic signals. The objective function of the proposed algorithm was to minimize the level time spent accelerating and decelerating. The algorithm received signal phase and timing information from a traffic signal and recommended speeds for on-coming vehicles. Up to a 12% reduction in fuel consumption and emissions were reported.

Sun et al. [12] endeavored to obtain the optimal fuel/emission efficient speed profile for on-coming vehicles at signalized intersections. Given the upcoming signal information, a dynamic programming approach was used to estimate the optimal speed with regard to fuel efficiency. Subsequently, the authors developed an eco-driving strategy that allows a velocity advisory to be delivered to drivers. Savings of up to 25% in fuel consumption and emissions were found in a driving simulator experiment for 15 drivers.

Malakorn and Park [41] have studied the potential benefits of Cooperative Adaptive Cruise Control (CACC) with regard to the environmental impacts and vehicular mobility. The authors integrated CACC with Intelligent Traffic Signals in which CACC produces optimum trajectories to vehicles approaching signalized intersections. Using upcoming signal information, the system minimized acceleration and deceleration distances and idling time. Simulation results indicated a 91 percent and a 75 percent reduction in delay and fuel consumption, respectively. On the other hand, this study did not consider the speed profile downstream of the signalized intersection. In addition, the results were completed using a fixed deceleration distance (100 ft (30.5 m)).

Wu et al. [42] studied the benefits of two types of advanced driving alert systems, namely: stationary ADAS and in-vehicle ADAS. The authors proposed these systems with the objective of helping drivers approaching signalized intersections to achieve smooth driving (i.e. avoid hard braking and hard-deceleration maneuver). Both of these systems alert the drivers of time to red so that they can make a decision in advance to stop safely and thereby smoothly. The simulation results revealed a positive impact on fuel consumption and emissions. However, this study provided drivers information on traffic signal status only when it was red. The authors did not consider informing the drivers of time to green. In addition, they did not consider the downstream intersection in providing a fuel-optimum trajectory.

Tielert et al. [43] studied the effect of Traffic-Light-to-Vehicle Communication on the environmental impacts (i.e. emissions and fuel consumption). In this study, the effect of speed

adaptation was tested by using different speeds in the simulation. The authors found that gear choice and the distance from the traffic light have a significant impact on fuel consumption and emissions. The simulation results showed a reduction of 22% for a single vehicle and 8% for multi vehicles.

Sanchez et al. [44] proposed a new driving model called Intelligent-Driver Model Prediction (IDMP). The proposed model uses the information sent from the traffic signal to advise approaching vehicles with the goal of minimizing idling time; thus reducing vehicle fuel consumption levels. The authors made use of this information to compute the recommended speeds that a driver should adopt to achieve the aforementioned goal. In the simulation experiment, they used the Akcelik and Biggs fuel consumption model [45] to compare the results between two scenarios using the Intelligent-Driver Model (IDM) [46]. The simulation results showed a reduction of 25% in fuel consumption levels in urban areas.

Li et al. [47] introduced an optimized method using an augmented Lagrangian genetic algorithm that provides an optimum speed advisory for on-coming vehicles to intersections with the objective of reducing trip time; thus reducing vehicle fuel consumption levels. The proposed algorithm guarantees that on-coming vehicles do not exceed the maximum permitted speed when passing signalized intersections. The authors used a car following model to handle multi-vehicles. The VT-Micro model [2] was used in the proposed model to calculate the fuel consumption but not in the optimization objective function. In a simulated environment, savings of up to 69.3 percent and 12.1 percent were reported in fuel consumption and trip time, respectively.

Alsabaan et al. [48] developed an optimization model to compute the optimum or close-to-optimum speed in the vicinity of signalized intersections in which driver behavior will be smooth and, thereby, fuel consumption and emissions will be minimized. The authors used traffic-light-signal-to-vehicle (TLS2V) and V2V communication to send SPaT information to approaching vehicles so that drivers can follow the optimum speed. The objective function of this model is minimizing vehicle fuel consumption and emissions using the VT-Micro model [2] for four different scenarios. Heuristic expressions were used to estimate the optimum speed or near-optimum speed.

Jin et al. [49] proposed a mathematical model to optimize vehicle trajectories crossing intersections using six different signal timing configurations. This research effort was intended to

reduce the idling time and unnecessary changes in speed in the vicinity of a signalized intersections. The objective function is minimizing acceleration and deceleration distances. Approaching drivers were notified of a suggested speed through a DSRC connection in which SPaT information was sent to drivers. The authors tested different scenarios (e.g. the current signal state is either red or green with different lengths) and optimized the vehicle trajectory for upstream and downstream of the traffic signal. The optimum speed was computed by calculating the emissions and fuel consumption using a vehicle specific power model (VSP). In a simulated environment, average savings in fuel consumption of up to 12.01% and 7.73%, respectively were reported, as well as an increase in travel time.

As has been shown, most of the aforementioned literature have used almost the same concept in which the approaching vehicles are provided with a smooth speed profile in the vicinity of signalized intersections with the goal of minimizing fuel consumption and/or emissions. However, most of these research efforts attempted to minimize vehicle fuel consumption levels by minimizing acceleration/deceleration distances, idling time, and/or travel time, so their objective function was not the explicit minimization of fuel consumption.

Several previously conducted eco-driving experiments have shown a positive impact with regard to fuel consumption and emissions [3, 17, 20, 23, 24, 28, 29, 31-37]. However, all these studies were conducted either by providing a training course for drivers before driving and measuring before-after differences or by delivering “static” advice while traveling. None have used real-time traffic sensing and SPaT information to deliver “dynamic” advice while driving. A few field experiments were conducted by delivering “dynamic” advice to drivers [25, 64]; however, none of them explicitly considered vehicle fuel consumption as the objective function.

This controlled field experiment was conducted using the Eco-CACC system that explicitly attempts to minimize vehicle fuel consumption levels. In the manual Eco-CACC system, participants received a dynamic speed recommendation using V2I communication and were asked to adjust their speeds accordingly, while in the automated Eco-CACC system, the dynamic speed recommendations were implemented directly in the testing vehicle. Results were compared to normal driving with regard to fuel consumption and travel time savings. The analyzed data indicates that the automated Eco-CACC system scenario results in the best fuel consumption saving levels among all tested scenarios and can produce fuel and travel time savings of up to 45 and 13 percent respectively. In addition, the study demonstrates that the

manual Eco-CACC system scenario can produce fuel savings ranging between 18.9 and 7.9 percent with decreases in travel times ranging between 10.1 and 5.3 percent.

4.4 Methodology

4.4.1 Test Facility

The Virginia Department of Transportation's (VDOT) Virginia Smart Road at the Virginia Tech Transportation Institute (VTTI) was the site of the field test. Located in the southwestern region of Virginia, the Smart Road serves as a distinctive, state-of-the-art, closed test-bed research facility. The Smart Road is a 2.2 mile (3.5 km) two-lane road (one-lane for each direction) with one four-way signalized intersection (Figure 4-1). The 1.6 mile (2.5 km) section used for the data collection includes only the section between two turnarounds with the four-way signalized intersection, as shown in Figure 4-2. The first end (T1) is a high-speed banked turnaround and the second end (T2) is a low-speed flat turnaround. Although there is some insignificant horizontal curvature, the test section's horizontal layout is generally straight. However, this curvature does not affect road speeds. The vertical layout of the test section has a grade of 3 percent (uphill and downhill). Due to the fact that study participants turned around at the conclusion of each trip, half the trips occurred on a 3 percent upgrade while the others were on a 3 percent downgrade. In this experiment, the speed limit of the testing facility was 40 mph (64 km/h).

The Eco-CACC system is activated when the testing vehicle is at 820 ft (250 meters) upstream of the stop line (denoted by d_{up}) and is deactivated when the testing vehicle is at 590 ft (180 meters) downstream of the stop line (denoted by d_{down}). This can be seen in Figure 4-2, in which the two maroon lines indicate the distance where the Eco-CACC is activated, while the two red lines represent the stop lines for each direction. It must be mentioned that these values (i.e. d_{up} and d_{down}) were chosen based on the geographical constraints of the testing site.



Figure 4-1 Signalized intersection in the VA Smart Road Test facility

4.4.2 Experimental Equipment

A VTTI automated vehicle (2014 Cadillac SRX) was used in the experiment. It is equipped with an onboard vehicle unit for V2V and V2I communication, a Differential Global Positioning System (DGPS), a real-time data acquisition system (DAS), and a laptop with installed VTTI proprietary programs to control the trips and road scenarios. The DAS is capable of data collection of up to 0.1-second precision. All data recorded were stored in a hard drive located in the truck, as shown in Figure 4-2.

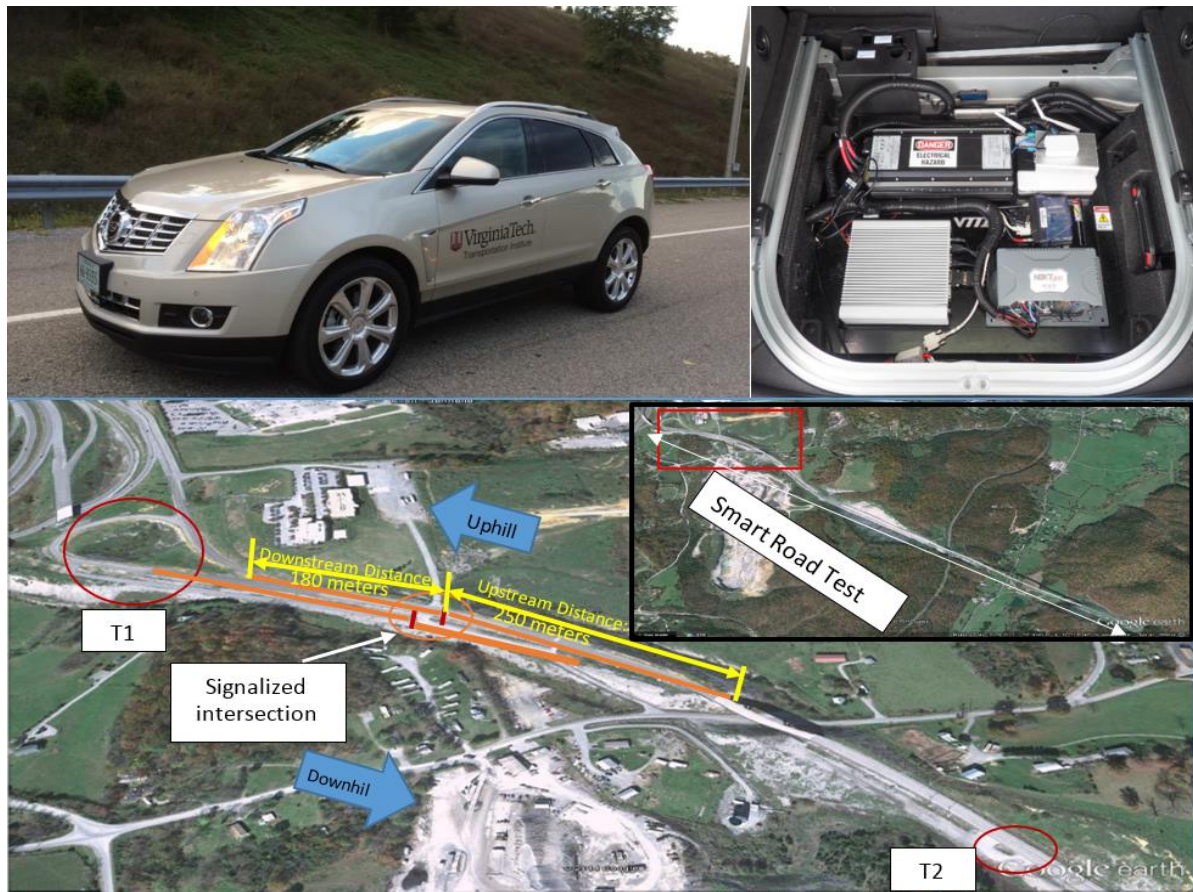


Figure 4-2 Instrumented vehicle and field test site

With the help from V2I communication, the test vehicle receives upcoming signal changes, namely: time from red to green, and simultaneously the vehicle onboard unit calculates the vehicle’s distance to the intersection and its current speed. These information will feed into the Eco-CACC algorithm to produce the fuel-efficient speed profile.

The optimum speed profile and target speed were calculated and provided to the test vehicle every 0.1 second. Given that the average driver perception reaction time is 1.5 seconds and the latency in the communication system is 0.5 seconds, the recommended speeds in the manual Eco-CACC system were delivered to participants at a 2-second interval. However, in the automated Eco-CACC system, the optimum speed profile was implemented directly into the instrumented vehicle and was updated every 0.1 second, and the test vehicle drove itself automatically following the fuel-efficient speed profile. A warning sound, “engage,” was turned on when the vehicle entered the Eco-CACC range, and “dismiss” was played when it left. This informed the participant when the test vehicle took over.

4.4.3 Participants

IRB approval was obtained in November 2015 from the Institutional Review Board (IRB #15-1092) at Virginia Tech before starting recruiting the subjects. Participants were licensed drivers recruited from the VTTI internal participant database, flyers, ads in the local Blacksburg, VA newspaper, and/or word-of-mouth. Participants were screened through a verbal questionnaire over the phone (Appendix D) to determine if they were licensed drivers and if they had any health concerns that would exclude them from participating in the study. Any participant with more than two driving violations or responsible for an injurious accident was excluded. A total of 32 participants between the ages of 18 to 30 were recruited. An equal number of males and females was assigned to this group. Participants were paid \$30 per hour for a 2 –3 hour session.

In order to have a representative sample for the local community and avoid newly licensed drivers, participating drivers were required to have U.S. driving experience of at least two years. Therefore, their driver's licenses were checked to verify this condition upon arrival at VTTI.

