



# Final Report

## Developing and Testing an Advanced Hybrid Electric Vehicle Eco-Cooperative Adaptive Cruise Control System at Multiple Signalized Intersections

**Hao Chen**

Virginia Tech Transportation Institute  
Phone: (540) 231-0254; Email: [hchen@vtti.vt.edu](mailto:hchen@vtti.vt.edu)

**Hesham Rakha**

Virginia Tech Transportation Institute  
Phone: (540) 231-1505; Email: [hrakha@vt.edu](mailto:hrakha@vt.edu)

**Mansoureh Jeihani**

Department of Transportation and Urban Infrastructure Studies,  
Morgan State University  
Phone: (443) 885-1873; Email: [mansoureh.jeihani@morgan.edu](mailto:mansoureh.jeihani@morgan.edu)

**Samira Ahangari**

Department of Transportation and Urban Infrastructure Studies,  
Morgan State University  
Phone: (443) 885-1873; Email: [saaha1@morgan.edu](mailto:saaha1@morgan.edu)

Date

October 2020

Prepared for the Urban Mobility & Equity Center, Morgan State University, CBEIS 327, 1700 E. Coldspring Lane,  
Baltimore, MD 21251



## ACKNOWLEDGMENT

This research was funded by the Urban Mobility & Equity Center at Morgan State University and the University Transportation Center(s) Program of the U.S. Department of Transportation.

### Disclaimer

---

*The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.*

<b>1. Report No.</b> UMEC-023	<b>2. Government Accession No.</b>	<b>3. Recipient's Catalog No.</b>	
<b>4. Title and Subtitle</b> Developing and Testing an Advanced Hybrid Electric Vehicles Eco-Cooperative Adaptive Cruise Control System at Multiple Signalized Intersections		<b>5. Report Date</b> October 2020	
		<b>6. Performing Organization Code</b>	
<b>7. Author(s) Include ORCID #</b> Hao Chen <a href="https://orcid.org/0000-0001-8272-734X">https://orcid.org/0000-0001-8272-734X</a> Hesham A. Rakha <a href="https://orcid.org/0000-0002-5845-2929">https://orcid.org/0000-0002-5845-2929</a> Mansoureh Jeihani <a href="https://orcid.org/0000-0001-8052-6931">https://orcid.org/0000-0001-8052-6931</a> Samira Ahangari <a href="https://orcid.org/0000-0002-4906-2005">https://orcid.org/0000-0002-4906-2005</a>		<b>8. Performing Organization Report No.</b>	
<b>9. Performing Organization Name and Address</b> Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061		<b>10. Work Unit No.</b>	
		<b>11. Contract or Grant No.</b> 69A43551747123	
<b>12. Sponsoring Agency Name and Address</b> US Department of Transportation Office of the Secretary-Research UTC Program, RDT-30 1200 New Jersey Ave., SE Washington, DC 20590		<b>13. Type of Report and Period Covered</b> Final October 2019 - September 2020	
		<b>14. Sponsoring Agency Code</b>	
<b>15. Supplementary Notes</b>			
<b>16. Abstract</b> This research develops an advanced Eco-Cooperative Adaptive Cruise Control System (Eco-CACC) for hybrid electric vehicles (HEVs) to pass signalized intersections with energy-optimized speed profiles, with the consideration of impacts by multiple signalized intersections. The research extends the Eco-CACC at signalized intersections (Eco-CACC-I) system previously developed by the research team for conventional internal combustion engine (ICE) vehicles to HEVs. In the proposed system, a simple HEV energy model is used to compute the instantaneous energy consumption level for HEVs. In addition, a vehicle dynamics model is used to capture the relationship between speed, acceleration level, and tractive/resistance forces on vehicles. The constraints of energy model and vehicle dynamics are used to develop two HEV Eco-CACC-I controllers for single-intersection and multiple-intersection, respectively. The developed HEV Eco-CACC-I controllers include two modes: automated and manual, for vehicles with or without an automated control system. The automated mode was implemented into the microscopic traffic simulation software so that connected and automated vehicles (CAVs) can directly follow the energy-optimized speed profile. Simulation tests using the INTEGRATION software validated the performances of the proposed controllers under the impact of signal timing, speed limit, and road grade. The simulation tests also demonstrated the improved benefits of using the proposed HEV Eco-CACC-I controllers in a traffic network with multiple intersections. Lastly, the manual model of the proposed HEV Eco-CACC controller was implemented in a driving simulator at Morgan State University so that drivers in connected vehicles (non-automated driving) can follow the recommended speed advisories. The data collected by the driving simulator with 48 participants demonstrated that the speed advisories calculated by the proposed controller can help drivers drive smoothly and save fuel while passing signalized intersections.			
<b>17. Key Words:</b> eco driving, Eco-Cooperative Adaptive Cruise Control, hybrid electric vehicles, multiple signalized intersection, driving simulator, microscopic traffic simulation.		<b>18. Distribution Statement</b>	
<b>19. Security Classif. (of this report) :</b> Unclassified	<b>20. Security Classif. (of this page)</b> Unclassified	<b>21. No. of Pages</b> 38	<b>22. Price</b>

# TABLE OF CONTENTS

Abstract.....	1
1. Introduction.....	2
2. Model Development.....	4
2.1 Develop HEV Eco-CACC-I for Single Intersection .....	4
2.2 Develop HEV Eco-CACC-I for Multiple Intersections .....	8
3. Simulation Tests.....	12
3.1 Sensitivity Analysis of HEV Eco-CACC-I Controller.....	12
3.2 Test HEV Eco-CACC-I Controller in INTEGRATION .....	19
3.3 Test HEV Eco-CACC-I MS Controller in INTEGRATION .....	22
4. Driving Simulator Tests .....	26
4.1 Participants and Designed Scenarios .....	26
4.2 Driving Performance.....	27
4.3 Data Collection .....	28
4.4 Data Analysis and Test Results.....	30
5. Conclusions.....	35
6. References.....	36

## LIST OF FIGURES

Figure 1: Vehicle optimum speed profile. ....	5
Figure 2: Vehicle equipped with HEV Eco-CACC controller passes two signalized intersections: (a) trajectories; (b) speed profiles. ....	10
Figure 3: Vehicle speed profile and energy consumption (fuel and electric power) under various speed limits on downhill roadway. ....	14
Figure 4: Vehicle speed profile and energy consumption (fuel and electric power) under various speed limits on uphill roadway. ....	15
Figure 5: Vehicle speed profile and energy consumption (fuel only) under various speed limits on downhill roadway. ....	17
Figure 6: Vehicle speed profile and energy consumption (fuel only) under various speed limits on uphill roadway. ....	18
Figure 7: Test in a traffic network with three signalized intersections. ....	19
Figure 8: Vehicle speed trajectories under 50% traffic demand (a) without HEV Eco-CACC-I; (b) with HEV Eco-CACC-I. ....	20
Figure 9: Average energy consumption per vehicle. ....	22
Figure 10: Average total delay per vehicle. ....	22
Figure 11: Test in a traffic network with two signalized intersections. ....	23
Figure 12: Comparison of vehicle speed trajectories: (a) basic case for HEVs; (b) Eco-CACC-I 1S for HEVs; (c) Eco-CACC-I MS for HEVs. ....	25
Figure 13: Test Eco-CACC-I controller for HEVs under various traffic demand levels. ....	26
Figure 14: Driving simulator. ....	29
Figure 15: Simulated study area. ....	30
Figure 16: Descriptive analysis of participants' socioeconomic characteristics. ....	31
Figure 17: Participants' attitude regarding usefulness and ease of speed guidance system. ....	32

## LIST OF TABLES

Table 1: Average performances for two test scenarios. ....	21
Table 2: Simulated scenarios. ....	27
Table 3: Descriptive and ANOVA results for speed guidance following behavior by different ESC scenarios.....	32
Table 4: ANOVA results for following speed guidance.....	33
Table 5: ANOVA results for fuel consumption. ....	34
Table 6: ANOVA analysis of fuel consumption by scenario.....	34

## **Abstract**

This research develops an advanced Eco-Cooperative Adaptive Cruise Control System (Eco-CACC) for hybrid electric vehicles (HEVs) to pass signalized intersections with energy-optimized speed profiles, with the consideration of impacts by multiple signalized intersections. The research extends the Eco-CACC at signalized intersections (Eco-CACC-I) system previously developed by the research team for conventional internal combustion engine (ICE) vehicles to HEVs. In the proposed system, a simple HEV energy model is used to compute the instantaneous energy consumption level for HEVs. In addition, a vehicle dynamics model is used to capture the relationship between speed, acceleration level, and tractive/resistance forces on vehicles. The constraints of energy model and vehicle dynamics are used to develop two HEV Eco-CACC-I controllers for single-intersection and multiple-intersection, respectively. The developed HEV Eco-CACC-I controllers include two modes: automated and manual, for vehicles with or without an automated control system. The automated mode was implemented into the microscopic traffic simulation software so that connected and automated vehicles (CAVs) can directly follow the energy-optimized speed profile. Simulation tests using the INTEGRATION software validated the performances of the proposed controllers under the impact of signal timing, speed limit, and road grade. The simulation tests also demonstrated the improved benefits of using the proposed HEV Eco-CACC-I controllers in a traffic network with multiple intersections. Lastly, the manual model of the proposed HEV Eco-CACC controller was implemented in a driving simulator at Morgan State University so that drivers in connected vehicles (non-automated driving) can follow the recommended speed advisories. The data collected by the driving simulator with 48 participants demonstrated that the speed advisories calculated by the proposed controller can help drivers drive smoothly and save fuel in the vicinity of signalized intersections.

## 1. Introduction

During the past decade, the rapid development of advanced communication technologies in connected vehicles ensure information can be quickly updated and shared between vehicles and transportation infrastructure facilities. Such technologies enable researchers to develop connected transportation systems to meet safety, economy, and efficiency challenges (USDOT, 2015). Studies have shown that vehicle acceleration/deceleration maneuvers and idling events near signalized intersections increase vehicle energy consumption and emission levels on arterial roads since vehicle are forced to stop ahead of traffic signals when encountering red indications, producing shock waves within the traffic stream (Barth & Boriboonsomsin, 2008; Rakha, Ahn, & Trani, 2003). Numerous studies using traditional methods have focused on changing traffic signal timing to optimize vehicle delay and fuel levels (Li, Li, Pang, Yang, & Tian, 2004; Stevanovic, Stevanovic, Zhang, & Batterman, 2009). In recent years, researchers have attempted to use connected vehicle and infrastructure technologies to develop eco-driving strategies to provide, in real-time, recommendations to drivers/vehicles so that vehicle maneuvers in the vicinity of signalized intersection can be optimized to improve mobility and reduce energy consumption and emission levels (Barth & Boriboonsomsin, 2009; Saboohi & Farzaneh, 2008, 2009).

The developed eco-driving strategies are mainly focused on internal combustion engine vehicles (ICEVs) since the car market is dominated by gasoline-powered vehicles. A cooperative adaptive cruise control system was proposed in (Malakorn & Park, 2010) using signal phase and timing (SPaT) information to minimize the absolute acceleration levels of vehicles and reduce vehicle fuel consumption levels. A dynamic programming-based fuel-optimization strategy was developed in (R. Kamalanathsharma & Rakha, 2014) using recursive path-finding principles, and the developed strategy was evaluated using an agent-based modeling approach. A schedule optimization algorithm was introduced in (Asadi & Vahidi, 2011) to allocate “green-windows” for vehicles to pass through a series of consecutive signalized intersections. This work was further extended in (Guan & Frey, 2013) to generate a brake-specific fuel consumption map that enables optimization of gear ratios using a dynamic programming algorithm.

With the rapid growth of battery electric vehicles (BEVs) on the market, a few studies have recently attempted to develop eco-driving systems to optimize the speed trajectory of BEVs to pass signalized intersections. For instance, an eco-driving technique for BEVs was developed in (Miyatake, Kuriyama, & Takeda, 2011) where the vehicle trajectory control problem was formulated as an optimization problem to minimize the summation of vehicle power. However, a simple energy model was used by assuming that the recharge efficiency is a constant value. Another BEV eco-driving algorithm was proposed in (Zhang & Yao, 2015), in which an energy consumption model based on the VT-Micro model was developed for different operation modes of BEVs, then an eco-driving model for a single signalized intersection was proposed using the developed energy model. However, the proposed energy consumption model was a statistical model based on limited collected data; thus, the accuracy may not be adequate for the purpose of developing an optimal control strategy for dynamic vehicle maneuvers. The same energy



consumption model was used in (Qi, Barth, Wu, Boriboonsomsin, & Wang, 2018) to develop a connected eco-driving system for BEVs. However, the case study used a 2012 Ford Escape with a hybrid engine to represent the performance of an actual BEV. Similar systems were developed in (Wu, He, Yu, Harmandayan, & Wang, 2015) and (De Nunzio, Wit, Moulin, & Di Domenico, 2016), but simplified energy consumption models were used without considering regenerative braking. The issues mentioned in these studies are considered in (Chen & Rakha, 2019; Chen & Rakha, 2020), and a robust BEV eco-driving system was developed by using (1) a realistic energy consumption model to accurately compute the real-time energy consumption level and regenerative braking using instantaneous vehicle speed; and (2) a vehicle dynamics model to constrain vehicle acceleration maneuvers. The simulation test demonstrated that this system produces average savings of 9.3% in energy consumption and 3.9% in vehicle delays.

Although the abovementioned studies considered ICEVs and BEVs to develop eco-driving strategies to pass signalized intersections, there is a gap in the research with regard to developing eco-driving strategies for hybrid electric vehicles (HEVs). First, the yearly sales of HEVs are the second only to ICEVs and are more than twice of the sales of BEVs and plug-in hybrid electric vehicles (PHEVs), according to the past 10 years of car sales data from the Bureau of Transportation Statistics in the United States (Statistics, 2019). Although BEVs are predicted to gain a significant market share in the future, HEVs will still be a larger or comparable portion of vehicles to BEVs over the next several years. Second, HEVs can dramatically increase fuel economy on city roads compared to ICEVs. The electric motor will work with the gasoline-powered engine in HEVs to reduce gasoline use or even allow the gasoline engine to turn off. Moreover, HEVs are fueled by gasoline (the same as ICEVs). In contrast, EVs can only be charged by plugging into an outlet or charging station and require a much longer time to recharge than a gasoline-powered vehicle needs to refuel. The limited number of electric charging stations may cause trouble to use BEVs for long trips. Considering these factors, there is an urgent need to develop eco-driving systems for HEVs.

Our previous studies in (Almanaa, Chen, Rakha, Loulizi, & El-Shawarby, 2019; Chen & Rakha, 2020; Chen, Rakha, Almanaa, Loulizi, & El-Shawarby, 2017) developed eco-driving systems called Eco-CACC-I for ICEVs and BEVs, which can assist drivers or automated vehicles to follow energy-optimized speed profiles to pass signalized intersections. In the developed Eco-CACC-I systems, the relationship of vehicle speed, maneuver, location, and signal phase and timing are formulated as an optimization problem to compute the energy-optimized speed profile. Here, a simple energy consumption model is needed to calculate each candidate speed profile's energy consumption level to find the optimal solution. Therefore, the HEV energy consumption model is a key component to developing the Eco-CACC-I algorithm for HEVs. However, HEVs are powered by both an ICE engine and an electric motor under three powertrain systems (hybrid, parallel hybrid, and series/parallels hybrid) with complicated energy management strategies; therefore, it is difficult to develop a general HEV energy consumption model that can be easily calibrated and used in the Eco-CACC-I system to compute energy consumption by using instantaneous speed data.

Recently, a few studies have investigated the modeling of HEV energy consumption. An HEV energy model was developed in (Boubaker, Rehim, & Kalboussi, 2013) by using engine speed (or RPM) and engine torque. However, the model requires MATLAB/Simulink software to estimate model variables due to the complexity and was not validated against real-world data. In addition, the National Renewable Energy Laboratory designed a well-known fuel estimation tool for HEVs called the Advanced Vehicle Simulator (ADVISOR) (Wipke, Cuddy, & Burch, 1999), but the input variables include vehicle features and drive cycle and it cannot be used for real-time application due to its complex modeling structure. Apparently, these HEV energy models cannot be used in our Eco-CACC-I system since additional input variables such as engine data are needed, but the Eco-CACC-I system is only provided with speed trajectory data.

This study considers the abovementioned problems to develop an Eco-CACC-I system for HEVs. In the proposed system, a simple HEV energy model developed in (Ahn & Rakha, 2019) is used to compute the instantaneous energy consumption level. This HEV energy model is selected since it is general, transferable, and can be easily used to compute instantaneous energy consumption levels for HEVs without the additional input of vehicle engine data or a complicated power control strategy. In addition, the vehicle dynamics model developed in (Fadhloun, Rakha, Loulizi, & Abdelkefi, 2015) is used to constraint the relationship between speed, acceleration level, and tractive/resistance forces on vehicles. In this way, the energy-optimum problem is formulated as an optimization problem with constraints and is solved using a moving-horizon dynamic programming approach. Two HEV Eco-CACC-I controllers for single-intersection and multi-intersections, are developed respectively. The developed HEV Eco-CACC-I controllers include two modes: automated and manual, for vehicles with or without an automated control system. The automated mode of the Eco-CACC system was implemented into the microscopic traffic simulation software so that connected and automated vehicles (CAVs) can directly follow the energy-optimized speed profile. The simulation tests using the INTEGRATION software validated the performances of the proposed controllers under the impact of signal timing, speed limit, and road grade. The simulation tests also demonstrated the improved benefits of using the proposed HEV Eco-CACC-I controllers in a traffic network with multiple intersections. Lastly, the manual model of the proposed HEV Eco-CACC controllers was implemented in a driving simulator at Morgan State University so that drivers in connected vehicles (non-automated driving) can follow the recommended speed advisories. The data collected by the driving simulator with 48 participants demonstrated that the speed advisories calculated by the proposed controller can help drivers to drive smoothly and save fuel in the vicinity of signalized intersections.

## **2. Model Development**

### **2.1 Develop HEV Eco-CACC-I for Single Intersection**

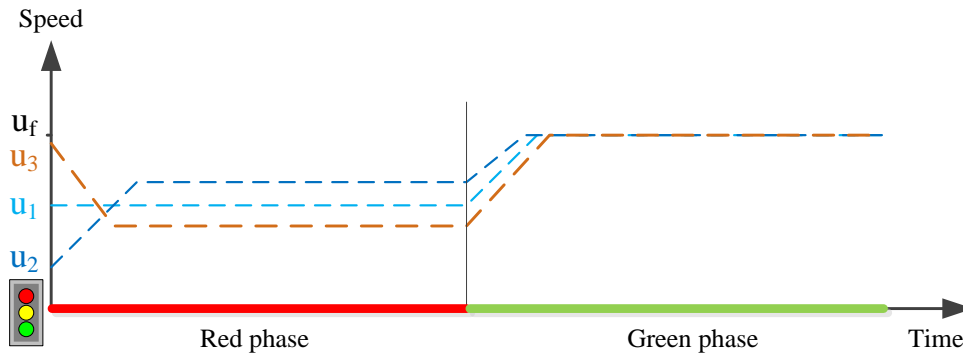
An Eco-CACC-I system for ICEVs was developed in our previous work in (Almanaa et al., 2019; Chen et al., 2017). The same control environment setup for ICE Eco-CACC-I is used here to develop Eco-CACC-I for HEVs. The control region is defined as vehicles follow the recommended speed by Eco-CACC-I from a distance upstream of the signalized intersection (defined as  $d_{up}$ ) to

a distance downstream of the intersection (defined as  $d_{down}$ ), as the HEV Eco-CACC-I controller optimizes speed profiles for vehicles approaching and leaving signalized intersections. Upon approaching a signalized intersection, the vehicle may accelerate, decelerate, or cruise (maintain a constant speed) based on a number of factors, such as vehicle speed, signal timing and phase, distance to the intersection, road grade, headway distance, etc. Within the control region, the vehicle's behavior can be categorized into one of two cases: (1) the vehicle can pass through the signalized intersection without decelerating; (2) the vehicle must decelerate to pass through the intersection. Given that vehicles drive in different manners for cases 1 and 2, the HEV Eco-CACC-I strategies are developed separately for the two cases.

Case 1 does not require the vehicle to decelerate to pass the signalized intersection. In this case, the cruise speed for the vehicle to approach the intersection during the red indication can be calculated by Equation (1) to maximize the average vehicle speed during the control region. When the vehicle enters the control region, it should adjust speed to  $u_c$  according to the vehicle dynamics model illustrated later in Equations (5) through (7). After the traffic light turns from red to green, the vehicle accelerates from the speed  $u_c$  to the maximum allowed speed (speed limit  $u_f$ ) by following the vehicle dynamics model until it leaves the control region.

$$u_c = \min\left(\frac{d_{up}}{t_r}, u_f\right) \quad (1)$$

The vehicle's energy-optimized speed profile for case 2 is illustrated in Figure 1. After entering the control region, the vehicle with the initial speed of  $u(t_0)$  needs to brake at a deceleration level denoted by  $a$ , then cruise at a constant speed of  $u_c$  to approach the signalized intersection. After passing the stop bar, the vehicle should increase speed to  $u_f$  per the vehicle dynamics model, and then cruise at  $u_f$  until the vehicle leaves the control region. In this case, the only unknown variables are the upstream deceleration rate  $a$  and the downstream throttle  $f_p$ . The following optimization problem is formulated to compute the optimum vehicle speed profile associated with the least energy consumption.



**Figure 1: Vehicle optimum speed profile.**

Assuming an HEV enters the Eco-CACC-I control region at time  $t_0$  and leaves the control region at time  $t_0 + T$ , the objective function entails minimizing the total energy consumption level as:

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

where  $EC$  denotes the HEV energy consumption at instant  $t$  using Equation (8). Note that the HEV energy consumption includes fuel consumption and energy consumption from electric power. Here, two options can be considered in the computation of HEV energy consumption by the Eco-CACC-I controller: (1) both fuel and electric power; and (2) only fuel consumption. For the first option, the fuel and electric power can be converted to British thermal units (BTUs) by using 1 kilowatt = 3,412 BTU and 1 milliliter = 31.79 BTU. The two options for calculating HEV energy consumption in the Eco-CACC-I controller will be tested and compared in the case study.