4.4.4 Procedure

The experiment was conducted solely on the Smart Road test facility and only during daylight hours in a dry pavement condition. The experiment was composed of two main phases. The first phase was comprised of the determination of eligibility and the procurement of informed consent from each participant. The second phase, the Smart Road test-track driving portion, required only one session in one day for each participant and took approximately 2-3 hours to complete. Each participant was assigned to three different scenarios with 16 trips each. The following are the three scenarios:

- ✓ **Scenario.1:** The participant was asked to drive freely following the signal as he/she would in a real signalized road.
- ✓ **Scenario.2 (Manual Eco-CACC system):** The participant was given a recommended speed in an audio message at two-second intervals using an in-vehicle device and he/she was asked to follow that recommended speed following the signal rules.
- ✓ **Scenario.3 (Automated Eco-CACC system):** Minimum interaction from the participant was needed since a semi-automated adaptive cruise control that receives information from the infrastructure was turned on and the vehicle adjusts

its speed by itself. Note the driver only controls the steering wheel in the range of ECO-CACC system.

Participants drove loops on the Smart Road, crossing a four-way signalized intersection between two turnarounds (Figure 4-2) where the data were collected. Exclusive of practice trips, each participant drove a total of 48 trips (16 trips for each scenario), where a trip consists of one approach to the intersection. Each participant was tested individually, using the same vehicle. These trips were split equally into four values of red indication offset, namely: 10, 15, 20, and 25 seconds. Each red indication offset was repeated two times for each direction. In each scenario, these trips were in a predetermined randomized order.

The red indication offset refers to the number of seconds when the traffic light turns from red to green. The values of red indication offset were chosen based on the fact that a vehicle traveling at 40 mph (64 km/h) over 820 ft (250 meters) (d_{up}) needs approximately 14 seconds to reach the stop line. Therefore, a baseline of 15 seconds was used, with one value before and two values after with a 5-unit interval.

The red indication offset is triggered when the testing vehicle approaches the signalized intersection and reaches the range of Eco-CACC (820 ft/250 meters). From the available values of red indication offset (10, 15, 20, and 25 seconds), one value will be randomly assigned to the traffic signal for each trip. In other words, when the testing vehicle reaches 820 ft (250 meters), the red indication offset will be either 10, 15, 20, or 25 seconds. It should be noted that the green phase was always set at 25 seconds in order to give the vehicle enough time to pass the range of Eco-CACC at a downstream distance of 590 ft (180 meters).

On test day:

Each participant reviewed and signed an informed consent form (appendix C) after arriving at VTTI. The experiment was explained in detail. Then, a Snellen vision test was administered to ensure that vision acuity was within the legal driving limit (at least corrected to 20/40). Following completion of the test, the participant was taken to the testing vehicle (SRX 2014). The participants familiarized themselves with the test vehicle (e.g., adjusting mirrors and seat, fastening seat belt), and then proceeded to the Smart Road with an in-vehicle experimenter. The experimenter was present in the testing vehicle at all times during the study to offer guidance to the participant, operation of the computer system and control scenarios, supervision of the experiment, and responses to any questions. Before the first official trip, the participant drove

three practice trials (intersection passes) to become familiar with the vehicle and the Smart Road. Participants were informed of the 40 mph (64 km/h) speed limit and asked to follow all normal traffic rules and obey all traffic laws.

All participants performed the three scenarios in order. Each started the test uphill, made a U-turn at the end of the road (T1), and went back, approaching the signalized intersection in the downhill direction toward the other U-turn (T2). The participant continuously drove the testing vehicle until all the trips (uphill and downhill) for all three scenarios were completed.

In order to calculate the vehicle fuel consumption of the entire maneuver near the signalized intersection and have fair comparison, participants were asked to drive at 40 mph (64 km/h) once they entered the ESC range of the intersection (820 ft/250 meters) and once they leave this range (590 ft/180 meters) (Figure 4-2). Four cones were put on the boundaries of the ECO-CACC range to inform the participants when the speed needed to be at 40 mph (64 km/h). Therefore, the entry and exit speed were the same for all trips. If a participant drove more than 3 mph above or below the instructed speed (40 mph/64 km/h), the trip was repeated. In addition, the participant was reminded of the instructed speed and the speed limit at turnaround T2. On completion of the experiment, the participant was asked to leave the Smart Road and fill out a questionnaire (Appendix G).

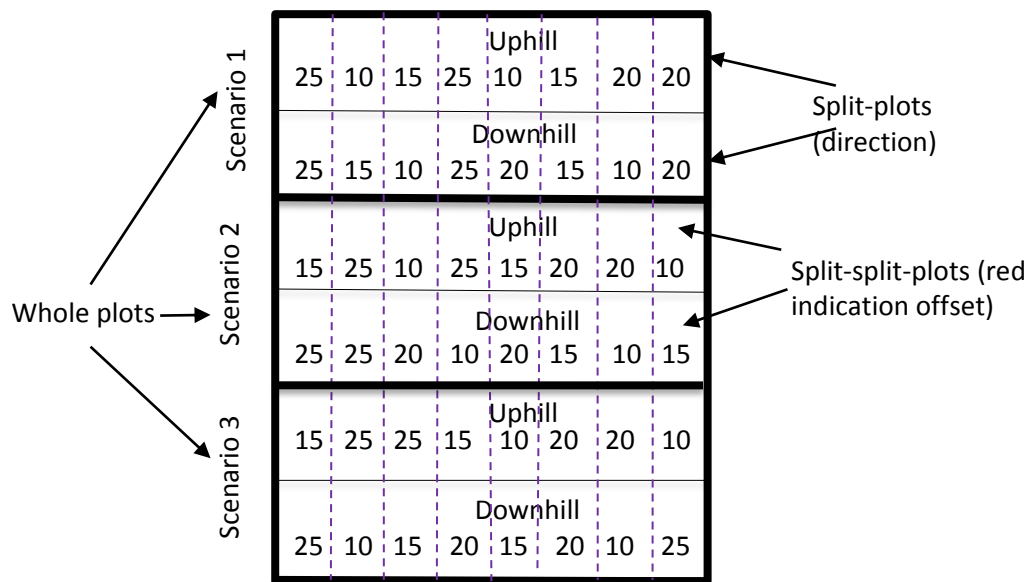
4.5 Field Data Analysis

The vehicle trip information (e.g. the current and recommended speed, distance to stop line, time, and SPaT information) were recorded each deci-second. Only the data in the range of ECO-CACC (820 ft (250 m) upstream and 590 ft (180 m) downstream) were extracted and analyzed. In total, 1536 trips were recorded for 32 participants. All the entry and exit speeds for each participant were checked to ensure they were in the allowable range of 37 to 43 mph (59.5 km/h to 69.2 km/h). Due to the fact that some participants found it difficult to follow the recommended speed at 2-second intervals in the Eco-CACC scenario, 10 % of the trips were found to be outliers. However, these trips were included in the analysis as they represent a variant in behavior of some drivers.

Several statistical designs have been considered for this experiment. One of which is a three-way factorial design in which the response is either the fuel consumption or travel time with three independent variables or factors: scenario, direction, and red indication offset. However, this model assumes that the three factors are randomized, which is not the case in this

experiment. The scenario factor cannot be randomized, as that may affect the participant's performance. To be specific, if a participant had tried driving with recommended speed information before driving normally, his/her behavior would be affected in the normal driving scenario. Additionally, the direction factor was found to be excessively time-consuming if randomized. Therefore, a split-split-plot design (SSPD) was chosen to analyze the data, given its power in accommodating the factors that were difficult to change [65]. SSPD is an extension of the split-plot design that was invented by Fisher in 1925.

The split-split-plot design is a blocked experiment with three levels of experimental units. The first level of the experimental units is the whole plot (scenario); the second level is the experimental units within the whole plot, called the split-plot (direction of travel in our case); and the third level is the experimental units within the split-plot, called the split-split plot (red indication offset in our case). The red indication offset factor was the only randomized factor in



the experiment, as shown in Figure 4-3.

Figure 4-3 Experimental design

As can be seen in Figure 4-3, each participant had a complete set of all treatment combinations (24 treatments), and each treatment combination replicated twice. In addition to the three aforementioned factors, gender and participant effects were added to the model. Given that there is a variation among drivers owing to their behaviors, the participant effect was considered

as a random effect and, thereby, was blocked, while the gender effect was treated as a fixed effect and tested.

The linear statistical model used for the split-split-plot design is as follows:

$$\begin{aligned}
 y_{kijl} &= \mu + \rho_k + \eta_k + \alpha_i + \varepsilon_{kih} && \text{(Whole plot)} \\
 &+ \gamma_j + (\alpha\gamma)_{ij} + \varepsilon_{kijh} && \text{(Split-plot)} \\
 &+ \beta_k + (\alpha\beta)_{il} + (\gamma\beta)_{jl} + (\alpha\gamma\beta)_{ijl} + \varepsilon_{kijlh} && \text{(Split-split-plot)}
 \end{aligned} \tag{4-1}$$

Where y_{kijlh} is the fuel consumed or travel time by the k th participant in the i th scenario, the j th direction and the l th red indication offset for the h th replicate in which $k = 1, \dots, 32$, $i = 1, 2, 3$, $j = 1, 2$, $l = 1, 2, 3, 4$, and $h = 1, 2$; μ is the grand mean; ρ_k is the random effect of the k th participant (blocking); η_k is the fixed effect of gender for the k th participant; α_i is the fixed effect of the i th scenario; ε_i is the whole-plot error representing unexplained variations among the three scenarios; γ_j is the fixed effect of the j th direction; $(\alpha\gamma)_{ij}$ is the interaction effect between the i th scenario and the j th direction; ε_{ij} is the split-plot error representing unexplained variations between each run in each direction; β_k is the fixed effect of the l th red indication offset; $(\alpha\beta)_{il}$ is the interaction effect between the i th scenario and the l th red indication offset; $(\gamma\beta)_{jl}$ is the interaction effect between the j th direction and the l th red indication offset; $(\alpha\gamma\beta)_{ijl}$ is the interaction effect between the i th scenario; the j th direction, and the l th red indication offset; and ε_{ijl} is the split-split-plot error representing unexplained variations between each run in each red indication offset.

Split-split-plot design assumes that the residuals are independent and normally distributed with common variances. These assumptions have been checked, and it has been found that the normality condition is the only assumption that has not been met for fuel consumption. Therefore, the Box-Cox transformation, a well-known parametric power transformation developed by Box & Cox in 1964, was used to transform the fuel consumption to meet the normality condition [66].

After applying SSPD, Tukey's Honest Significance Test (HSD) at a 5-percent significance level ($\alpha = 0.05$) was used to analyze all pairwise comparisons between the three scenarios to determine which, if any, are significantly different from each other [67].

The in-field data results show that fuel consumption measurements are not reliable as they don't capture the sudden changes in speeds and, also, give a value of zero when the vehicle is decelerating as shown in Figure 4-4. Consequently, The Virginia Tech Comprehensive Power-based Fuel Model, Type 1 (VT-CPFM-1) was used to estimate the fuel consumption rate because of its simplicity, accuracy, and ease of calibration [58]. VT-CPFM-1 uses instantaneous power to estimate the fuel consumption rates as given in Equations (2-9) and (2-10).

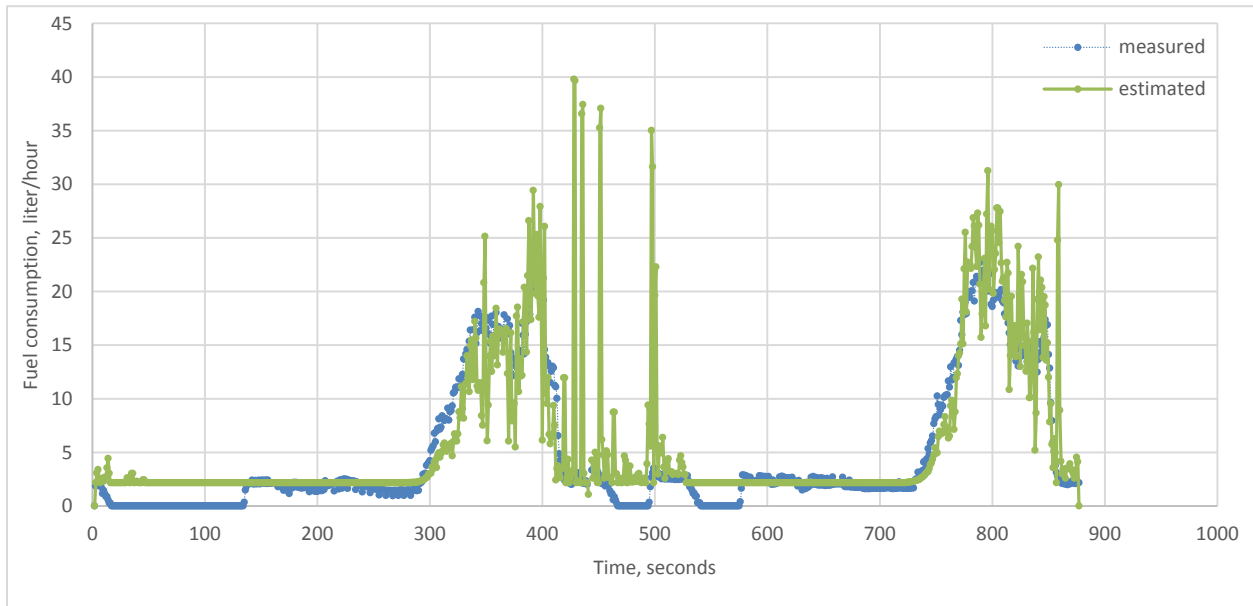


Figure 4-4 Fuel consumption comparison

4.5.1 Fuel Consumption

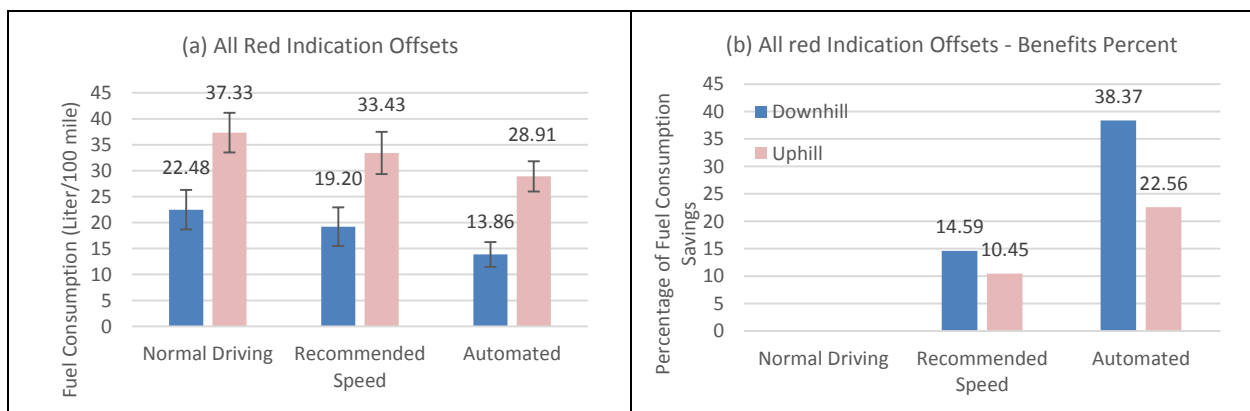
The field test results clearly demonstrate that both the manual or automated Eco-CACC systems always result in a fuel economy enhancement for every treatment combination of trip direction and red indication offset value. Additionally, the automated Eco-CACC system results in a higher fuel economy compared to the manual Eco-CACC system for all of the values of red indication offsets. Notably, these benefits were generally found to be larger in the downhill direction than the uphill direction, which is in compliance with previous research that showed using conventional cruise control always produced a better result in the downhill direction than the uphill direction [68].