The constraints to solve the optimization problem can be built according to the relationships between vehicle speed, location, and acceleration/deceleration as presented below:

$$u(t): \begin{cases} u(t) = u(t_0) - at & t_0 \leq t \leq t_1 \\ u(t) = u_c & t_1 < t \leq t_r \\ u(t + \Delta t) = u(t) + \frac{F(f_p) - R(u(t))}{m} \Delta t & t_r < t \leq t_2 \\ u(t) = u_f & t_2 < t \leq t_0 + T \end{cases} \quad (3)$$

$$\begin{aligned} u(t_0) \cdot t - \frac{1}{2} at^2 + u_c(t_r - t_1) &= d_{up} \\ u_c &= u(t_0) - a(t_1 - t_0) \\ \int_{t_r}^{t_2} u(t) dt + u_f(t_0 + T - t_2) &= d_{down} \\ u(t_2) &= u_f \\ a_{min} &< a \leq a_{max} \\ f_{min} &\leq f_p \leq f_{max} \\ u_c &> 0 \end{aligned} \quad (4)$$

In Equation (3), function  $F$  denotes vehicle tractive force calculated by Equation (6); and function  $R$  represents all the resistance forces (aerodynamic, rolling, and grade resistance forces) calculated by Equation (7). Note that the maximum deceleration is limited by the comfortable threshold felt by average drivers. The throttle value ranges between 0 and 1. In order to solve the optimization problem, dynamic programming is used to list all the candidate solutions with the associated electric energy consumption levels. This allows calculation of optimal parameters for upstream deceleration  $a$  and downstream throttle  $f_p$  by finding the candidate solution associated with the

minimum energy consumption for a vehicle passing the control region. The detailed description of using dynamic programming in the Eco-CACC-I system can be found in (Chen & Rakha, 2020).

### *Vehicle Dynamics Model*

The proposed HEV Eco-CACC-I system uses a vehicle dynamics model to compute vehicle acceleration behavior. Here, the vehicle acceleration follows the vehicle dynamics model developed in (Yu, Yang, & Yamaguchi, 2015). 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 (R. K. Kamalanathsharma, 2014), a constant throttle level of 0.6 is assumed in the vehicle dynamics model to simplify the calculations in the Eco-CACC-I system for case 1. In case 2, the throttle level ranges between 0.1 and 1.0, and the optimum throttle level can be estimated by deriving the speed profile that results in the minimum energy consumption level. The vehicle dynamics model is summarized as

$$u(t + \Delta t) = u(t) + \frac{F(t) - R(t)}{m} \Delta t \quad (5)$$

$$F = \min \left( 3600 f_p \beta \eta_D \frac{P_{max}}{u}, m_{ta} g \mu \right) \quad (6)$$

$$R = \frac{\rho}{25.92} C_d C_h A_f u(t)^2 + mg \frac{c_{r0}}{1000} (c_{r1} u(t) + c_{r2}) + mgG \quad (7)$$

where  $F$  is the vehicle tractive effort;  $R$  represents the resultant resistance forces, including aerodynamic, rolling, and grade resistance forces;  $f_p$  is the driver throttle input [0, 1] (unitless);  $\beta$  is the gear reduction factor (unitless), and this factor is set to 1.0 for light-duty vehicles;  $\eta_D$  is the driveline efficiency (unitless);  $P_{max}$  is the maximum vehicle power (kW);  $m_{ta}$  is the mass of the vehicle on the tractive axle (kg);  $g$  is the gravitational acceleration (9.8067 m/s<sup>2</sup>);  $\mu$  is the coefficient of road adhesion (unitless);  $\rho$  is the air density at sea level and a temperature of 15 °C (1.2256 kg/m<sup>3</sup>);  $C_d$  is the vehicle drag coefficient (unitless), typically 0.30;  $C_h$  is the altitude correction factor (unitless);  $A_f$  is the vehicle frontal area (m<sup>2</sup>);  $c_{r0}$  is rolling resistance constant (unitless);  $c_{r1}$  is the rolling resistance constant (h/km);  $c_{r2}$  is the rolling resistance constant (unitless);  $m$  is the total vehicle mass (kg); and  $G$  is the roadway grade at instant time  $t$  (unitless).

### *Energy Consumption Model for HEVs*

An HEV energy consumption model developed in (Ahn & Rakha, 2019) is used in the proposed HEV Eco-CACC-I system to compute instantaneous energy consumption levels for HEVs. The model is selected here for three main reasons: (1) speed is the only required input variable for this model, so it is easy to use to solve the proposed optimization problem; (2) the model has been validated and has demonstrated its ability to produce good accuracy compared to empirical data;

and (3) the model can be easily calibrated to a specific vehicle using the Environmental Protection Agency combined fuel economy data. The empirical energy data was analyzed and the following HEV energy consumption behaviors were found to develop the HEV energy model. First, the amount of fuel consumed is proportionally related to both vehicle power and speed; second, the HEV operates in electric vehicle (EV) mode when the power is less than 0; third, the HEV utilizes only electric power when the speed is lower than an EV mode speed ( $v_a$ ) and the required power is lower than a specific power ( $P_a$ ); and fourth, the HEV utilizes an EV mode if the test vehicle operates at a constant speed and the speed is lower than a specific speed ( $v_b$ ). Consequently, the HEV energy consumption model is formulated as below.

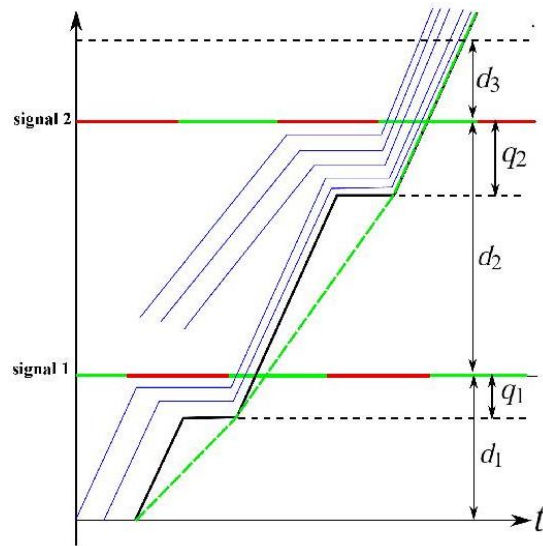
$$EC(t) = \begin{cases} Energy_{EV\_mode} & \text{for } \begin{cases} P \leq 0 \\ v < v_a \text{ and } P < P_a \\ v \text{ is constant and } v < v_b \end{cases} \\ a + b * v(t) + c * P(t) + d * P(t)^2 & \text{for } \begin{cases} P > 0 \text{ and } v \geq v_a \\ v < v_a \text{ and } P \geq P_a \\ v \text{ is not constant or } v \geq v_b \end{cases} \end{cases} \quad (8)$$

where  $Energy_{EV\_mode}$  is the energy consumption rate in EV mode and estimated by the Virginia Tech Comprehensive Power-based Electric Vehicle Energy Consumption Model (VT-CPEM) developed in (Fiori, Ahn, & Rakha, 2016);  $P(t)$  is the instantaneous total power in kilowatts (kW); and  $v$  is the instantaneous vehicle speed in kilometers per hour or miles per hour. Statistical analysis of the empirical data found that the optimum values for  $v_a$ ,  $v_b$ , and  $P_a$  are 32 km/h, 72 km/h, and 10 kW, respectively. The model coefficients  $a$ ,  $b$ ,  $c$ , and  $d$  for the 2010 Toyota Prius are 0.006, 0.003998, 0.077092, and -9.155E-05, respectively. The details of how to compute these coefficients can be found in (Ahn & Rakha, 2019). The coefficients for the 2010 Toyota Prius are used in the case study to compute energy consumption.

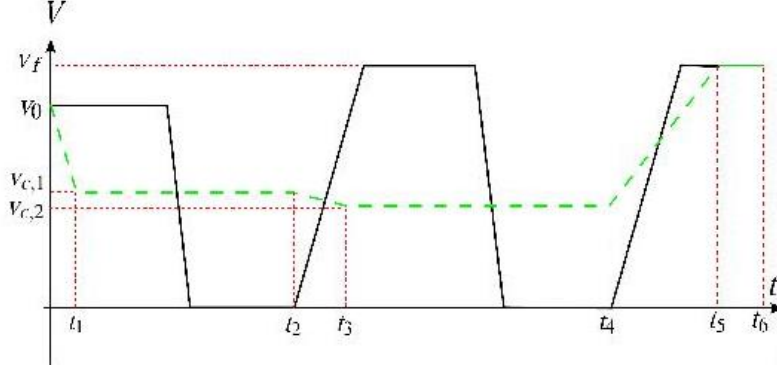
## 2.2 Develop HEV Eco-CACC-I for Multiple Intersections

The previously developed HEV Eco-CACC-I controller only considers the impact of a single signalized intersection to calculate the energy-optimized speed trajectory. However, the speed trajectory may not work effectively in minimizing energy consumption for multiple intersections. A previous study in (Yang, Almutairi, & Rakha, 2017) (Yang et al., 2019) demonstrated the importance of considering the impact of multiple intersections in computing a fuel-optimum speed profile for ICEVs. Therefore, we extended the HEV Eco-CACC-I controller to multiple signalized intersections, called HEV Eco-CACC-I MS. In addition, the previous work on ICEV and HEV Eco-CACC-I MS controllers was coded using the Layhey Fortran compiler. Recently, the team improved the INTEGRATION software by solving many bugs and improving computation efficiency by using the GFortran compiler. Therefore, the team coded the Eco-CACC-I MS controller for ICEVs, BEVs, and HEVs into the latest version of INTERGATION using GFortran.

Figure 2(a) presents the trajectories of vehicles passing two consecutive signalized intersections. The solid black line represents the trajectory of one vehicle experiencing two red lights without control (assuming that the vehicle has infinite acceleration/deceleration rates). The vehicle is stopped ahead of both intersections by the red lights and the vehicle queues. After using the Eco-CACC-I multiple signalized intersection (Eco-CACC-I MS) controller, the vehicle cruises to each intersection with a constant speed (represented by the dashed green line in Figure 2[a]). However, the assumption that the acceleration and deceleration rates of the equipped vehicle are infinite is not realistic. Figure 2(b) compares the speed profiles of the vehicle with (green line) and without (black line) the Eco-CACC-I MS controller considering both the duration of acceleration and deceleration. Without using the controller, the vehicle has to stop completely at the first intersection. Between the two intersections, the vehicle first accelerates to the speed limit and then decelerates to 0 again. The stop-and-go behaviors and the long idling time waste a great deal of energy. However, the vehicle using the Eco-CACC-I MS controller decelerates to a speed  $v_{c,1}$ , and then cruises to the first intersection. Between the two intersections, it decelerates or accelerates from  $v_{c,1}$  to  $v_{c,2}$ , and then cruises to the second intersection. Here,  $v_{c,1}$  and  $v_{c,2}$  are the cruise speeds to the first and second intersection, respectively. Once the queue at the second intersection is released, the vehicle accelerates to the speed limit. Compared to the base case without using the controller, both the vehicle trajectory and the speed profile with Eco-CACC-I MS are much smoother.