Figure 4-5 presents a comparison of fuel consumption levels between all three scenarios for 10, 15, 20, and 25 second red indication offset values. As can be seen, the average fuel consumption levels continually decrease from scenario 1 to 3, and generally scenario 3 (i.e. the automated Eco-CACC system) produced the lowest fuel consumption levels under all values of

red indication offset. The analysis shows that, on average, driving with the automated Eco-CACC system reduces fuel consumption levels in the downhill and uphill direction by 38.37% and 22.56%, respectively, when compared to normal driving. When driving with the manual Eco-CACC system, the reductions in fuel consumption in both the downhill and uphill directions in fuel consumption are 14.59% and 10.45%, respectively.

The maximum fuel consumption saving levels for the automated Eco-CACC system is 44.6 % and 27.5 % for a red indication offset value of 15 seconds in the downhill and uphill directions respectively (Figure 4-5 (f)). As for driving with the manual Eco-CACC system is concerned, the maximum fuel consumption saving levels is 18.9% in the downhill direction. This occurs under a 15 second red indication offset value (Figure 4-5 (f)). A savings of 15.5% is produced in the uphill direction for a red indication offset value of 10 seconds (Figure 4-5 (d)).

It must be noted that a red indication offset value of 10 seconds means drivers can continue driving at their current speed (i.e. entry speed of 40 mph/64 km/h) without any deceleration, while the 15 second red indication offset value requires a slight deceleration (i.e. decelerating from 40 to 35 mph/64 km/h to 56 km/h). When compared to normal driving, most of the drivers had unnecessary deceleration or hard deceleration for a red indication offset value of 10 seconds or 15 seconds respectively This explains why the maximum fuel consumption saving levels occur under 10 and 15 second red indication offsets.



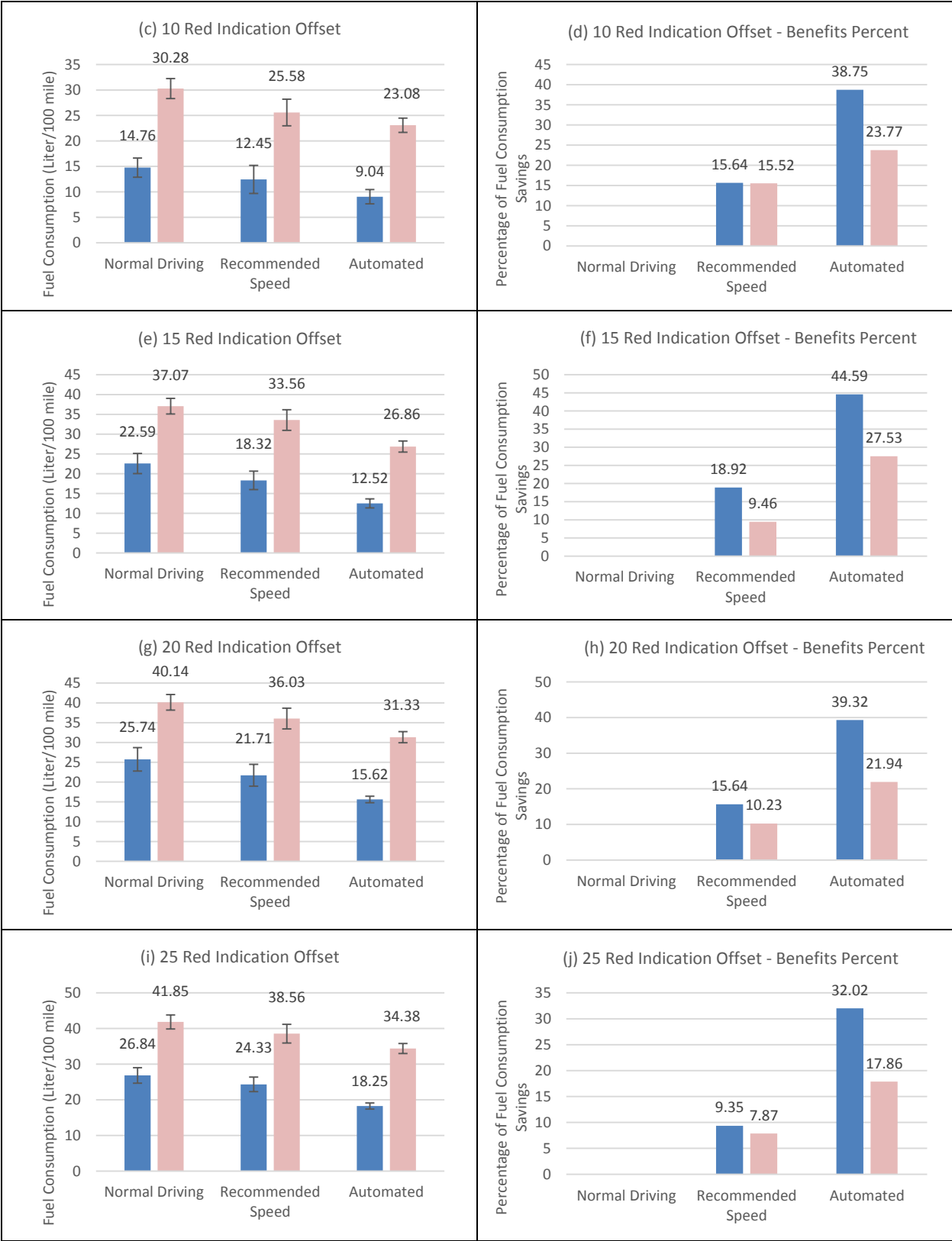


Figure 4-5 Fuel consumption comparison between all the three scenarios with standard deviation

It can be concluded that driving with either the manual or automated Eco-CACC systems is very efficient in reducing fuel consumption levels at shorted red indication offsets. This can also be easily observed in Figure 4-6, which presents the percentage of fuel consumption saving levels across the values of red indication offset for both the manual and automated Eco-CACC systems. It should be noted that, generally, the percentage of fuel consumption savings for the automated Eco-CACC system is approximately twice the percentage of fuel consumption savings for the manual Eco-CACC system.

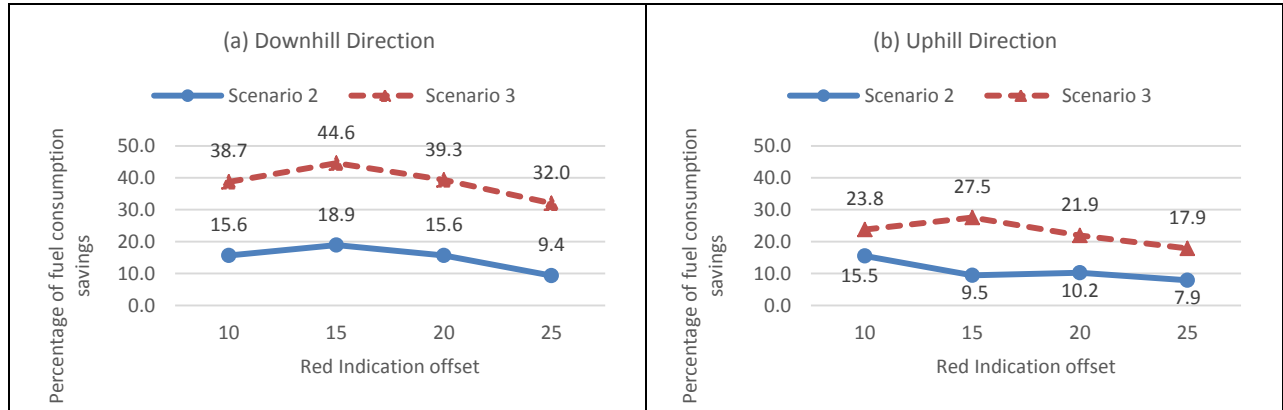


Figure 4-6 The trend of the percentage of fuel consumption savings across all the values of red indication offsets

Table 4-1 gives a summary of the observations of average fuel consumption levels with the percentage of reductions compared to normal driving for different combinations of trip direction and red indication offset values.

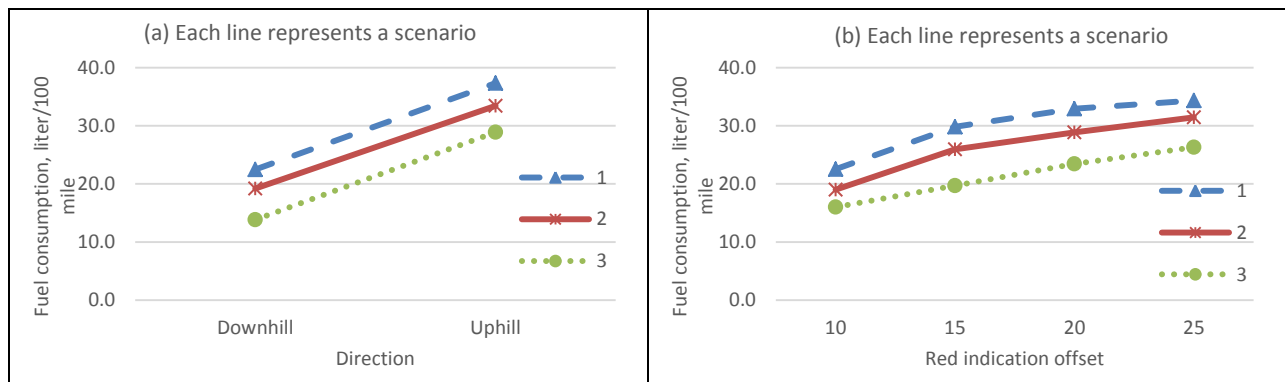
Table 4-1 Average fuel consumption (FC) levels

Direction	Red Indication Offset (sec)	Scenario 1	Scenario 2		Scenario 3	
		FC (liter/100 mile)	FC (liter/100 mile)	Reduction (%)	FC (liter/100 mile)	Reduction (%)
Downhill	10	14.8	12.5	15.6	9.0	38.7
	15	22.6	18.3	18.9	12.5	44.6
	20	22.7	21.7	15.6	15.6	39.3
	25	26.8	24.3	9.4	18.2	32.0
Uphill	10	30.3	25.6	15.5	23.0	23.8
	15	37.1	33.6	9.5	26.9	27.5
	20	40.1	36.0	10.2	31.3	21.9
	25	41.9	38.6	7.9	34.4	17.9
Average (downhill)		22.5	19.2	14.9	13.9	38.4
Average (uphill)		37.3	33.4	10.8	28.9	22.6
Total Average		29.9	26.3	12.8	21.4	30.5

Table 4-2 presents the analysis of SSPD at a 5-percent significance level where DF and DFDen indicate the degrees of freedom in the numerator and denominator respectively. The coefficient of determination for the model is approximately 92%. The SSD ANOVA shows that there are significant interactions in the model, and thereby the main effects (scenario, direction, and red indication offset) cannot be examined individually. Therefore, these significant interactions (scenario-direction, scenario-red indication offset, and red indication offset-direction) were studied and drawn in Figure 4-7. It is observable that all these interactions are co-directional, which means that each line has the same pattern. As a result, the main effects can be tested separately.