(a)



(b)

**Figure 2: Vehicle equipped with HEV Eco-CACC controller passes two signalized intersections: (a) trajectories; (b) speed profiles.**

The objective of developing the Eco-CACC-I MS controller is to minimize the vehicle energy consumption in the vicinity of the two intersections. In addition to the shape of the vehicle speed shown in Figure 2(b), the algorithm determines the optimum upstream acceleration and deceleration levels of the controlled speed profile. The mathematical formulation of the controller can be cast as

$$\min \int_{t_0}^{t_6} EC(v(t)) \cdot dt \quad (9)$$

s.t.

$$v(a_1, a_2, a_3) = \begin{cases} v_0 + a_1 t & 0 < t \leq t_1 \\ v_{c,1} & t_1 < t \leq t_2 \\ v_{c,1} + a_2(t - t_2) & t_2 < t \leq t_3 \\ v_{c,2} & t_3 < t \leq t_4 \\ v_{c,2} + a_3(t - t_4) & t_4 < t \leq t_5 \\ v_f & t_5 < t \leq t_6 \end{cases} \quad (10)$$

$$v_{c,1} = v_0 + a_1 \cdot t_1 \quad (11)$$

$$v_0 \cdot t_1 + \frac{1}{2} a_1 t_1^2 + v_{c,1} (t_2 - t_1) = d_1 - q_1 \quad (12)$$

$$t_2 = t_{g,1} + \frac{q_1}{w_1} \quad (13)$$

$$v_{c,2} = v_{c,1} + a_2 \cdot (t_3 - t_2) \quad (14)$$

$$v_{c,1}(t_3 - t_2) + \frac{1}{2} a_2 (t_3 - t_2)^2 + v_{c,2} (t_4 - t_3) = d_2 + q_1 - q_2 \quad (15)$$

$$t_4 = t_{g,2} + \frac{q_2}{w_2} \quad (16)$$



$$v_{c,2} + a_3 (t_5 - t_4) = v_f \quad (17)$$

$$v_{c,2}(t_5 - t_4) + \frac{1}{2} a_3 (t_5 - t_4)^2 + v_f (t_6 - t_5) = d_3 + q_2 \quad (18)$$

$$a_-^s \leq a_1 \leq a_+^s \quad (19)$$

$$a_-^s \leq a_2 \leq a_+^s \quad (20)$$

$$0 \leq a_3 \leq a_+^s \quad (21)$$

where

- $EC(v(t))$ : the vehicle energy consumption rate at any instant  $t$  computed using the HEV energy consumption model developed by the research team;
- $v(t)$ : the advisory speed limit for the equipped vehicle at time  $t$ ;
- $a_k$ : the acceleration/deceleration rates for the advisory speed limit,  $k=1,2,3$ ;
- $v_0$ : the speed of the vehicle when it enters the upstream control segment of the first intersection;
- $v_f$ : the road speed limit;
- $d_1$ : the length of the upstream control segment of the first intersection;
- $d_2$ : the distance between the two intersections;
- $d_3$ : the length of the downstream control segment of the second intersection;
- $t_{g,1}$ : the time instant that the indicator of the first signal turns to green;
- $t_{g,2}$ : the time instant that the indicator of the second signal turns to green;
- $t_k$ : the time instant defined in Figure 2(b);
- $v_{c,1}$ : the cruise speed to approach the first intersection;
- $v_{c,2}$ : the cruise speed to approach the second intersection;
- $q_1$ : the queue length at the first immediate downstream intersection;
- $q_2$ : the queue length at the second immediate downstream intersection;
- $w_1$ : the queue dispersion speed at the first immediate downstream intersection;
- $w_2$ : the queue dispersion speed at the second immediate downstream intersection;
- $a_-^s$ : the saturation deceleration level;
- $a_+^s$ : the saturation acceleration level.

Equation (9) demonstrates that given the traffic state, including queue lengths, the start and end times of the indicators of the two intersections, and the approaching speed of the controlled vehicles, the speed profile varies as a function of the acceleration/deceleration levels ( $a_1, a_2, a_3$ ). Equations (10~12) define that the equipped vehicle decelerates to  $v_{c,1}$  and passes the first intersection just when the queue is released. Equations (13~15) determine that the vehicle passes the second intersection when the queue is released. Equations (16~17) show how the vehicle recovers its speed back up to the speed limit. The Eco-CACC-I MS controller searches for the three acceleration levels to minimize the energy consumption of the controlled vehicle over the

entire control section. Note that, in the proposed controller, we only look ahead at two downstream intersections at a time.

### 3. Simulation Tests

Three case studies are included in this section. The first case study aims to test the proposed HEV Eco-CACC-I algorithm to investigate the impact of signal timing, speed limit, and road grade on the optimal solution. In the second case study, the proposed HEV controller was implemented into microscopic traffic simulation software and tested on an arterial corridor with three signalized intersections to validate its networkwide performance. In the third test, the proposed HEV Eco-CACC-I controller for multiple intersections was tested in the INTEGRATION simulation software.

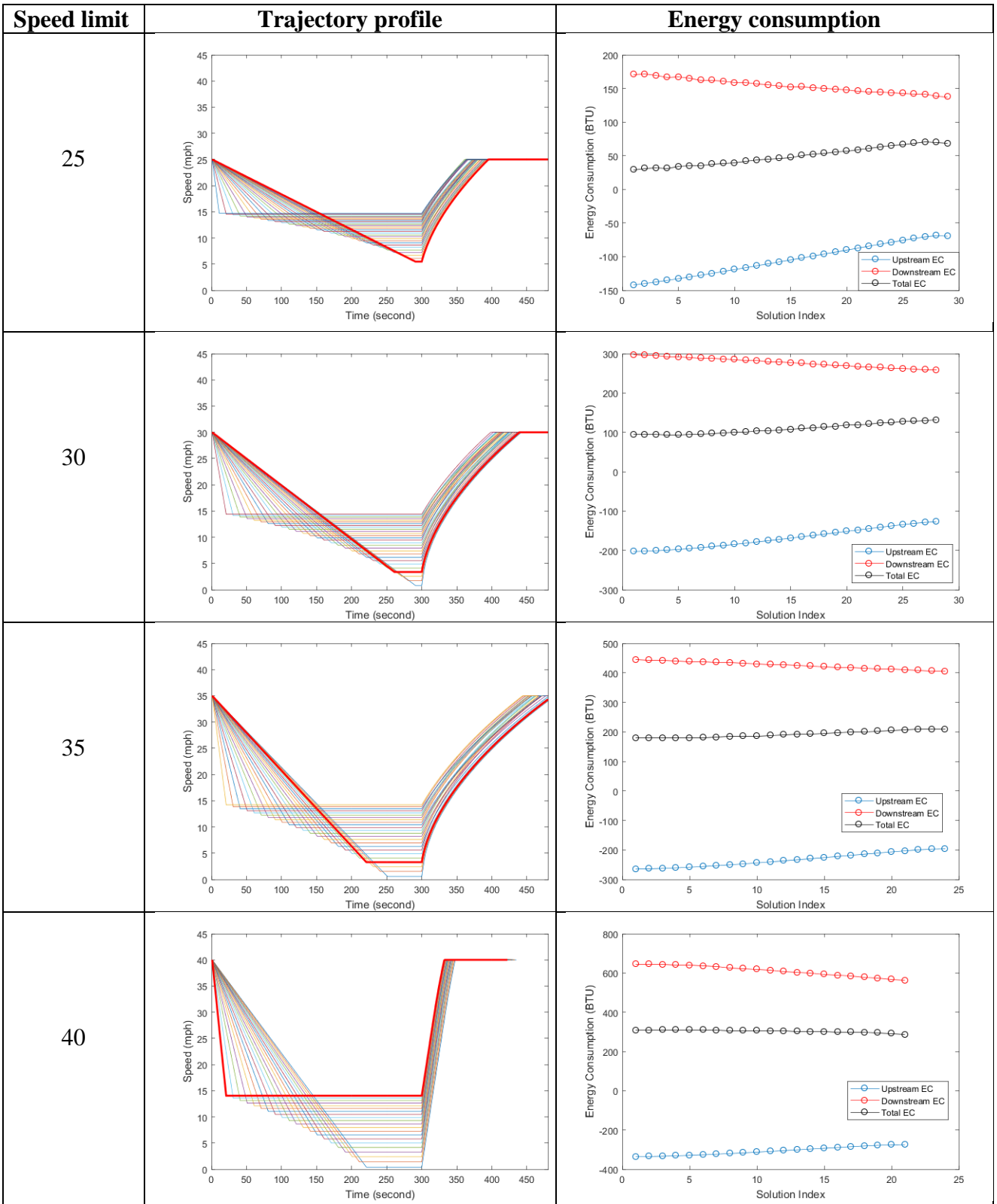
#### 3.1 Sensitivity Analysis of HEV Eco-CACC-I Controller

The test road consists of a single signalized intersection with a control length starting 200 meters upstream and ending 200 meters downstream of the intersection (total length of 400 meters). The automated connected vehicle equipped with the HEV Eco-CACC system is assumed to completely follow the optimal speed profile calculated by the HEV Eco-CACC algorithm within the controlled 400-meter distance. The combinations of speed limit (25, 30, 35, 40 mph), red indication (15, 20, 25, 30 seconds), and road grade (3% and -3%) are tested. Note that there are two options for calculating energy consumption in the proposed HEV Eco-CACC-I controller: considering both fuel and electric power energy consumption or only fuel consumption. These two options are tested and compared in the case study. Given that the test results under different red indication values are very similar, we only present the test results for 30 seconds of red indication.

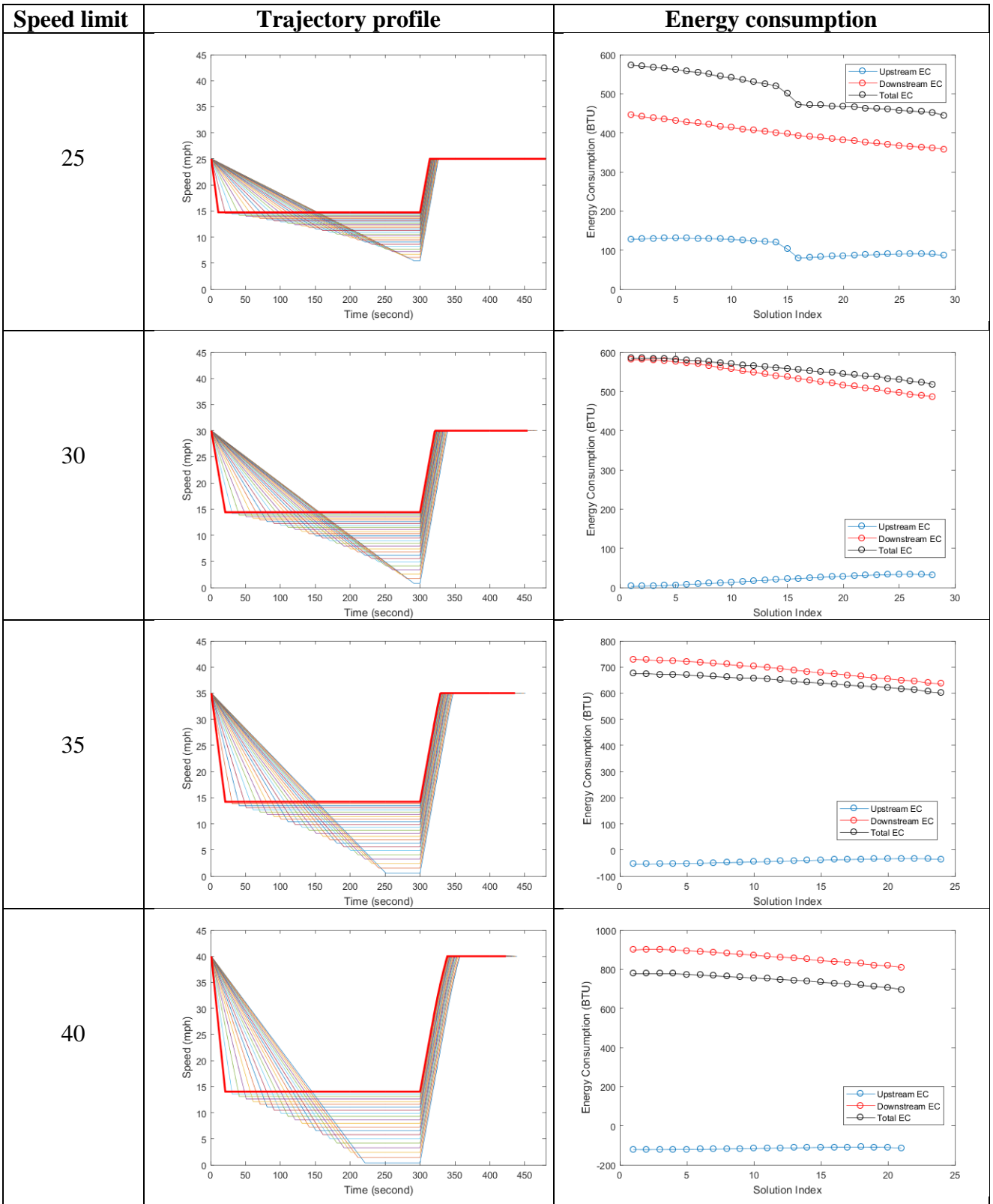
Figure 3 shows the test results for 30 seconds of red indication under different speed limits on a downhill roadway, and both fuel and electric power are considered to compute energy consumption in the objective function of the Eco-CACC-I controller. Each plot in the left column presents the sampling of numerous feasible solutions (trajectory profile) for each combination of parameters. For instance, the left bottom image in Figure 3 includes 21 curves; each curve represents a feasible solution of a vehicle trajectory profile when a vehicle traverses the intersection with a certain deceleration level ( $a_i$ ) upstream of the intersection. The throttle level downstream of the intersection is the optimal throttle corresponding to the minimal energy consumption given the upstream deceleration level of  $a_i$ . Each feasible solution is plotted in a different color, and the optimal solution, which corresponds to the minimal energy consumption, is highlighted in a bold red. Each plot in the right column illustrates the energy consumption of each feasible solution for an upstream roadway, downstream roadway, and the entire trip. The left column plots indicate that the speed limit can affect the optimal solution of HEV Eco-CACC-I on a downhill roadway. The trajectory profile associated with the minimum deceleration level is the optimal solution for the speed limit of 25 mph, but the trajectory profile associated with the maximum deceleration level is the optimal solution for the speed limit of 40 mph. This can be explained by the fact that the regenerative electric power for each feasible solution varies a lot