Table 4-2 Results of fixed effects of the split-split-plot ANOVA using the fuel consumption as the dependent variable for scenario, direction, and red indication offset

Source	DF	DFDen	F Ratio	Prob > F
scenario	2	158	431.6683	<.0001
red indication offset	3	1134	1195.234	<.0001
direction	1	189	9570.199	<.0001
scenario*direction	2	189	46.1809	<.0001
scenario*red indication offset	6	1134	9.1072	<.0001
red indication offset*direction	3	1134	29.3418	<.0001
scenario*red indication offset*direction	6	1134	1.6299	0.1354
gender	1	30	1.0889	0.3050



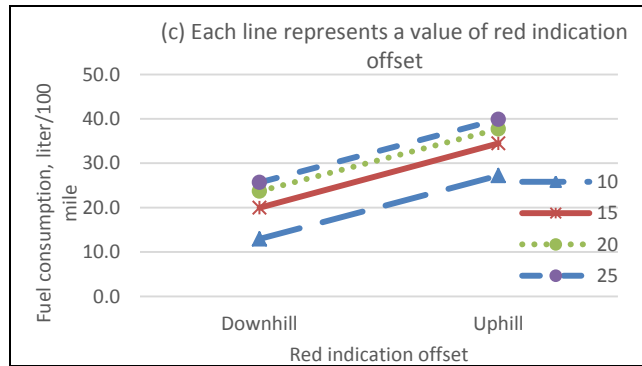
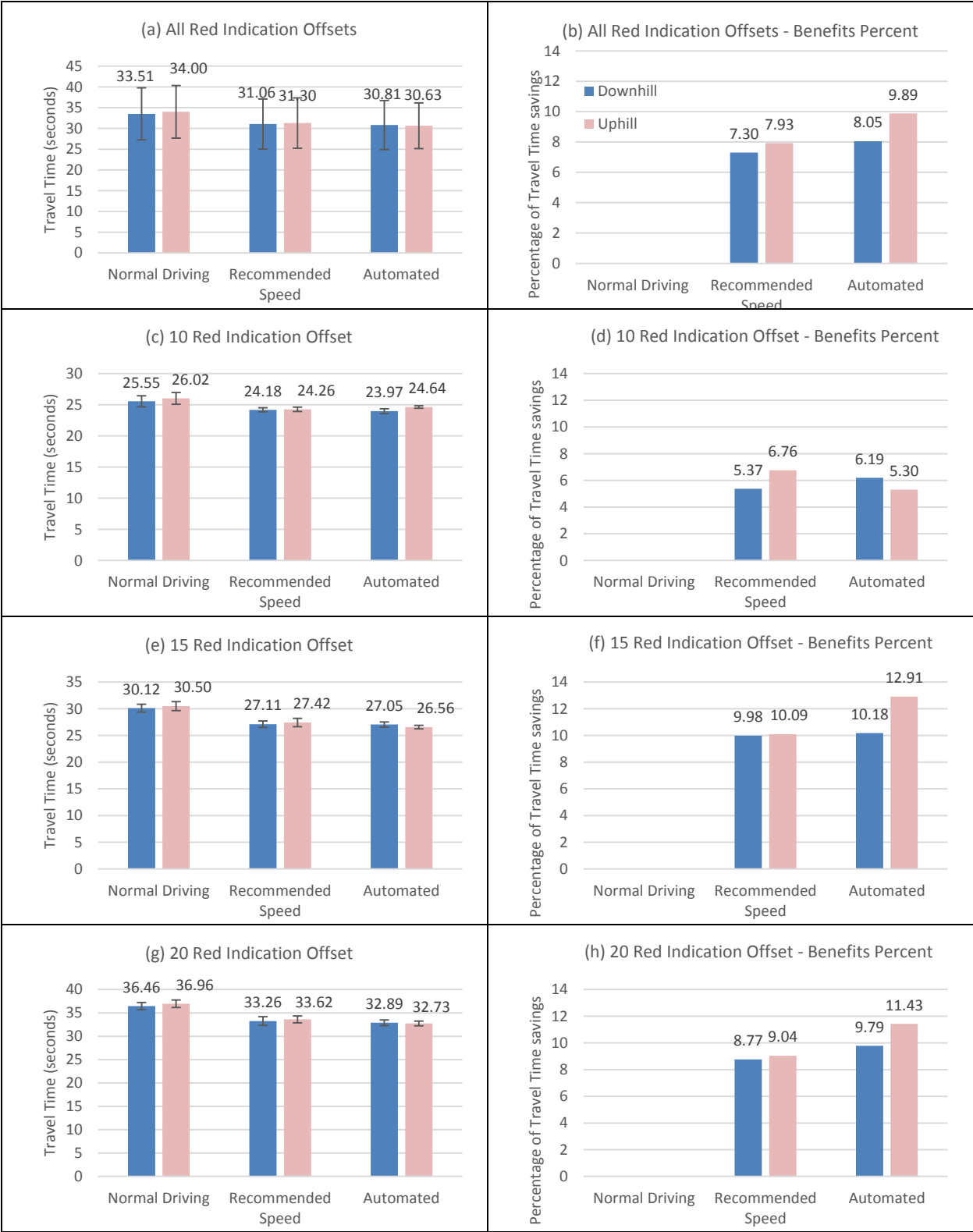


Figure 4-7 Fuel consumption comparison

The analysis of SSPD at a 5-percent significance showed that the effect of the scenario is significant with a p-value less than 0.0001. Subsequently, a multiple comparison using Tukey’s HSD was carried out to analyze the differences in fuel consumption between all the similar treatment combinations. The analysis shows that the differences between normal driving and either manual or automated Eco-CACC systems are statistically significant for all the values of red indication offset. Moreover, Tukey’s HSD test indicated that the automated Eco-CACC system differs significantly from the manual Eco-CACC system under all the values of red indication offset. Surprisingly, females tend to consume more gas than males under all the values of red indication offset, but this was considered statistically insignificant.

4.5.2 Travel Time

The travel time results from the manual and automated Eco-CACC systems were compared to scenario 1 (normal driving) and presented in Figure 4-8. The trend of the reductions in travel time is similar to the trend of the reductions in fuel consumption. For the same treatment combination, travel time continually decreases from scenario 1 to 3, and shows the lowest travel time in scenario 3. On average, the travel time savings in the automated Eco-CACC system are 8.05% and 9.89% in the downhill and uphill directions respectively, while they are 7.3% and 7.93% when driving with the manual Eco-CACC system. Therefore, the automated Eco-CACC system is slightly more advantageous.



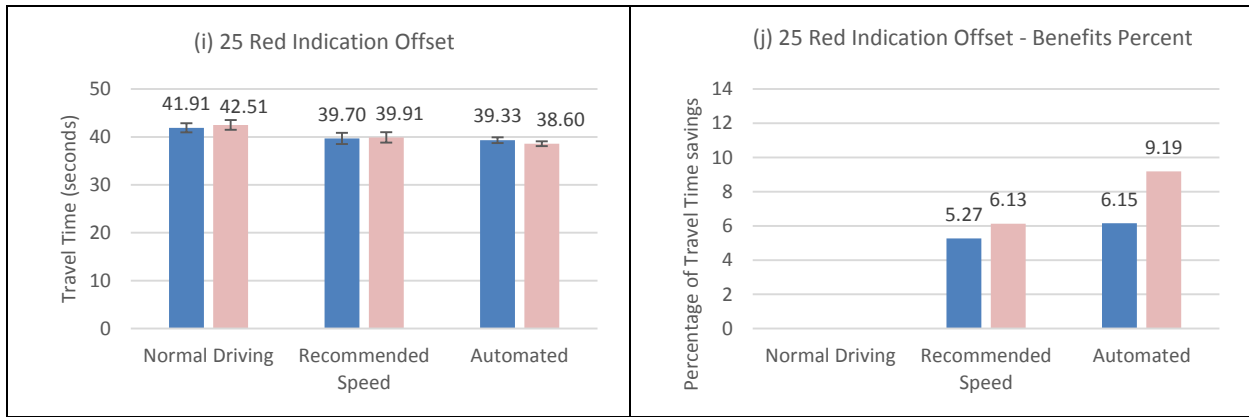


Figure 4-8 Travel time comparison between all the three scenarios for all the values of red indication offset with standard deviation

The trend of the percentage of travel time savings within the values of red indication offset for both the manual and automated Eco-CACC systems is shown in Figure 4-9. It is easily observed that both the manual and automated Eco-CACC systems have the same pattern, in which the maximum travel time savings occur under the 15 second red indication offset. The maximum reductions for driving downhill and uphill with the automated Eco-CACC system are 10.2% and 12.9%, while the maximum reductions in the manual Eco-CACC system are 10% and 10.1% downhill and uphill respectively. It should be noted that the difference in the reduction of travel time between the manual and automated Eco-CACC systems in the downhill direction is smaller than the uphill direction.

Unlike fuel consumption saving levels, the uphill direction has a higher benefit in travel time savings than the downhill direction for most of the treatment combinations. This can be explained by the fact that driving smoothly and efficiently in the uphill direction is more difficult than the downhill direction for both the manual and automated Eco-CACC systems.

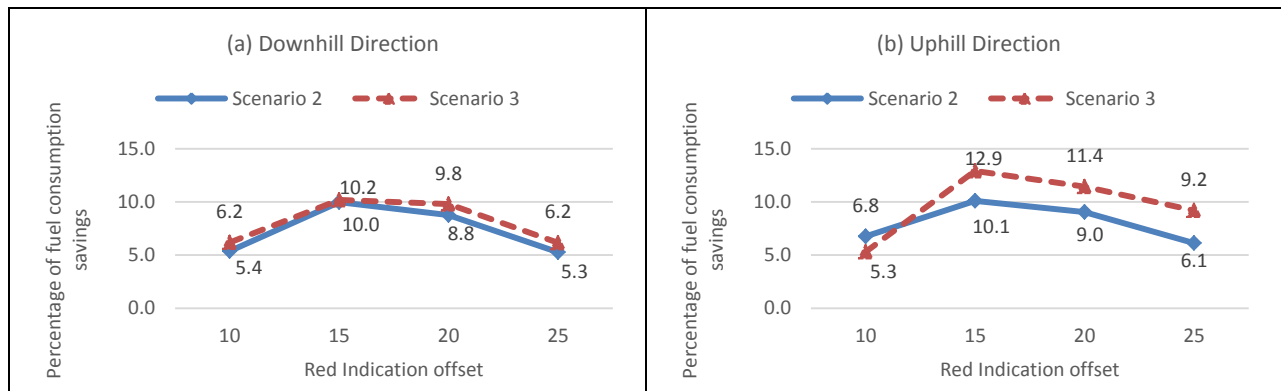


Figure 4-9 The trend of the percentage of fuel consumption savings across all the values of red indication offsets

Table 4-3 presents a summary of the average trip times with the percentage of reduction for each scenario.

Table 4-3 Average travel times (TT)

Direction	Red indication offset (sec)	Scenario 1	Scenario 2		Scenario 3	
		TT (sec)	TT (sec)	Reduction (%)	TT (sec)	Reduction (%)
Downhill	10	25.6	24.2	5.4	24.0	6.2
	15	30.1	27.1	10.0	27.0	10.2
	20	36.5	33.3	8.8	32.9	9.8
	25	41.9	39.7	5.3	39.3	6.2
Uphill	10	26.0	24.3	6.8	24.6	5.3
	15	30.5	27.4	10.1	26.6	12.9
	20	37.0	33.6	9.0	32.7	11.4
	25	42.5	39.9	6.1	38.6	9.2
Average (downhill)		33.5	31.1	7.3	30.8	8.1
Average (uphill)		34.0	31.3	8.0	30.6	9.9
Total Average		33.8	31.2	7.7	30.7	9.0

The SSPD Analysis-of-Variance was conducted, as shown in Table 4-4. Ninety-nine percent of the variations in the response (i.e. travel time) were captured given the three effects (i.e. scenario, red indication offset, and direction) and their interactions. As can be seen, all the interactions were found to be significant. Therefore, each interaction was studied and drawn individually to decide whether it is an anti-directional interaction or not. Figure 4-10 shows that the significant interactions are co-directional.

Table 4-4 Results of fixed effects of the split-split-plot ANOVA using travel time as the dependent variable for scenario, direction, and red indication offset

Source	DF	DFDen	F Ratio	Prob > F
scenario	2	158	1095.597	<.0001
red indication offset	3	1134	42785.10	<.0001
direction	1	189	38.2531	<.0001
scenario*direction	2	189	42.7106	<.0001
scenario* red indication offset	6	1134	94.2986	<.0001
red indication offset *direction	3	1134	6.7566	0.0002
scenario*red indication offset*direction	6	1134	11.5020	<.0001
gender	1	30	0.0008	0.9781

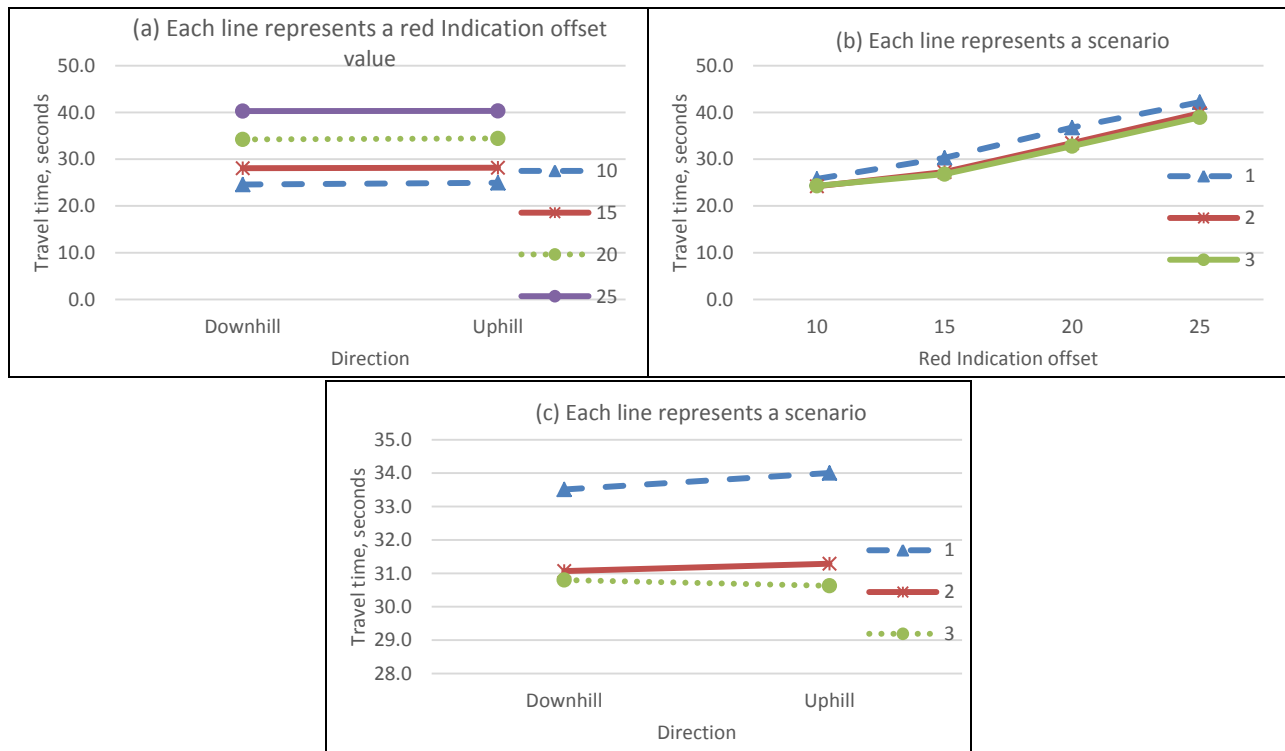


Figure 4-10 Travel time comparison

Tukey’s HSD was conducted to assess the differences in travel time between each treatment combination. Results show that the differences between normal driving and either the manual or automated Eco-CACC systems are statistically significant under all the values of red indication offset for both directions. However, there is no significant difference in travel times between the manual and automated Eco-CACC systems, except for 15, 20, and 25 second red indication offset values in the uphill direction.

4.6 Findings

The results show that both the manual and automated Eco-CACC systems always improve the vehicle trajectory for all of the treatment combinations. In particular, they decrease acceleration and deceleration maneuvers and provide a smooth speed profile. This can be seen in Figure 4-11 and Figure 4-12 in which an example of vehicle speed profile and a trajectory comparison for the three scenarios for each value of red indication offset are presented. It has to be noted that when the time is zero, the instrument vehicle enters the range of Eco-CACC system. In Figure 4-11 (g), in the normal driving scenario, the driver came to a complete stop at the intersection and waited for 10 seconds. However, in the manual Eco-CACC system, the driver tried to follow the recommended speed by decelerating initially, and then continued cruising at 17 mph (27 km/h)

with slight deceleration and acceleration intervals until he/she passed the intersection. Finally, in the automated Eco-CACC system, the testing vehicle decelerated initially and then kept cruising at 19 mph (30.5 km/h) until it passed the intersection.

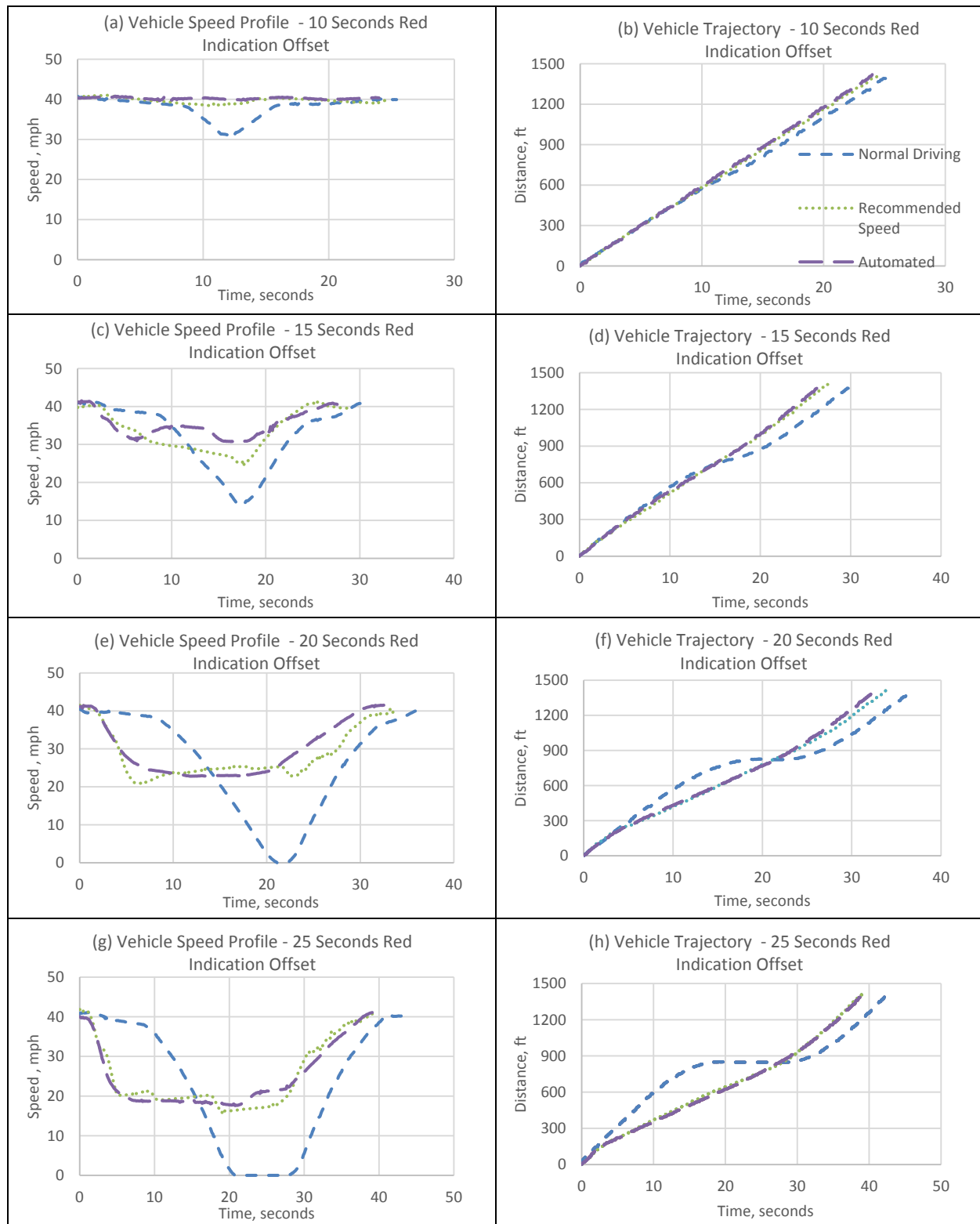


Figure 4-11 Example vehicle speed profile and trajectory, downhill direction

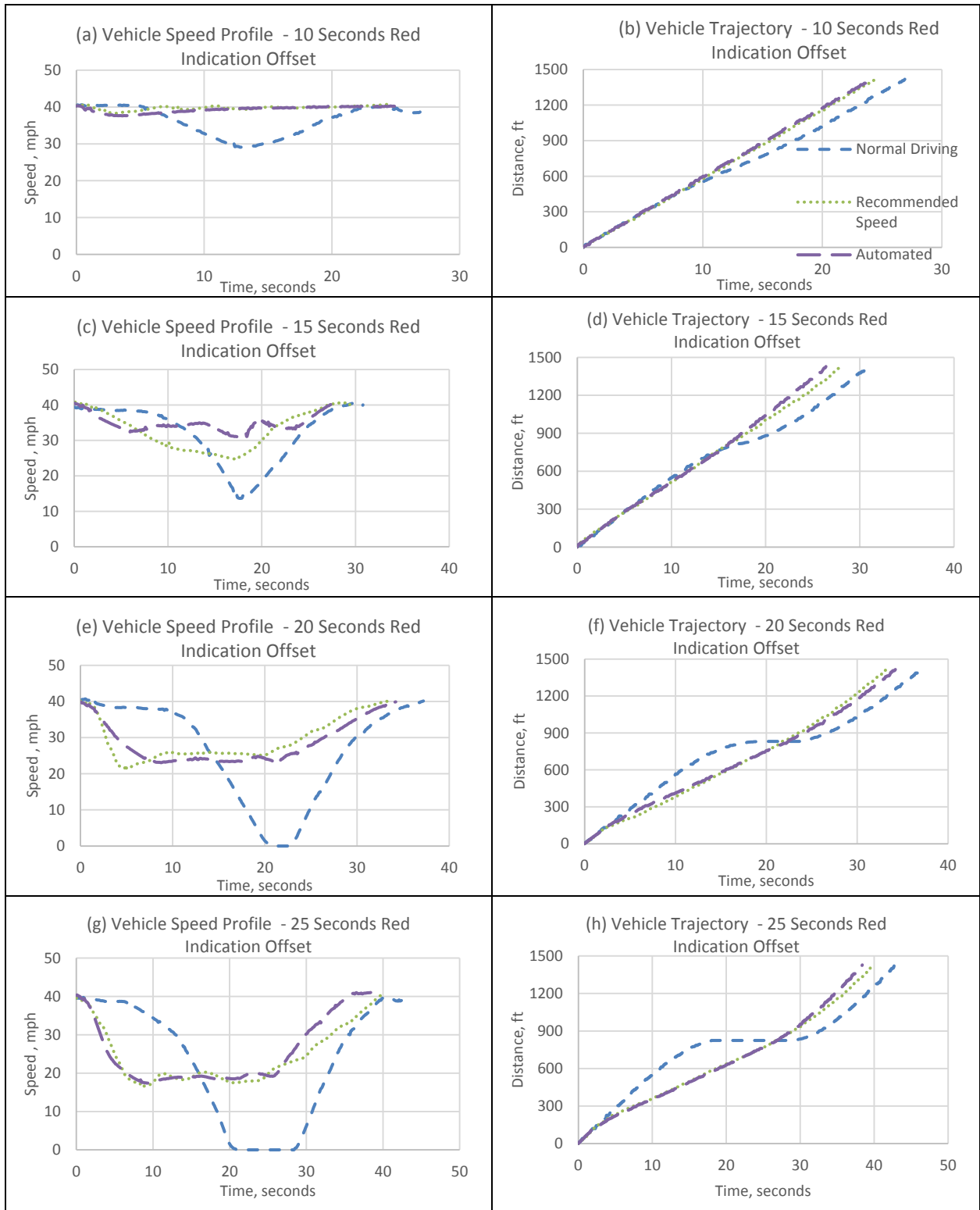


Figure 4-12 Example vehicle speed profile and trajectory, uphill direction

It is clear that the manual or automated Eco-CACC systems helped the vehicle to avoid a complete stop and increased the instantaneous speed when passing the intersection and this can

be seen in Figure 4-13 and Figure 4-14. Figure 4-13 shows that the percentage of time idling at the intersection continues reducing from scenario 1 to 3, and becomes zero at the second and third scenarios under all the values of red indication offset.

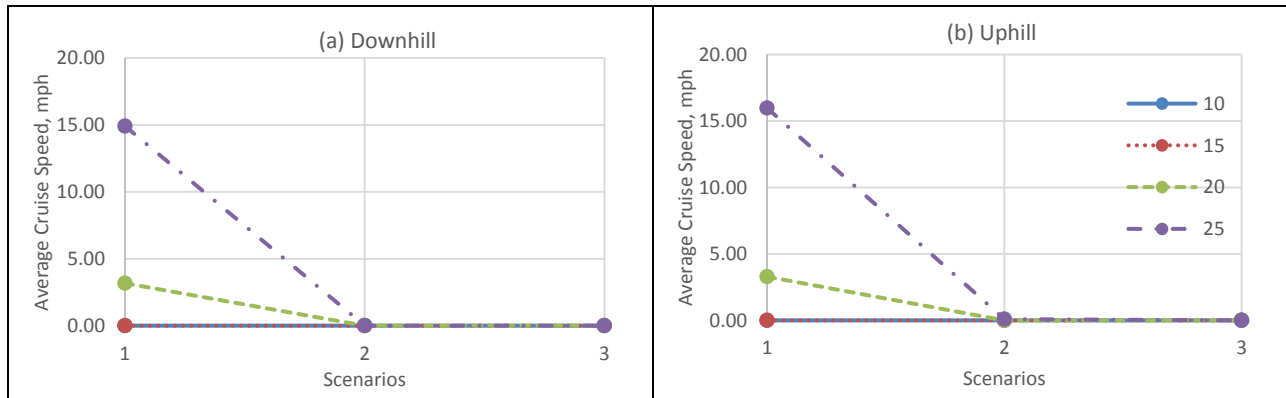
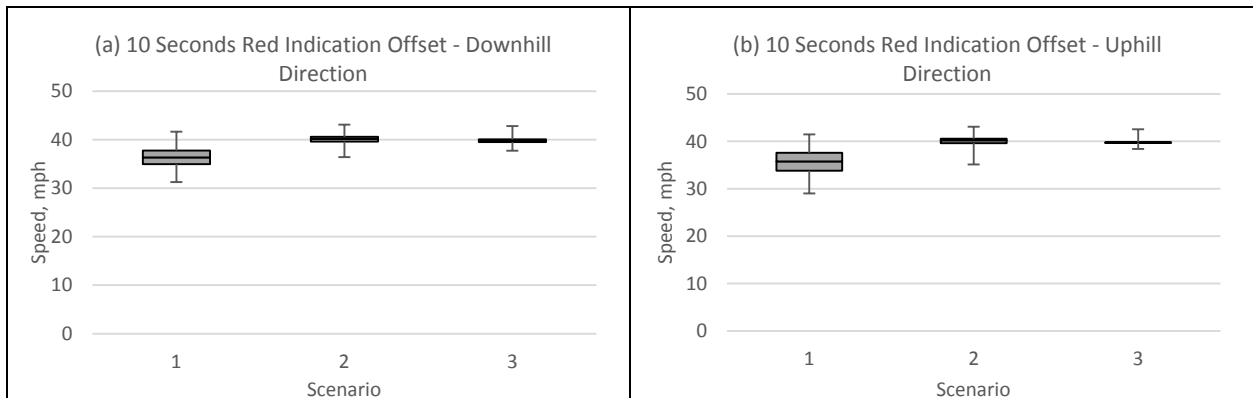


Figure 4-13 The percentage of time idling under different values of red indication offset for each scenario

Figure 4-14 represents the instantaneous speed when the testing vehicle passed the intersection under 10, 15, 20, and 25 second red indication offset values respectively. As can be seen, the average cruising speed continually increases from scenario 1 to 3, and generally scenario 3 has a higher speed than the other two scenarios for all the values of red indication offset. It should be mentioned that the variance of the instantaneous speed for the automated Eco-CACC system under 20 and 25 second red indication offset values is larger than the speed variance for the manual Eco-CACC system due to a braking issue which occurred in the automated Eco-CACC system. This issue caused the test vehicle to not brake initially, thereby decreasing the cruising speed at the intersection. However, the effect of this issue is limited, as it happened for only 5-7 participants.