under low speed limits in the energy consumption plots. But the regenerative electric power for each feasible solution is very similar under higher speed limits.

Figure 4 shows the test results for 30 seconds of red indication under different speed limits on an uphill roadway. Different from the trends on a downhill roadway, the trajectory profile associated with the maximum deceleration level or longest cruise time is the optimal solution under all speed limits. This is due to the fact that the energy consumption for each feasible solution by driving on the roadway upstream of the intersection is very similar, so the maximum deceleration level can result in passing the signalized intersection with the maximum cruise speed to save downstream energy consumption.



**Figure 3: Vehicle speed profile and energy consumption (fuel and electric power) under various speed limits on downhill roadway.**

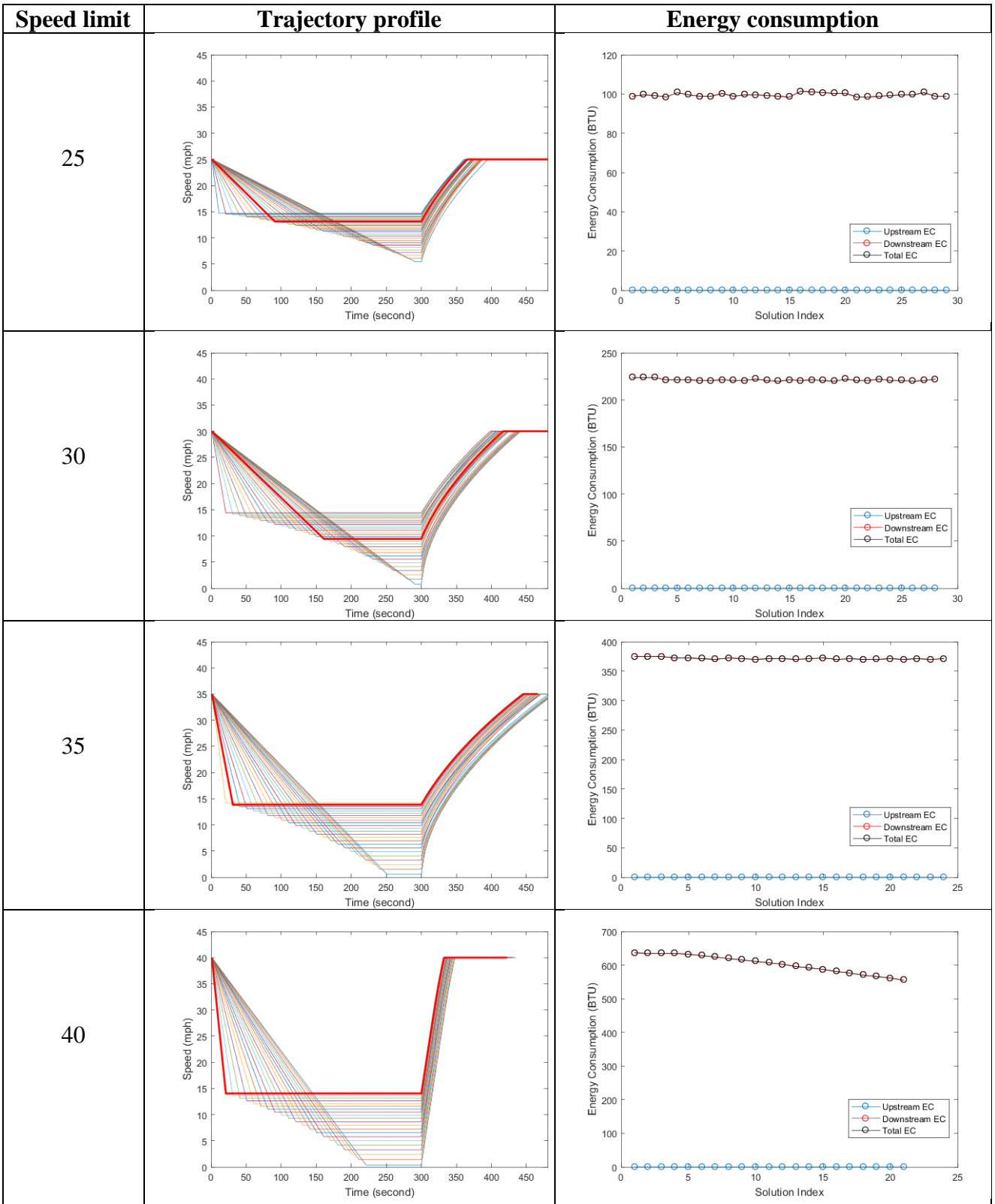


**Figure 4: Vehicle speed profile and energy consumption (fuel and electric power) under various speed limits on uphill roadway.**

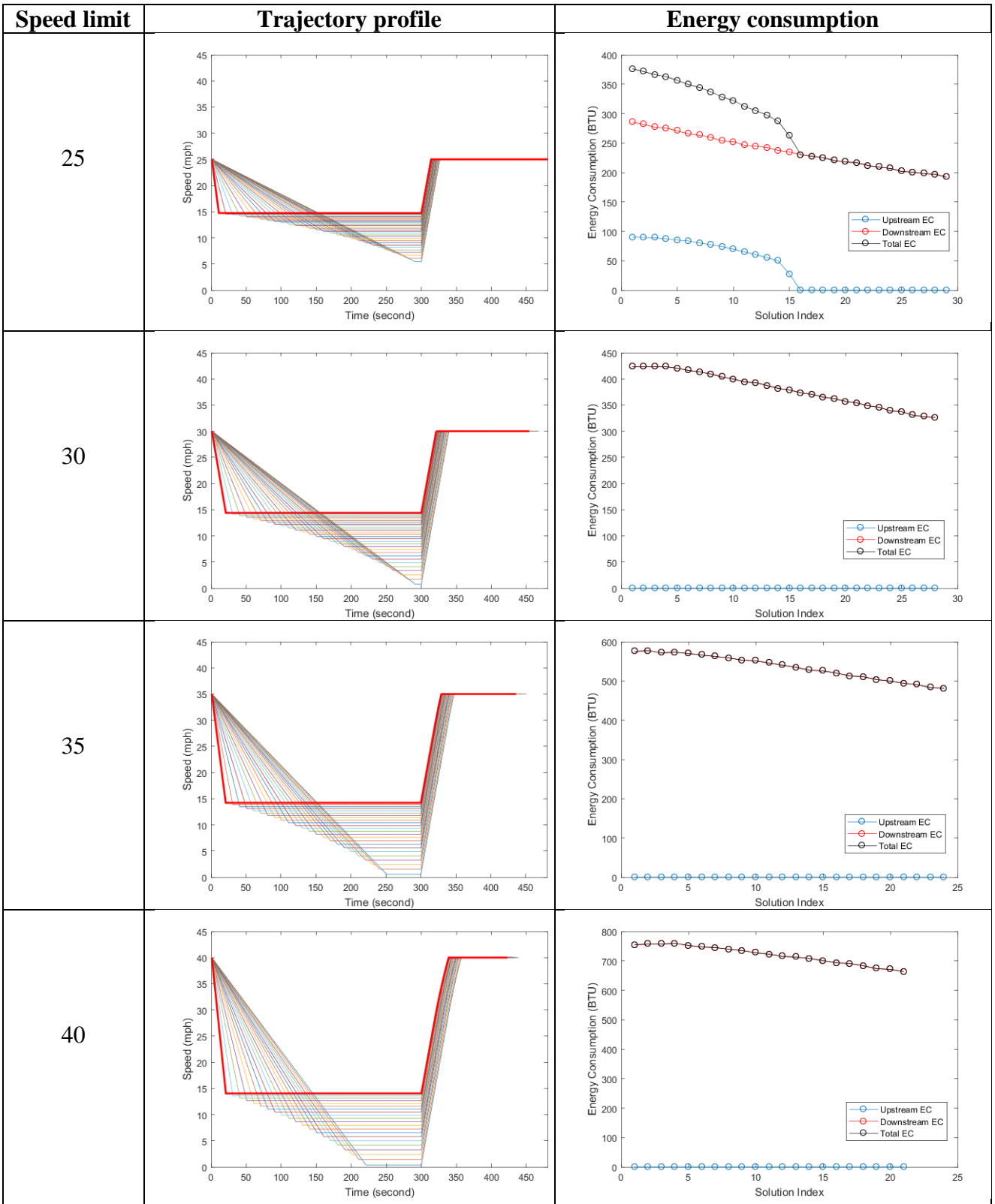
Figure 5 shows the test results for 30 seconds of red indication under different speed limits on downhill roadway, and only fuel is considered to compute energy consumption in the objective function of the Eco-CACC-I controller. The optimal solutions in this figure are different from the results in Figure 2, where both fuel and electric power are considered to compute energy consumption. The trajectory profile associated with the middle level of deceleration is the optimal solution for the speed limit of 25 mph, but the trajectory profile associated with the maximum deceleration level is the optimal solution for the speed limit of 40 mph. The energy consumption plots indicate that the energy consumption for each feasible solution by driving on the roadway upstream of the intersection is zero. When an HEV drives at a speed higher than the threshold to use electric power under a high speed limit, then the maximum deceleration level on the upstream roadway can result in passing the signalized intersection with the maximum cruise speed to save downstream fuel consumption. But the HEV may use electric power under a low speed limit, which affects the optimal solution so that the middle level of deceleration is used on the upstream roadway.