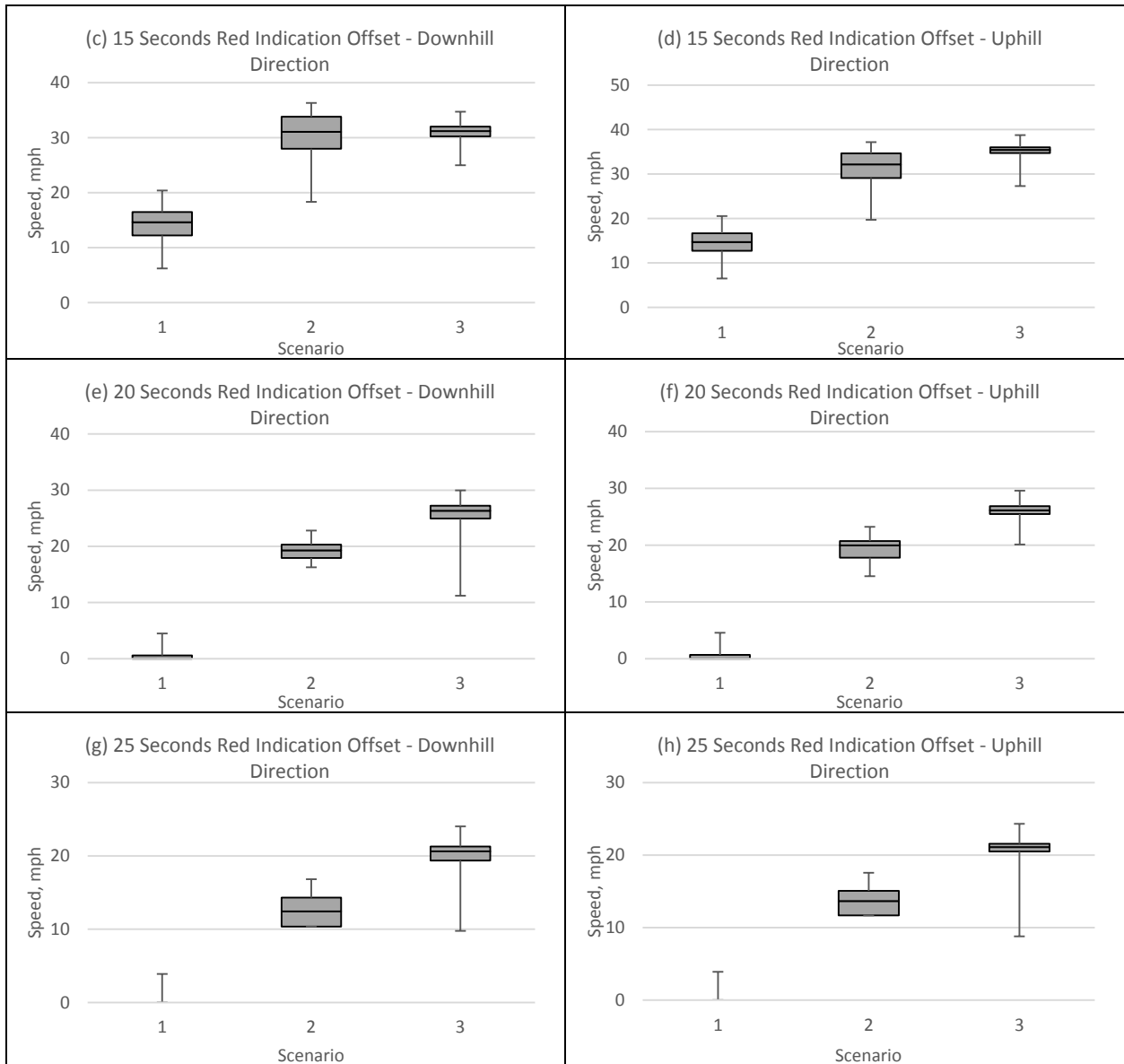


Figure 4-14 Box plot of the instantaneous speed at the intersection

A post-driving survey (appendix G) was conducted to evaluate drivers' perceptions of the three scenarios in terms of enhancing fuel efficiency, comfort, safety, and overall experience in the vicinity of the signalized intersection. The participants were asked to rank the three scenarios that would achieve the best fuel consumption saving levels, make driving more comfortable, and enhance safety. The results are given in Figure 4-15.

It is interesting to note that the automated Eco-CACC scenario is generally the most preferred scenario among the three, while the manual Eco-CACC system is the least preferred scenario. This may be explained by the fact that the frequency of the recommended speed information given in the manual Eco-CACC system is very high (2-second interval) and difficult

for the participants to follow. Therefore, participants found it distracting and dangerous to both pay attention to the road and adjust their speed every 2 seconds. In addition, some of the participants expressed their concern that driving with the manual Eco-CACC encourages them to pass at the onset of a green indicator which they consider to be unsafe.

Moreover, the participants were asked if they were in favor of implementing the automated Eco-CACC system into their cars. Over 90% of the participants supported adding the automated Eco-CACC system into their cars if it would save 10 to 15 percent in fuel consumption (Figure 4-16).

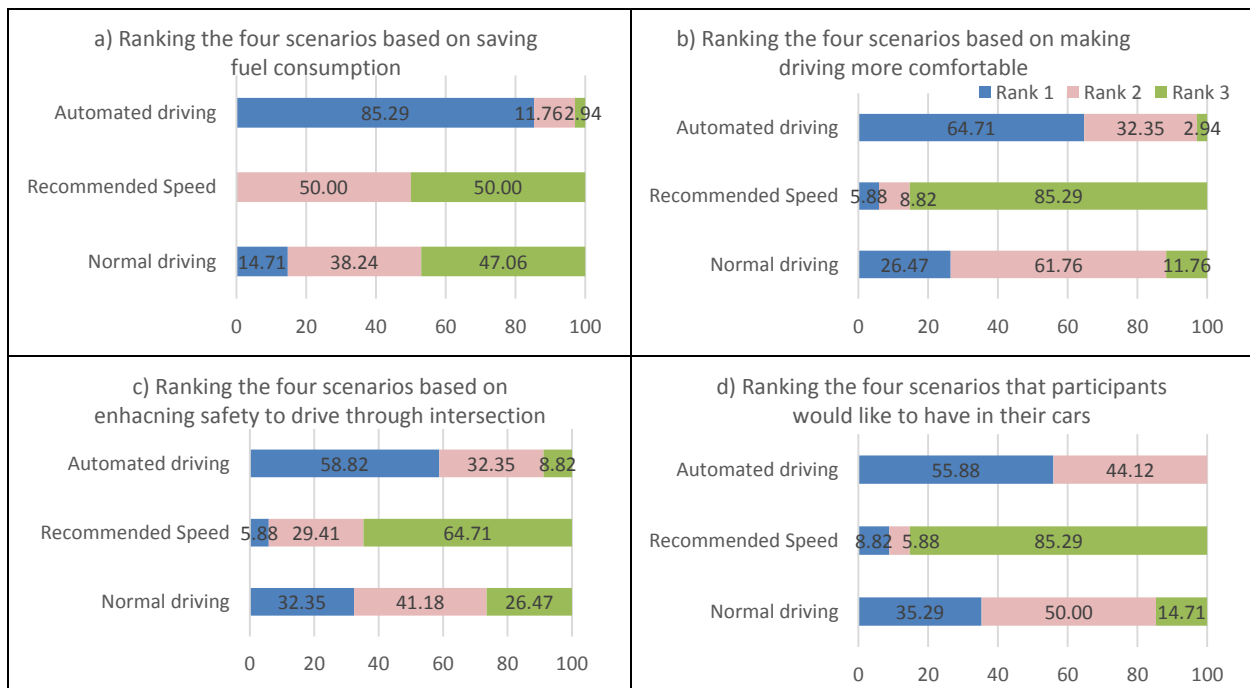


Figure 4-15 Respondent ranking of the three scenarios

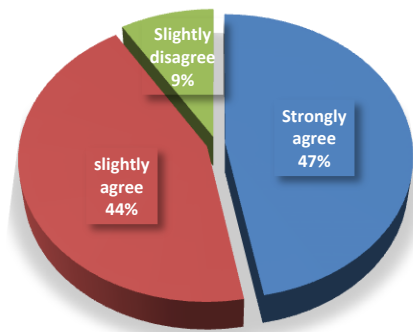


Figure 4-16 Perception on whether the participants would like to have the automated Eco-CACC system in their cars if it saves 10-15% in fuel consumption

4.7 Conclusions and Recommendations for Future Research

The research presented in this chapter investigated the benefits of an Eco-CACC system that computes the fuel-optimal velocity of a vehicle using SPaT information within the vicinity of a traffic signalized intersection. A controlled real experiment of 32 participants was conducted on the Smart Road test facility at VTTI. The experiment included three scenarios, namely: normal driving, driving with the manual Eco-CACC system, and driving with the automated Eco-CACC system. Each scenario had four different red indication offset values (10, 15, 20, and 25 seconds) with downhill and uphill directions. In total, 1536 trips were recorded and compared in terms of fuel economy and travel time in the entire maneuver of a signalized intersection. The study found that the manual and automated Eco-CACC systems always produce fuel economy enhancement and reduce travel times, at different percentages depending on the value of red indication offset and the direction. In particular, both the manual and automated Eco-CACC systems are very effective in producing fuel economy enhancement when traveling downhill and reducing travel time when traveling uphill. The study found that the automated Eco-CACC system results in higher fuel economy than the manual Eco-CACC system for all of the values of red indication offset. Compared to normal driving, the automated Eco-CACC system reduced fuel consumption levels and travel time, on average, by nearly 31 and 9 percent respectively. Additionally, it was found that the Eco-CACC system reduced the percentage of time idling at the intersection to zero and increased the average speed when passing the intersection.

In order to continue the work presented in this chapter with further improvement, the authors recommend conducting the same experiment considering the following precautions:

1. Increase the range of the ECO-CACC (the control length) from 820 and 590 ft (250 and 180 meters) upstream and downstream of the intersection to the ideal control length of 1640 ft (500 meters), which provides the greatest fuel consumption saving levels [69].
2. Examine the impact of multiple conditions of roadway grades (including a zero grade), road-weather, time of day, and travel-speeds on the benefits of the Eco-CACC system and driver's response to the provided information.
3. Investigate the impact of different frequencies of the recommended speed information on the benefits of the manual Eco-CACC system and the driver's response to the provided information.
4. Investigate the age effect on driver-acceptance of the advisory speeds using different age groups.

5. Investigate the impact of the presence of Eco-CACC non-equipped vehicles on Eco-CACC ones at single-lane and two-lane intersections.

4.8 Acknowledgments

This research effort was jointly funded by the Connected Vehicle Initiative University Transportation Center (CVI-UTC), the TranLIVE University Transportation Center, and NPRP Grant # 5-1272-1-214 from the Qatar National Research Fund (a member of The Qatar Foundation). The authors acknowledge the help of researchers from the hardware group at VTTI for their assistance in developing the hardware and software environment.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

The research presented in this thesis entailed an extensive discussion of the experiment that was conducted on the Smart Road test facility at the Virginia Tech Transportation Institute. This controlled field experiment was designed and conducted to quantify the benefits of the newly developed eco-driving algorithm that was proposed by the Center for Sustainable Mobility at the Virginia Tech Transportation Institute. This algorithm, named in Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system, receives advanced signal information (SPaT) from downstream-signalized intersections and, then, forecast the fuel-optimal trajectory for vehicles within the vicinity of a traffic signalized intersection. The forecasted trajectory can be delivered as recommended speeds to drivers in an audio message or be implemented directly in the testing vehicle. In this experiment, the objective function of the Eco-CACC system is the explicit minimization of the total fuel consumed to travel from 820 ft (250 m) upstream of the intersection to 590 ft (180 m) downstream of the intersection.

The controlled field experiment included four different scenarios, namely: normal driving, driving with count down information provided to drivers (time left from red to green), driving with recommended speed information also provided to drivers (manual Eco-CACC system), and automated driving (automated Eco-CACC system). In total, 2112 trips were conducted by 32 different participants between the ages of 18 and 30 with an equal number of males and females. Participants drove loops on the Smart Road, crossing a four-way signalized intersection between two turnarounds where the data were collected. Exclusive of practice trips, the participant drove a total of 64 trips (16 trips for each scenario), where a trip consists of one approach to the intersection.

The collected data were compared with regard to fuel economy and travel time, and it was found that the manual and automated Eco-CACC systems always produce a fuel economy enhancement and reduce travel times, at different percentages depending on the value of red indication offset and the direction. In particular, the manual and automated Eco-CACC systems are very effective in producing a fuel economy enchantment when traveling downhill and reducing travel time when traveling uphill. Moreover, the study found that the automated Eco-CACC system results in a higher fuel economy than the manual Eco-CACC system for all of the values of

red indication offset. Compared to normal driving, the automated Eco-CACC system reduced fuel consumption levels and travel time by nearly 31 and 9 percent respectively, on average, while the manual Eco-CACC system reduced fuel consumption levels and travel time by nearly 13 and 8 percent. Finally, it was found that driving with count down information produced the least fuel consumption savings levels and travel time compared to the manual and automated Eco-CACC systems.

Split-split-plot design was used to analyze the data and test significant differences between the four scenarios in fuel consumption and travel time. The analysis shows the differences between normal driving and driving with either the manual or automated Eco-CACC systems are statistically significant for all the values of red indication offsets.

Moreover, the study found that both the manual and automated Eco-CACC systems always improve the vehicle trajectory for each treatment combination of a value of red indication offset and direction. In particular, it decreases acceleration and deceleration maneuvers and provides a smooth speed profile. The analyzed data shows that the Eco-CACC system helps the vehicle to avoid a complete stop at the intersection, and, therefore, increase the instantaneous speed when passing the intersection.

Interestingly, post-drive survey results show the automated Eco-CACC system is the most preferred scenario among the four, while the manual Eco-CACC system is the least preferred scenario. Additionally, the survey results show that 90% of the participants would like to have the automated Eco-CACC system implemented in their cars if it would save 10 to 15 percent in fuel consumption.

5.2 Recommendations for Future Work

In order to continue the work presented in this thesis with further improvement, the authors recommend to conduct the same experiment considering the following precautions:

1. Increase the range of the Eco-CACC (the control length) from 820 and 590 ft (250 and 180 meters) upstream and downstream of the intersection to the ideal control length of 500 meters, which provides the greatest fuel consumption saving levels [69].
2. Examine the impact of multiple conditions of roadway grades (including a zero grade), road-weather, and travel-speeds on the benefits of the Eco-CACC system and driver's response to the provided information.