Figure 6 shows the test results for 30 seconds of red indication under different speed limits on uphill roadway, and only fuel is considered to compute energy consumption in the objective function of the Eco-CACC-I controller. The optimal solutions in this figure for various speed limits always use the maximum deceleration level on the upstream roadway, which are the same as the results in Figure 3 where both fuel and electric power are considered to compute energy consumption. This is due to the fact that the fuel consumption is greatly increased for the uphill roadway, which offsets the impact of using electric power under low speed limits. Hence, the maximum deceleration level on the upstream roadway can result in passing the signalized intersection with the maximum cruise speed to save downstream fuel consumption.

The test results indicate that the optimal solutions for the HEV Eco-CACC-I controller are impacted by different speed limits, red indication values, roadway grades, and the energy consumption calculation. When HEVs drive on downhill roadway, and both fuel and electric power are considered to compute energy consumption in the objective function of the HEV Eco-CACC-I controller, the trajectory profile associated with the minimum deceleration level is the optimal solution for the speed limit of 25 mph, but the trajectory profile associated with the maximum deceleration level is the optimal solution for the speed limit of 40 mph. When HEVs drive on a downhill roadway, and only fuel is considered to compute energy consumption in the objective function of the HEV Eco-CACC-I controller, the trajectory profile associated with the middle level of deceleration level is the optimal solution for the speed limit of 25 mph, but the trajectory profile associated with the maximum deceleration level is the optimal solution for the speed limit of 40 mph. When HEVs drive on an uphill roadway, the trajectory profile associated with the maximum deceleration level or longest cruise time is the optimal solution under all speed limits.



**Figure 5: Vehicle speed profile and energy consumption (fuel only) under various speed limits on downhill roadway.**



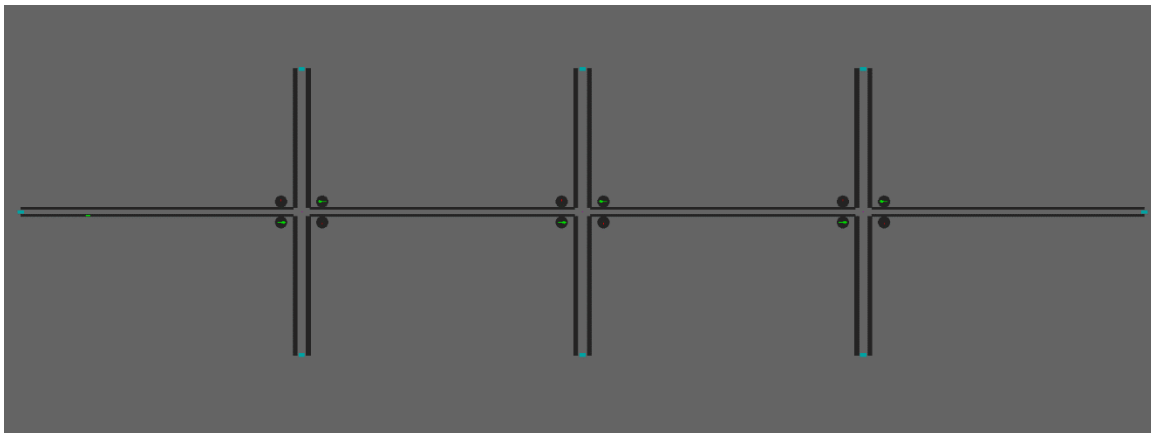
**Figure 6: Vehicle speed profile and energy consumption (fuel only) under various speed limits on uphill roadway.**



### 3.2 Test HEV Eco-CACC-I Controller in INTEGRATION

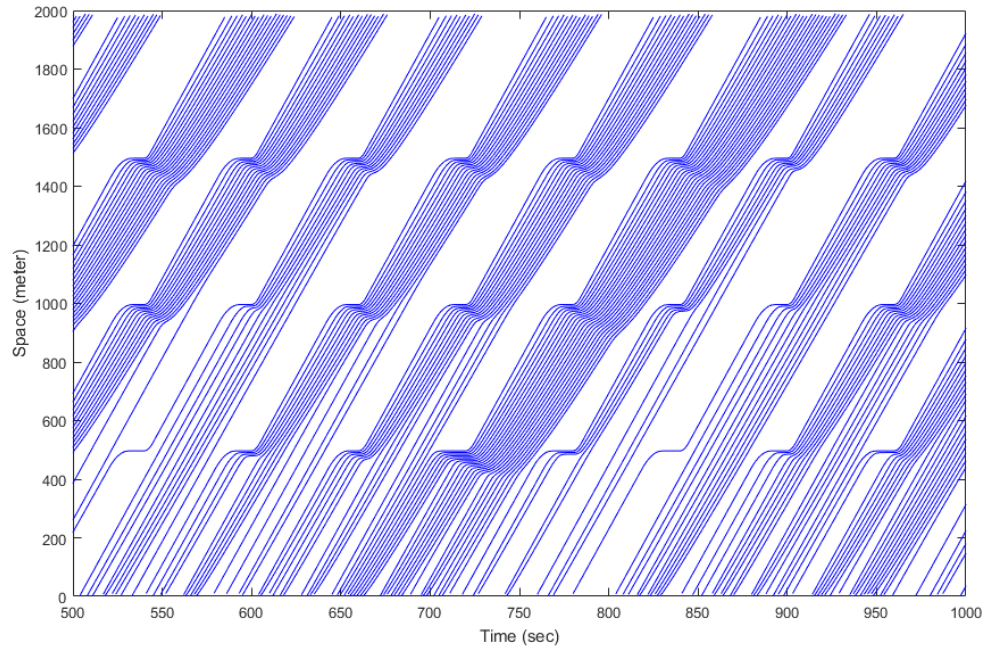
This test aims to evaluate the system performance of using the HEV Eco-CACC-I controller in microscopic traffic simulation software. The HEV Eco-CACC-I controller was implemented into the INTEGRATION simulation software to evaluate the networkwide performance. Given that the controller was developed by considering a single signalized intersection, each controller works independently for each signalized intersection. The INTEGRATION software is a trip-based, microscopic traffic assignment, simulation, and optimization model that has the capability of modeling networks of up to 3,000,000 vehicle departures. A more-detailed description of INTEGRATION is provided in the literature (Aerde & Rakha, 2007a, 2007b). Note that the HEV energy consumption model in INTEGRATION only computes the fuel consumption data, so electric or battery power is not considered in this case study.

A simulated traffic network with three signalized intersections as shown in Figure 7 is used in this test. All the vehicles in the simulation network are the 2010 Toyota Prius. The traffic stream parameters on the major road include a free-flow speed of 40 mph, a speed at capacity of 30 mph, a saturation flow rate of 1,600 veh/h/lane, and a jam density of 160 veh/km/lane. The three traffic signals (500 meters apart) have the same signal timing plan with a 60-second cycle length, 42-second phase length for the main street with 5 seconds of yellow or all-red time for phase transition. The signal offsets are set to be 0 seconds. Two scenarios are considered in the test: scenario 1 without the HEV Eco-CACC-I controller and scenario 2 with the HEV Eco-CACC-I controller. For each scenario, various traffic demand levels (25%, 50%, and 75% demand) on the main street are tested. The flow rate of 1,600 veh/h/lane is defined here as 100% demand.

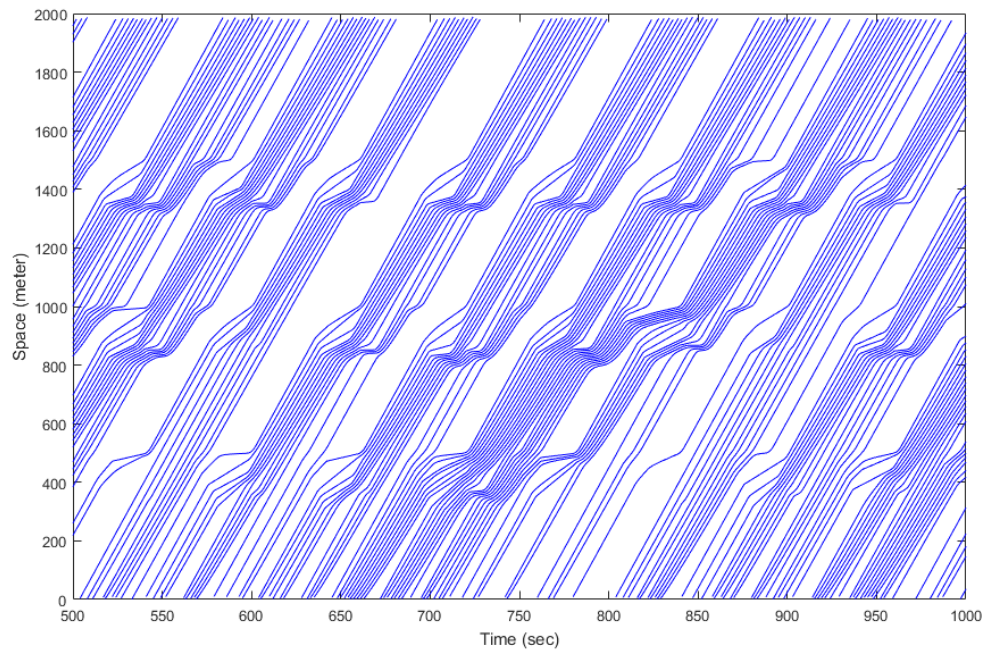


**Figure 7: Test in a traffic network with three signalized intersections.**

Figure 8 presents some vehicle trajectories in two scenarios under a 50% traffic demand load on the major street. Vehicles in the no HEV Eco-CACC-I controller scenario (scenario 1) experienced full stops, as demonstrated in Figure 8(a). By activating the HEV Eco-CACC-I (scenario 2), vehicles followed smooth trajectories to pass the signalized intersections, as shown in Figure 8(b). Comparing the two scenarios, less energy was consumed by each vehicle in scenario 2 due to smoother vehicle trajectories and fewer full stops.



(a)



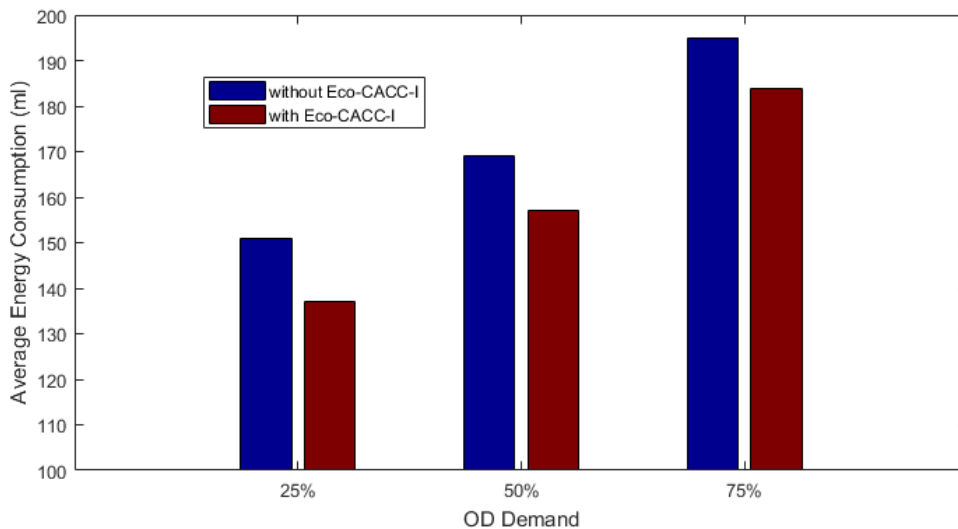
(b)

**Figure 8: Vehicle speed trajectories under 50% traffic demand (a) without HEV Eco-CACC-I; (b) with HEV Eco-CACC-I.**

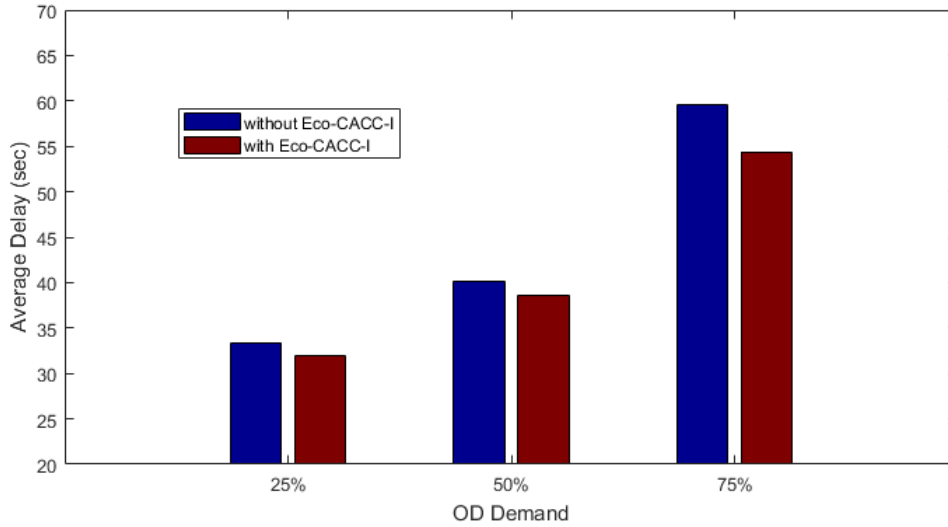
The average performances for each vehicle under various traffic demands and the two scenarios are summarized in Table 1. The test results demonstrate that the HEV Eco-CACC-I controller can efficiently reduce the energy consumption of each vehicle in the traffic network. The average energy reductions are 9.5% for 20% traffic demand, 6.9% for 50% traffic demand, and 5.8% for 75% traffic demand. This shows that the proposed HEV Eco-CACC-I controller works better under light traffic loads, since the impacts of intersection queues and multiple intersections are not considered yet. Savings in traffic delay are a side benefit of using the HEV Eco-CACC-I controller since it helps vehicles to drive smoothly. The reductions in total delay for each vehicle under traffic demands of 25%, 50%, and 75% are 4.6%, 4.1%, and 8.8%, respectively. After combining all the results under different origin-destination (OD) demand levels, the average savings for energy consumption, traffic delay, and vehicle stops are 7.4%, 5.8%, and 23%, respectively. The bar plot in Figure 9 shows the average fuel consumption per vehicle for the two scenarios under various traffic demands. Figure 10 presents the average delay per vehicle for the two scenarios under various traffic demands. The results clearly demonstrate the benefits of using HEV Eco-CACC-I in terms of energy consumption and traffic delay.

**Table 1: Average performances for two test scenarios.**

OD Demand	Test Scenario	Average Energy Consumption (ml)	Average Total Delay (s)	Average Vehicle Stops
25% Demand	Without Eco-CACC-I	151	33.4	1.79
	With Eco-CACC-I	137	31.9	1.32
	Reduction	9.5%	4.6%	26%
50% Demand	Without Eco-CACC-I	169	40.2	2.01
	With Eco-CACC-I	157	38.6	1.59
	Reduction	6.9%	4.1%	21%
75% Demand	Without Eco-CACC-I	195	59.6	2.33
	With Eco-CACC-I	184	54.4	1.82
	Reduction	5.8%	8.8%	22%



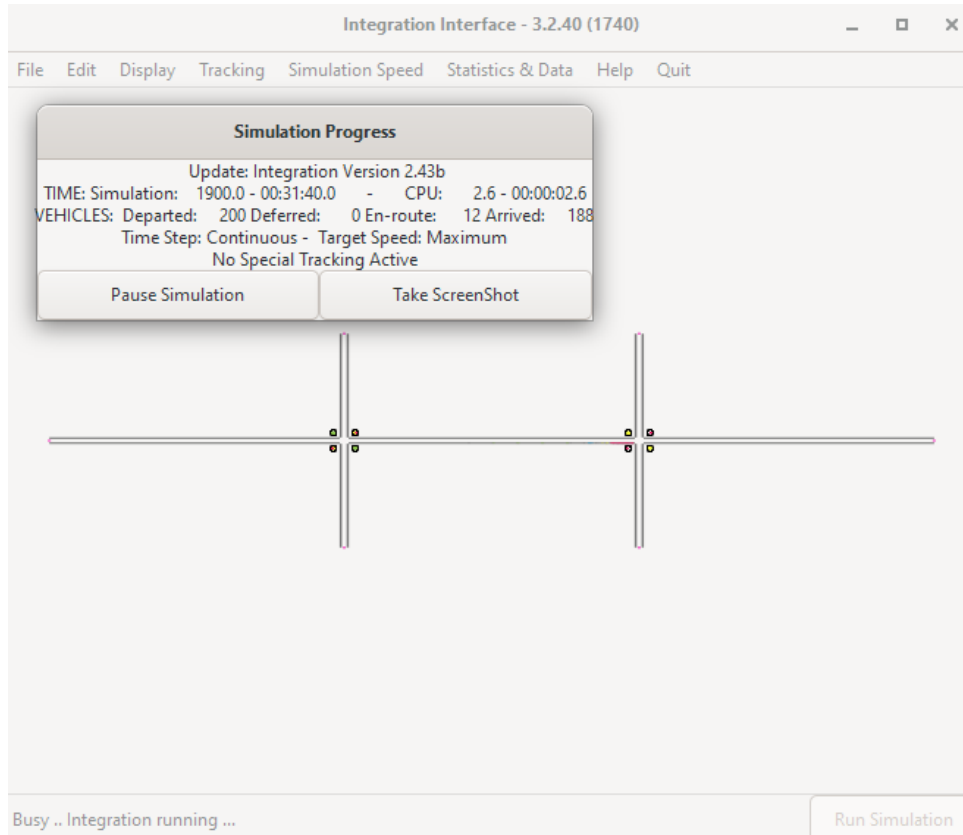
**Figure 9: Average energy consumption per vehicle.**



**Figure 10: Average total delay per vehicle.**

### 3.3 Test HEV Eco-CACC-I MS Controller in INTEGRATION

This test evaluates the system performance of using Eco-CACC-I MS controller in the INTEGRATION software. A simulated traffic network with two signalized intersections, as shown in Figure 11, is used in this test. The traffic stream parameters on the major road are a free-flow speed of 80 km/h, a speed at capacity of 60 km/h, a saturation flow rate of 1,600 veh/h/lane, and a jam density of 150 veh/km/lane. The two signals are 1,000 meters apart. The cycle lengths of both signals are 120 seconds, and the durations of the green, yellow, and all-red indicators of the through traffic are all 61, 4, and 2 seconds, respectively. The offset of the second signal with respect to the first one is 100 seconds, since a 100-second offset gives a high probability for us to observe two stops for one equipped vehicle. Various traffic demand levels (100, 200, 400, and 800 veh/h/lane) below the saturated flow are used during the test.



**Figure 11: Test in a traffic network with two signalized intersections.**

All HEVs are assumed in the simulation environment to validate the system performance under the following three scenarios.

*Scenario 1: Basic case for HEVs*

No Eco-CACC controller is activated in the system. Each HEV only follows the normal traffic rules (such as vehicle dynamics model, car following model, collision avoidance) to pass the signalized intersection.

*Scenario 2: HEV Eco-CACC-I for single signalized intersection (HEV Eco-CACC-I IS)*

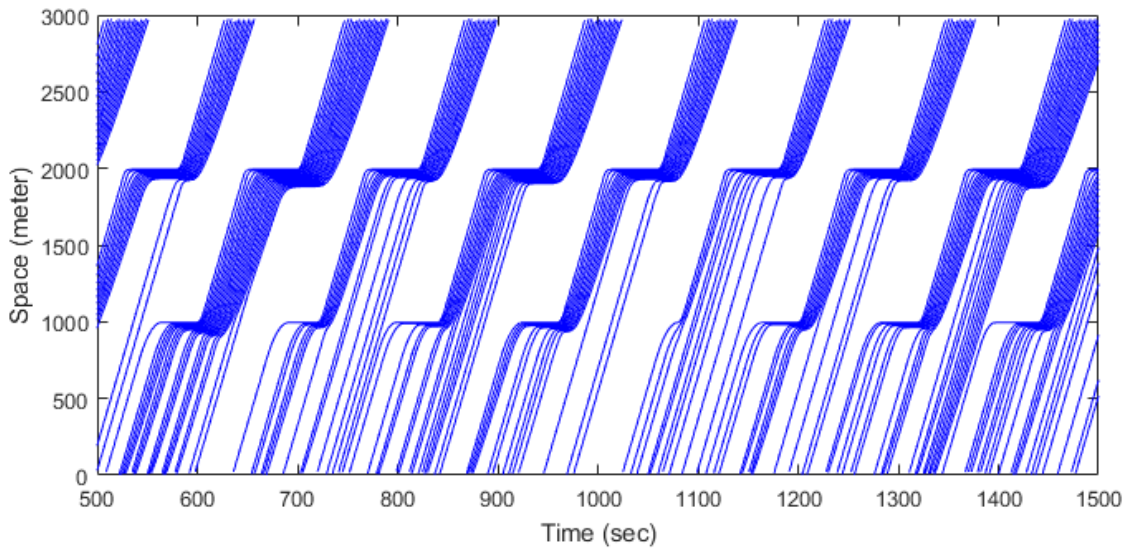
The HEV Eco-CACC-I controller we previously developed for a single signalized intersection is activated in the system when a vehicle is within a 200-meter range (both upstream and downstream) of each signalized intersection.

*Scenario 3: HEV Eco-CACC-I MS*

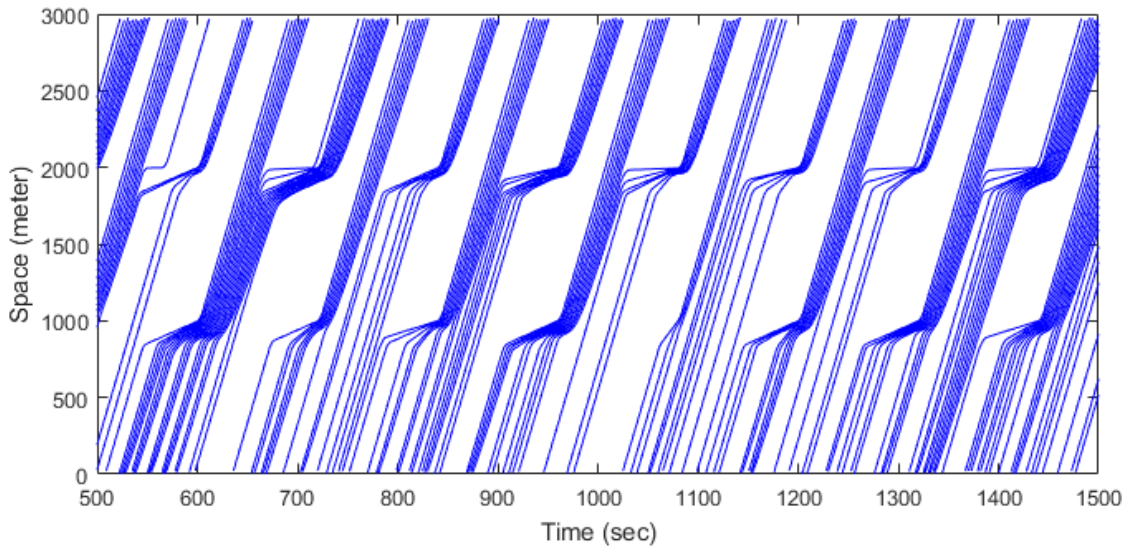
The HEV Eco-CACC-I MS controller is activated in the system when a vehicle arrives 200 meters upstream of the first signalized intersection, and the controller is deactivated when a vehicle arrives 200 meters downstream of the second signalized intersection.