3. Investigate the impact of different frequencies of the recommended speed information on the benefits of the Eco-CACC system and the driver's response to the provided information.
4. Investigate the age effect on driver-acceptance of the advisory speeds using different age groups.
5. Investigate the impact of the presence of Eco-CACC non-equipped vehicles on Eco-CACC ones at single-lane and two-lane intersections.

APPENDIX A – VIRGINIA TECH INSTITUTIONAL REVIEW BOARD APPROVAL LETTER



Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website <http://www.irb.vt.edu>

MEMORANDUM

DATE: November 18, 2015
TO: Hesham A Rakha, Ihab E Elshawarby, Hao Chen, Mohammed Hamad Almannaa, Jinghui Wang, Karim Fadhoun, Mani Venkat Sai Kumar Ala, Istiak Ahmed
FROM: Virginia Tech Institutional Review Board (FWA00000572, expires July 29, 2020)
PROTOCOL TITLE: Eco-Driving Study
IRB NUMBER: 15-1092

Effective November 18, 2015, the Virginia Tech Institutional Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

<http://www.irb.vt.edu/pages/responsibilities.htm>

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: Expedited, under 45 CFR 46.110 category(ies) 4,5,7
Protocol Approval Date: November 17, 2015
Protocol Expiration Date: November 16, 2016
Continuing Review Due Date*: November 2, 2016

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

Date*	OSP Number	Sponsor	Grant Comparison Conducted?
11/17/2015	12096310	US Department of Transportation	Compared on 11/18/2015

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

APPENDIX B – PARTICIPANT RECRUITMENT MATERIAL



The Virginia Tech Transportation Institute is looking for
PARTICIPANTS FOR AN ECO-DRIVING STUDY

\$30 per hour (between 2 to 3 hours in total)

- Are you 18 to 30 years of age?
- Are you a U.S. Citizen or permanent resident with a valid green card?
- Have a valid driver's license?
- Driving in the US for at least 2 years?

If yes, please e-mail: XXXXXXXXXX@vt.edu
or call [XXX-XXX-XXXX](tel:XXX-XXX-XXXX)

You can also sign up to become a future participant
at:

<http://www.vtti.vt.edu/participate/participate-in-a-study.html>

APPENDIX C – IRB APPROVED INFORMED CONSENT FORM

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY *Informed Consent for Participants of Investigative Projects*

Title of Project: Eco-Driving Study

Investigators: Hesham Rakha, Ihab El-Shawarby, Hao Chen, Mohammed Almannaa

I. THE PURPOSE OF THIS RESEARCH PROJECT

The project is intended to test a new in-vehicle system around a signalized intersection. The in-vehicle system developed by Virginia Tech Transportation Institute (VTTI) consists of several driving assistant technologies, which deliver audio information (messages) to help drivers to pass through the signalized intersection. The data collected will help in the evaluation and improvement of future in-vehicle technologies. Up to 40 participants between the ages of 18 to 30 will be used to conduct the research. The results from this study will be used for writing a project report, as part of theses/dissertations, and journal/conference papers.

II. PROCEDURES

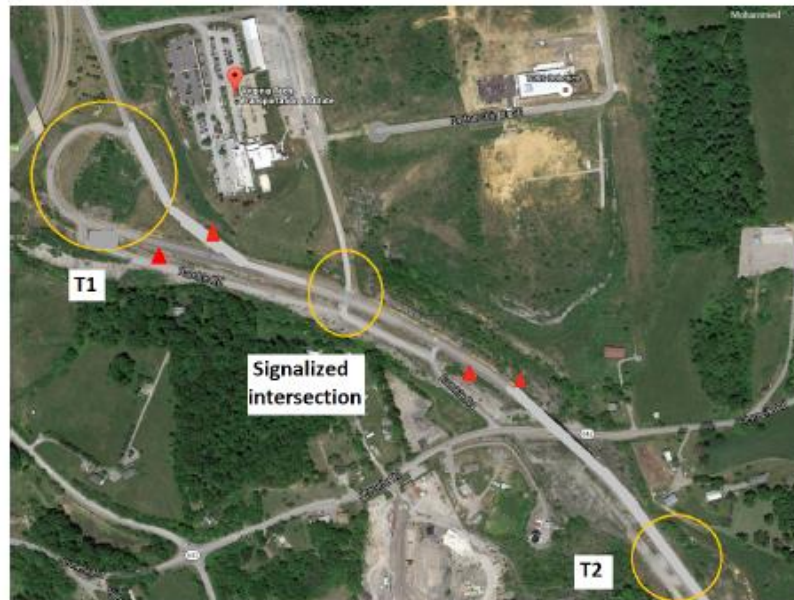
During the course of this experiment, you will be asked to perform the following tasks:

- 1) Read this Informed Consent Form and sign it if you agree to participate.
- 2) Show the experimenter your valid driver's license.
- 3) Take the vision test.
- 4) Drive an instrumented vehicle on the Smart Road, while following instructions provided by an in-vehicle intersection information system, maintaining a speed of about 40 miles per hour. An experimenter will be with you throughout the study.
- 5) Complete the post-run questionnaire.
- 6) Complete a W9 tax form for payment purposes.

It is important for you to understand that we are not evaluating you or your performance in any way. You are helping us to evaluate in-vehicle technology and to improve its ease of use while driving. The opinions you have will help us determine appropriate guidelines for new in-vehicle interfaces. The information and feedback that you provide is very important to this project. **Total experiment time will be approximately 2-3 hours.**

The experiment requires you to drive an instrumented vehicle on the Smart Road crossing a four-way signalized intersection and to **maintain a speed of about 40 miles per hour**, follow all normal traffic rules, and to obey all traffic laws during testing. At the beginning, you will have 3 trials to make yourself familiar with the experiment (you can have more if needed). After that, the experimenter will ask you start the official driving session.

As shown in the following map, you will drive through this signalized road between T1 and T2. (T1 is a curve and T2 is a U-turn). There are four cones (the red triangles) located on the right shoulder of the road (two at each direction). You need to drive at 40 miles per hour each time before you approach a cone.



There are 4 different scenarios to be tested, so you will be asked to complete all of them in one day. The experimenter will inform you when you need to switch between these four scenarios. The four scenarios are as follows:

Scenario 1: You will be driving the instrumented vehicle normally with no communication between your car and the traffic signal. It is like driving a normal car on a normal road.

Scenario 2: Your vehicle be communicating with the signalized traffic and you will be given an audio message with the number of seconds left to the next signal change. You can use this information to help you to proceed through the intersection. Note: the number of seconds will be given to you once you pass the cone while heading to the signalized intersection.

Scenario 3: You will be given an audio message with an instructed speed. You should adjust your speed according to the audio message. Note: the instructed speed will be given to you once you pass the cone while heading to the signalized intersection (you will drive 2 practice trials to make yourself familiar with this scenario).

Scenario 4: This is a semi-automated scenario as the vehicle will control the gas and brake pedals within a certain range of the signalized intersection. The instrumented vehicle will adjust its speed automatically. You will hear "Engage" when the vehicle becomes semi-automated and "Dismiss" when it returns to normal. Note: that you will have full control of the steering wheel at all times.

On completion of the testing (all the four scenarios), the experimenter will ask you to drive back to VTTI where you will be paid using a pre-loaded MasterCard and sign a receipt of payment and complete the questionnaire.

III. RISKS

The tasks described here are believed to pose no more than minimal risk to your health or well-being. The risks of driving the test vehicle on the Smart Road for this experiment are similar to that of driving an unfamiliar vehicle during daylight hours while using unfamiliar technology with no other traffic present.

While the risk of participation in this study is considered to be no more than that encountered in everyday driving, if you are pregnant you should talk to your physician and discuss this consent form with them before making a decision about participation.

Please be aware that events such as equipment failure, changes in the test track, stray or wild animals entering the road, and weather changes may require you to respond accordingly. If at any point in the session the experimenter believes that continuing the session would endanger you or the equipment, he/she will stop the testing.

In the event of an accident or injury in an automobile owned or leased by Virginia Tech, the automobile liability coverage for property damage and personal injury is provided. The total policy amount per occurrence is \$2,000,000. This coverage (unless the other party was at fault, which would mean all expense would go to the insurer of the other party's vehicle) would apply in case of an accident for all volunteers and would cover medical expenses up to the policy limit. For example, if you were injured in an automobile owned or leased by Virginia Tech, the cost of transportation to the hospital emergency room would be covered by this policy.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation; under Commonwealth of Virginia law, worker's compensation does not apply to volunteers; therefore, if not in the automobile, the participants are responsible for their own medical insurance for bodily injury. Appropriate health insurance is strongly recommended to cover these types of expenses. For example, if you were injured outside of the automobile owned or leased by Virginia Tech, the cost of transportation to the hospital emergency room would be covered by your insurance.

The following precautions will be taken to ensure minimal risk to you:

1. An experimenter will be with you at all times to monitor your driving and to ask you to stop if he/she feels the risks are too great to continue.
2. You may take breaks or decide not to participate at any time.
3. You will be required to maintain a maximum speed of 40 miles per hour throughout the session.
4. The testing will take place on a closed, controlled test track.
5. The experimenter will be present while you are driving. As long as you are driving the research vehicle, it remains your responsibility to drive in a safe and legal manner.
6. You will be required to wear your lap and shoulder belt restraint system while in the car. The vehicle is equipped with a driver's side and passenger's side airbag supplemental restraint system, fire extinguisher, and first aid kit. The experimenter will also have a cell phone.

7. All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to you in any foreseeable case.
8. You will drive at least 1.5 practice lap (three intersection passes) to familiarize yourself with the vehicle and the testing site.
9. Testing will only be conducted when the road is dry and free of excess debris.
10. For scenario 4, there is an emergency button that can be used by the experimenter, to stop the semi-automatic mode if necessary.
11. You do not have any medical condition that would put you at a greater risk, including but not restricted to history of neck/spine injury, epilepsy, balance disorders, lingering effects of head injuries and stroke, and advanced osteoporosis.
12. In the event of a medical emergency, or at your request, VTTI staff will arrange medical transportation to a nearby hospital emergency room. You may elect to undergo examination by medical personnel in the emergency room.

IV. BENEFITS

While there are no direct benefits to you from this research, you may find the experiment interesting. No promise or guarantee of benefits is made to encourage you to participate. Participation in this study will contribute to the improvement of future in-vehicle technology.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The data gathered in this experiment will be treated with confidentiality. Shortly after participation, your name will be separated from your data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 1). You may elect to have your data withdrawn from the study if you so desire, but you must inform the experimenters immediately of this decision so that the data may be promptly removed.

VTTI researchers will not release data identifiable to an individual to anyone other than VTTI staff without your written consent. The data collected in this study may be used in future VTTI transportation research projects. It is expected that there will be follow-on data analyses conducted using all of the data, probably for years to come. These follow-on analyses will be conducted by qualified researchers who may or may not be part of the original project team. IRB approval will be obtained prior to accessing the data for other projects. De-identified data (study data that cannot be used to identify you) may be given to the study sponsor.

It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. COMPENSATION

You will be paid \$30 per hour. The study is expected to last between 2 - 3 hours for the whole experiment (preparation room + actual testing). Your payment is prorated at \$7.5 for each quarter hour, or fraction thereof. You will be paid at the end of the session, whether for the full amount or any partial amount, using a pre-loaded MasterCard. Please allow up to 1 full business day for activation of the card. Once activated, this card cannot be used past its expiration date. If there is no activity on the card for 5 months, the card will become inactive.

You will be asked to provide researchers with your social security number or Virginia Tech I.D. number for the purposes of being paid for your participation. For tax recording purposes, the

fiscal and accounting services office at Virginia Tech (also known as the Controller's Office) requires that all participants provide their social security number or Virginia Tech I.D. number to receive payment for participation in our studies.

VII. FREEDOM TO WITHDRAW

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty. If you choose to withdraw during the study session, please inform the experimenter of this decision and he/she will drive you back to the building.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University.

IX. PARTICIPANT'S RESPONSIBILITIES

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To follow the experimental procedures as well as you can.
2. To inform the experimenter if you have difficulties of any type.
3. To wear your seat and lap belt.
4. To maintain safe operation of the instrumented vehicle at all times.
5. To adhere to 40 mph (maximum) speed limit on the VA Smart Road for this experiment.

X. PARTICIPANT'S ACKNOWLEDGMENTS

Check all that apply:

- I am not under the influence of any substances or taking any medications that may impair my ability to participate safely in this experiment.
- I am in good health and not aware of any health conditions that would increase my risk including, but not limited to, lingering effects of a heart condition.
- I have been driving in the United States for at least two years.
- I have informed the experimenter of any concerns/questions I have about this study.
- If I am pregnant, I acknowledge that I have either discussed my participation with my physician, or that I accept any additional risks due to pregnancy.

XI. PARTICIPANT'S PERMISSION

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. **If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.**

Participant's name (Print)	Signature	Date
----------------------------	-----------	------

Researcher's name (Print)	Signature	Date
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XII. QUESTIONS OR CONCERNS

Should I have any questions about this research or its conduct, I may contact:

Hesham Rakha @ (540) 231-1505, or by email: HRakha@vtti.vt.edu

Ihab Elshawarby @ (540) 231-1577, or by email: IEI-Shawarby@vtti.vt.edu

Hao Chen @ (540) 231-0254, or by email: HChen@vtti.vt.edu

Mohammed Almannaa @ (512) 761-2719, or by email: almannaa@vt.edu

If I should have any questions about the protection of human research participants regarding this study, I may contact: Dr. David Moore, Chair of the Virginia Tech Institutional Review Board for the Protection of Human Subjects, telephone: (540) 231-4991; email: moored@vt.edu;

APPENDIX D - TELEPHONE SCRIPT AND SCREENING QUESTIONNAIRE

Screening Date _____ Screener _____ Screening #: _____

"Eco Driving" Phone Screening

Note:

Initial contact between participants and researchers may take place over the phone. If this is the case, read the following Introductory Statement, followed by the questionnaire. Regardless of how contact is made, this questionnaire must be administered verbally before a decision is made regarding suitability for this study.

Introductory Statement:

After prospective participant calls or you call them, use the following script as a guideline in the screening interview.

Hello. My name is _____ and I'm with the Virginia Tech Transportation Institute, here at the Smart Rd, in Blacksburg, VA. We are currently recruiting people to participate in a research study. This study involves participating in one session, lasting approximately 2-3 hours, during daytime hours (8am-5pm). Based on your eligibility, you will be asked to drive our research vehicle on our test track, the Smart Road. An experimenter will be with you at all times; the research vehicle is equipped with data collection equipment. Prior to driving you will need to complete a simple vision test.

Participants will be paid \$30/hour with a pre-loaded MasterCard.

Any questions yet?

If you are interested in possibly participating, I need to go over some screening questions to see if you meet all the eligibility requirements of this study. Any information given to us will be kept secure and confidential.

Do I have your consent to ask the screening questions? [If yes, continue with the questions. If no, then thank him/her for their time and end the phone call.]

Participant Eligibility Questions:

- | |
|--|
| 1. Do you currently hold a valid U.S. driver's license, which you can present at the time of the study? YES _____ NO _____ if yes, how long have you held a U.S. license? _____ |
| <i>Criterion: they are ineligible to participate if unable to present a VALID U.S. driver's license at their appointment and they must be an experienced U.S. driver (at least 2 years).</i> |
| <i>NOTE: They will be reminded they must present a driver's license at their appointment if scheduled.</i> |
| 2. What is your current age? _____ YOB _____ |
| <i>Criterion: Must be 18-30 years old to participate.</i> |

<p>9. Current heart condition which limits your ability to participate in certain activities? YES ____ NO ____</p> <p>If yes, please explain: _____</p> <p><i>Cannot have a current heart condition which limits their ability to participate in certain activities.</i></p>
<p>10. Current respiratory disorder/disease or any condition which requires oxygen? YES ____ NO ____ Notes: _____</p> <p><i>Cannot have current respiratory disorder/disease or disorder/disease requiring oxygen.</i></p>
<p>11. Any epileptic seizures or lapses of consciousness within the past twelve months? YES ____ NO ____ Notes: _____</p> <p><i>Cannot have had an epileptic seizure or lapse of consciousness within the past 12 months.</i></p>
<p>12. Chronic migraines or tension headaches? YES ____ NO ____ If yes, do they occur more than once a month on average? YES ____ NO ____ Notes: _____</p> <p><i>Cannot have, on average, more than one migraine or severe headache per month during the past yr.</i></p>
<p>13. Current problems with the inner ear, dizziness, vertigo, or balance problems? YES ____ NO ____</p> <p><i>Cannot have current problems with inner ear, dizziness, vertigo, or balance problems.</i></p>
<p>14. Do you have diabetes which requires insulin? YES ____ NO ____ If yes, please explain: _____</p> <p><i>Cannot have uncontrolled diabetes (have they been recently diagnosed or have they been hospitalized for this condition, or any changes in their insulin prescription during the past 3 months)</i></p>
<p>15. Have you had any major surgery within the past six months, including any eye procedures? YES ____ NO ____</p> <p><i>Must not have had any major surgery within the past 6 months (including eye procedures).</i></p>
<p>16. Do you currently suffer from motion sickness while in a motor vehicle? YES ____ NO ____</p> <p><i>Cannot suffer from moderate to severe motion sickness while in a vehicle. (if state they get motion sickness while trying to read and ride, that is ok, as long as they are ok while driving and is not a severe problem)</i></p>

<p>17. Are you currently taking any medicines or substances that may cause drowsiness or impair your driving ability? YES ____ NO ____</p> <p><i>Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities)</i></p>
<p>18. (Females only) Are you currently pregnant? (if "yes," politely inform the participant: while being pregnant does not disqualify you from participating in this study, you are encouraged to talk to your physician about your participation to make sure that you both feel it is safe. If you like, we can send you a copy of the consent form to discuss with your physician. Answer any questions) YES ____ NO ____</p> <p><i>(Can still participate, but encourage them to speak with their doctor first)</i></p>
<p>19. Do you have normal, or corrected to normal, vision in both eyes? YES ____ NO ____</p> <p><i>Criterion: Must have normal or corrected to normal vision in both eyes.</i></p>
<p>20. Do you have normal, or corrected to normal, hearing? YES ____ NO ____</p> <p><i>Criterion: Must be able to hear and follow researcher's verbal directions while driving. Must have normal or corrected to normal hearing.</i></p>
<p>21. Are you able to drive an automatic transmission without assistive devices or special equipment? Yes ____ No ____</p> <p><i>Criterion: Must be able to drive an automatic transmission without assistive devices/special equipment.</i></p>
<p>22. Have you had any moving violations in the past 3 years? If so, please explain. YES ____ NO ____</p> <p><i>Criterion: Must not have been convicted of more than two driving violations in the past 3 years.</i></p>
<p>23. Have you been involved in any automobile accidents in the past 3 years? YES ____ NO ____ If so, please explain _____</p> <p><i>Criterion: Must not have been convicted of an injurious accident (driving violation) in the past 3 years.</i></p>

How did you hear about this project? _____

Screening Date _____ Screener _____ Screening #: _____

Recruiting Others:

Do you know anyone else with that may be interested in hearing about this study?
If yes, may we send you the information so you can forward it to them? (Or they can provide our phone #, email, website address to others; we will be happy to speak to anyone interested in hearing more)

Do you prefer we send you the info by Email: _____ or USPS mail
(address): _____

If Eligible:

Availability: _____

Scheduled on (date & time): _____

Name: _____

Home Phone #: _____ Cell# _____ Work # _____

We encourage you to read a copy of the Informed Consent prior to coming in for your scheduled appointment. Please review it ahead of time and contact us with any questions or concerns. You will be asked to read & sign a copy of this document upon arrival at VTTI prior to participating. Do not bring this document with you to the appointment; we simply ask for you to review the document ahead of time and to let us know you received it. Do you prefer we send as an email attachment or by USPS?

E-mail or mailing address: _____

Town or city you live & approximate travel time to VTTI:

Would you like to be contacted for future studies? Yes: _____ No: _____

If yes, collect the following:

Last Name: _____ First Name: _____

Y.O.B. _____

Home Phone #: _____ Cell# _____ Work # _____

Town or city: _____ State: _____

Specialty Driver's License _____

if CDL, endorsements/restrictions _____

Make and Model of Primary Vehicle (light) _____

APPENDIX E – LEFT MESSAGE SCRIPT

Eco-Driving Study

Phone script for leaving a message (speak slowly):

Hello, my name is _____ and I am calling from the Smart Road at the Virginia Tech Transportation Institute in Blacksburg, VA. We are looking for people to participate in a driving study; this study involves driving our research vehicle on the Smart Road here at VTTI. This project pays \$30/hour and would require coming in for one visit lasting between 2 and 3 hours.

*If you are interested and would like to hear more, please call **XXX-XXX-XXXX**. Again, my name is _____ and my phone number is **XXX-XXX-XXXX**. Please reference the 'Eco-Driving' study in your message.*

Thank you and have a great day.

APPENDIX F – APPOINTMENT CONFIRMATION



3500 Transportation Research Plaza (0536)
Blacksburg, Virginia 24061
540/231-1500 Fax: 540/231-1555
www.vtti.vt.edu

Dear _____,

Please reply to this email/mail so we know you received it and you are able to open the attachment. Please do not bring the paperwork with you; we only ask that you review it prior to coming in for your appointment.

We have you scheduled to come in to VTTI on **XXXXXXXXXX at XXXX am/pm**, for the “Eco-Driving” study. If there is inclement weather, we may have to cancel or reschedule the appointment. We will call you if there is a need to change the appointment.

- Please bring your driver’s license
- Please wear only closed toe shoes when you come to VTTI as no flip-flops or sandals will be allowed
- Please bring reading glasses if needed

If you have any questions, please don’t hesitate to give us a call, **XXX-XXX-XXXX**.

Directions: Our address is 3500 Transportation Research Plaza, Blacksburg, VA, 24060.

From I-81N or S

- Take Exit 118B to Rt. 460W
- Follow signs to Virginia Tech/Blacksburg
- Take Exit 5AB (Smart Road/Industrial Park Drive)
- Follow 5A to the Right on Exit ramp to Industrial Park Drive
- Turn Right at end of ramp onto Industrial Park Drive
- Then make an immediate Right onto Transportation Research Drive
- Make first Left onto Transportation Research Plaza, come up hill
- Turn Right at top of hill and
- Make a Left into parking lots at top of hill-look for the parking spaces designated for participants or park anywhere

From 460E

- Take Exit 5B
- On ramp, bear Left onto 5B toward Blacksburg
- Turn Left at light at end of ramp onto Main Street
- Turn Right at 1st light onto Industrial Park Drive
- Turn Right immediately after passing exit ramp from 460W (at large blue sign) onto Transportation Research Drive
- Make first Left onto Transportation Research Plaza, come up hill
- Turn Right at top of hill and
- Make a Left into parking lots at top of hill- look for the parking spaces designated for participants or park anywhere

The Main Entrance to VTTI is in the multi-story building, there is a reception desk in the lobby; please check in. Please inform the staff you are here for the “Eco-Driving” study. If you are scheduled outside of normal business hours (M-F, 8-5pm), please wait outside the main entrance, as all buildings will be locked. If outside of normal business hours, please contact _____ at XXX-XXX-XXXX if you need to reach someone immediately.

Thank you,

Advancing Transportation through Innovation

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

APPENDIX G – QUESTIONNAIRE



Participant Number: Enter number

1. Regarding "improve your ability to make decision on how to proceed through intersection", please rank the following options with 1 for most-favored and 3 for least-favored.
 - [–] Scenario 1: normal driving
 - [–] Scenario 2: driving with count down
 - [–] Scenario 3: driving with advised speed
2. Regarding "avoid completely stop at intersection", please rank the following options with 1 for most-favored and 3 for least-favored.
 - [–] Scenario 1: normal driving
 - [–] Scenario 2: driving with count down
 - [–] Scenario 3: driving with advised speed
3. Regarding "save fuel consumption", please rank the four scenarios with 1 for most-favored and 4 for least-favored.
 - [–] Scenario 1: normal driving
 - [–] Scenario 2: driving with count down
 - [–] Scenario 3: driving with advised speed
 - [–] Scenario 4: automated driving
4. Regarding "make driving more comfortable", please rank the four scenarios with 1 for most-favored and 4 for least-favored.
 - [–] Scenario 1: normal driving
 - [–] Scenario 2: driving with count down
 - [–] Scenario 3: driving with advised speed
 - [–] Scenario 4: automated driving
5. Regarding "enhance safety to drive through intersection", please rank the four scenarios with 1 for most-favored and 4 for least-favored.
 - [–] Scenario 1: normal driving
 - [–] Scenario 2: driving with count down
 - [–] Scenario 3: driving with advised speed
 - [–] Scenario 4: automated driving

6. Please rank the following options that you would like to have in your car.

- [--] Scenario 1: normal driving
- [--] Scenario 2: driving with count down
- [--] Scenario 3: driving with advised speed
- [--] Scenario 4: automated driving

7. Considering the automated driving of Eco-Speed Control generally saves 10~15% fuel consumption, would you like to have this technology in your car?

Choose one

APPENDIX H – PAYMENT ACKNOWLEDGMENT



Payment Acknowledgment

Project: Eco-Driving Study

Fund: 451182

Principle Investigator: Hesham Rakha

Date: _____

Participant Name: _____

Social Security Number: _____

I have received a MasterCard preloaded with \$ _____ for my participation today. I understand that the funds on this card may not be available for up to 1 business day. I also understand the card will become invalid if there is a period of inactivity exceeding 5 months.

Participant Signature: _____

Experimenter Initials: _____

*Please note that payments you receive in accordance with this research are considered taxable income. If payment exceeds \$600.00 in any one calendar year, Virginia Tech is required to file a 1099 form with the IRS. For amounts less than \$600.00, you are responsible for reporting additional income, but no 1099 tax forms will be filed with the IRS.

APPENDIX I – W-9 FORM



VENDOR REGISTRATION
 Substitute Form W-9
 Mail, e-mail or Fax completed form to:
 201 Southgate Center, Blacksburg, VA 24061
 W9@vt.edu Phone: (540) 231-2544/Fax: (540) 231-7221

Legal Name: _____
(as it appears on your tax return)

Trade Name: _____
(DBA)

Mail PURCHASE ORDERS and BIDS to:		Mail PAYMENTS to:	
PO Telephone # <i>(preferably toll free)</i>	PO Fax # <i>(preferably toll free)</i>	Email address:	
		AP email address:	

Taxpayer Identification Number:

Employer Identification Number(EIN):	AND/OR	Social Security Number (SSN):

Entity Type (one MUST be checked)

<input type="checkbox"/> Corporation	<input type="checkbox"/> LLC	<input type="checkbox"/> Partnership
	If "LLC" is checked, type MUST be marked below:	
<input type="checkbox"/> Government Entity	<input type="checkbox"/> C Corporation (C)	<input type="checkbox"/> Sole Proprietor
<input type="checkbox"/> Non-Profit Organization	<input type="checkbox"/> S Corporation (S)	<input type="checkbox"/> Individual (see below)
	<input type="checkbox"/> Partnership (P)	

For Individuals ONLY:

I am a U.S. Citizen, **or**

I have been granted permanent residency (green card holder), **or**

I am a Resident Alien for tax purposes and have contacted the international tax specialist at 540-231-3754 or jakunz@vt.edu to discuss additional documentation that is required by federal law.

Business Classification Type (check ALL that apply): *for descriptions see: <http://www.purch.vt.edu/Vendor/class.html>*

Large Business Small Business Minority owned Business Women Owned Business Other

Certification: Under penalties of perjury, I certify that:

(1) The number(s) shown on this form is my correct taxpayer identification number(s) (or I am waiting for a number to be issued to me), **and** (2) The organization entity and all other information provided is accurate, **and** (3) I am not subject to backup withholding either because I have not been notified that I am subject to backup withholding as a result of a failure to report all interest or dividends, or the Internal Revenue Service has notified me that I am no longer subject to backup withholding.

You must cross out item (3) above if you have been notified by IRS that you are currently subject to backup withholding because of underreporting interest or dividends on your tax return.

Authorized Signature Title

Printed or Typed Name Phone Number Date

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