The test results for the three scenarios under a traffic demand of 400 veh/h/lane are demonstrated in Figure 12. Figure 12(a) presents the speed trajectories in the basic case for HEVs. We can see

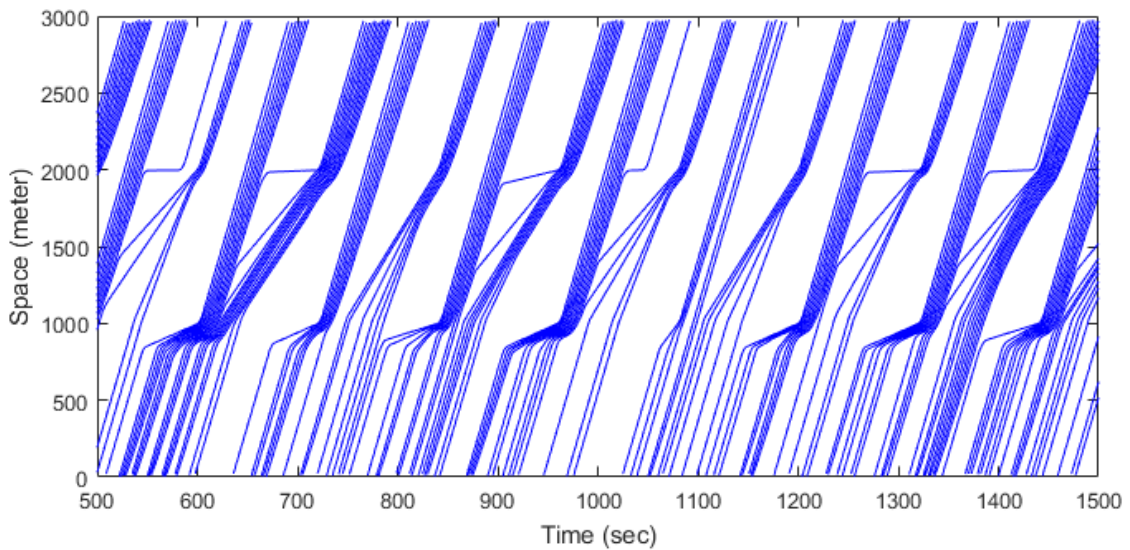
that almost all the vehicles are fully stopped before signalized intersections, which are represented by the horizontal lines in the trajectories. Figure 12(b) presents the speed trajectories with the Eco-CACC-I 1S controller for HEVs. Our previous work showed that an HEV equipped with the Eco-CACC-I controller works in the similar way as an ICEV under a higher speed limit (80 km/h in our test). The vehicle quickly reduces speed and then cruises at a constant speed to approach the intersection during red light signal timing on a downhill roadway. The INTEGRATION simulation results in scenario 2 are consistent with our previous findings, and the vehicles produce very smooth trajectories without any full stops as shown in Figure 12(b). Note that the HEV Eco-CACC-I 1S only considers the impact of a single signalized intersection; therefore the vehicle behaves in the same way approaching two intersections. More specifically, a vehicle quickly speeds up to the speed limit after passing the first intersection and then quickly reduces speed to a very low cruise speed when it is very close to the second intersection (within 200 meters). Lastly, the test results using the HEV Eco-CACC-I MS controller are presented in Figure 12(c). The trajectories demonstrate that vehicles approach the first signalized intersection in the same way as in scenario 2. However, most of the vehicles proceed differently after passing the first intersection compared to scenario 2. Most vehicles in scenario 3 drive at a constant speed (lower than the speed limit) to cruise towards the second signalized intersection. All the vehicles in scenario 3 also do not experience full stops approaching the signalized intersections, and the trajectories are even smoother and thus consume less fuel compared to the trajectories in scenario 2.



(a)



(b)

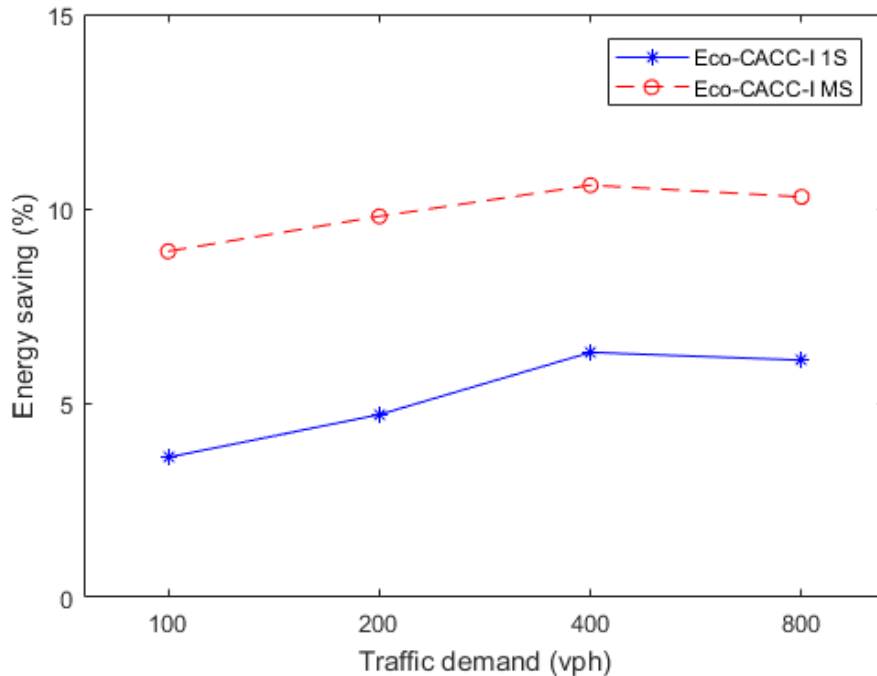


(c)

**Figure 12: Comparison of vehicle speed trajectories: (a) basic case for HEVs; (b) Eco-CACC-I 1S for HEVs; (c) Eco-CACC-I MS for HEVs.**

The test results for HEVs equipped with the Eco-CACC-I controllers are presented in Figure 13. The results demonstrate that the HEV Eco-CACC-I controllers produce energy savings for all demand levels compared to the base case without the Eco-CACC-I controller. The average energy savings from using the BEV Eco-CACC-I 1S controller are 3.5%, 4.7%, 6.3%, and 6.1% for demand levels of 100, 200, 400, and 800 veh/h/lane, respectively. The Eco-CACC-I MS controller further improves the average energy savings by 8.9%, 9.8%, 10.6%, and 10.3% under the same demand levels. Note that the demand of 400 veh/h/lane results in the maximum energy savings of

10.6% for the entire traffic network. The results demonstrate that the HEV Eco-CACC-I MS controller produces average energy savings of 10%, which outperforms the Eco-CACC-I 1S controller with 5.2% average energy savings.



**Figure 13: Test Eco-CACC-I controller for HEVs under various traffic demand levels.**

## 4. Driving Simulator Tests

### 4.1 Participants and Designed Scenarios

After Institutional Review Board approval, 48 participants were recruited from Morgan State University and the Baltimore metro area via the dissemination of flyers to drive the nine different scenarios described in Table 2. The flyer’s content included contact information, a summary of the requirements for the study, and an explanation of the monetary compensation for driving the simulator. Subsequently, prospective participants were screened for a valid driver’s license and scheduled to drive in the simulator environment.

Researchers simulated a road segment with a signalized intersection, including nine scenarios with different road characteristics and traffic conditions to investigate driver behavior and the fuel consumption reduction in the presence of the eco-speed control (ESC) system. Each scenario took 1 to 2 minutes to drive. As shown in Table 1, scenario 1 was the base (no guidance was provided to benchmark participants’ driving behavior in the vicinity of a signalized intersection in the absence of the ESC system). Scenarios 2 to 7 recommended a speed via voice that allowed participants to pass through the signalized intersection without stopping if they followed the guidance. In Scenarios 8 and 9, a countdown traffic signal was implemented to help participants adjust their speed based on the signal state. The even-numbered scenarios with information



provision were on an uphill road, while the odd ones were on a downhill road. Scenarios 1 to 3, as well as 8 and 9, had no traffic and the road had only one lane to analyze only the effect of the guidance provided; however, there was mild traffic in Scenarios 4 to 7 to analyze the influence of traffic on driver compliance behavior. Scenarios 4 to 7 tested the effects of maneuverability and lane changing due to additional lanes and/or the presence of traffic.

The developed HEV Eco-CACC-I algorithm was implemented in the driving simulator to test the participants' performance. The implemented ESC controller provides a recommended speed for drivers to follow. Participants were asked to drive each scenario several times, as shown in Table 2, and the data analysis was based on the average of all experiences for each scenario. Since the main goal of the research was to evaluate the ESC system on a single-lane roadway with no vehicle interaction, the first three scenarios were conducted 10 times to generate a sufficient sample size. However, six supplementary scenarios were defined to provide additional observations for further analysis. The primary evaluation of driving experiments revealed that there were no significant changes in drivers' behavior after the third drive. Therefore, additional scenarios were limited to three tests.

**Table 2: Simulated scenarios.**

Scenario	Information Type	Traffic Type	Road Condition	Number of Lanes	Number of Runs
1	No Information	No Traffic	Uphill	1 lane	10
2	Eco- Speed	No Traffic	Uphill	1 lane	10
3	Eco- Speed	No Traffic	Downhill	1 lane	10
4	Eco- Speed	Mild Traffic	Uphill	1 lane	3
5	Eco- Speed	Mild Traffic	Downhill	1 lane	3
6	Eco- Speed	Mild Traffic	Uphill	3 lanes	3
7	Eco- Speed	Mild Traffic	Downhill	3 lanes	3
8	Countdown	No Traffic	Uphill	1 lane	3
9	Countdown	No Traffic	Downhill	1 lane	3

## 4.2 Driving Performance

To study drivers' behavior in the vicinity of a signalized intersection in the presence of speed guidance, the participants started driving in a base scenario with no guidance to compare that driving behavior with ESC guidance. Participants then drove ESC guidance scenarios in different road conditions (uphill/downhill, 1 lane/3 lanes, and no traffic/mild traffic) on a simulated network.

The driving performance data consisted of vehicle speed, distance to stop bar, traffic light timing and phasing status, and recommended speed for each scenario 250 meters (820 feet) before and 250 meters after the intersection. In the above-mentioned ESC range, the participants were given the recommended speed via voice every 2 seconds, and participants were instructed to adjust their speed based on the recommendations. Participants were supposed to drive at the posted speed limit

of 40 mph and change their speed in response to the guidance provided via ESC (except in the base scenario) to go through the signalized intersection without stopping. The goal of the study was to measure drivers' ability to follow the speed recommendation.

Participants were told in advance that if they followed the provided guidance during their experiment, they would traverse the intersection without stopping, which reduces fuel consumption. However, there was no enforcement or incentive to follow the ESC guidance. Some participants were able to follow the provided speed guidance while others were not. For most participants, it took them a while (after driving 2 or 3 scenarios) to be able to follow and adjust their speed to the recommended speed. All participants drove different scenarios and their speed behavior was analyzed for each scenario, including without any guidance (base), with the ESC guidance, and with countdown timing guidance.

### **4.3 Data Collection**

#### *Questionnaires*

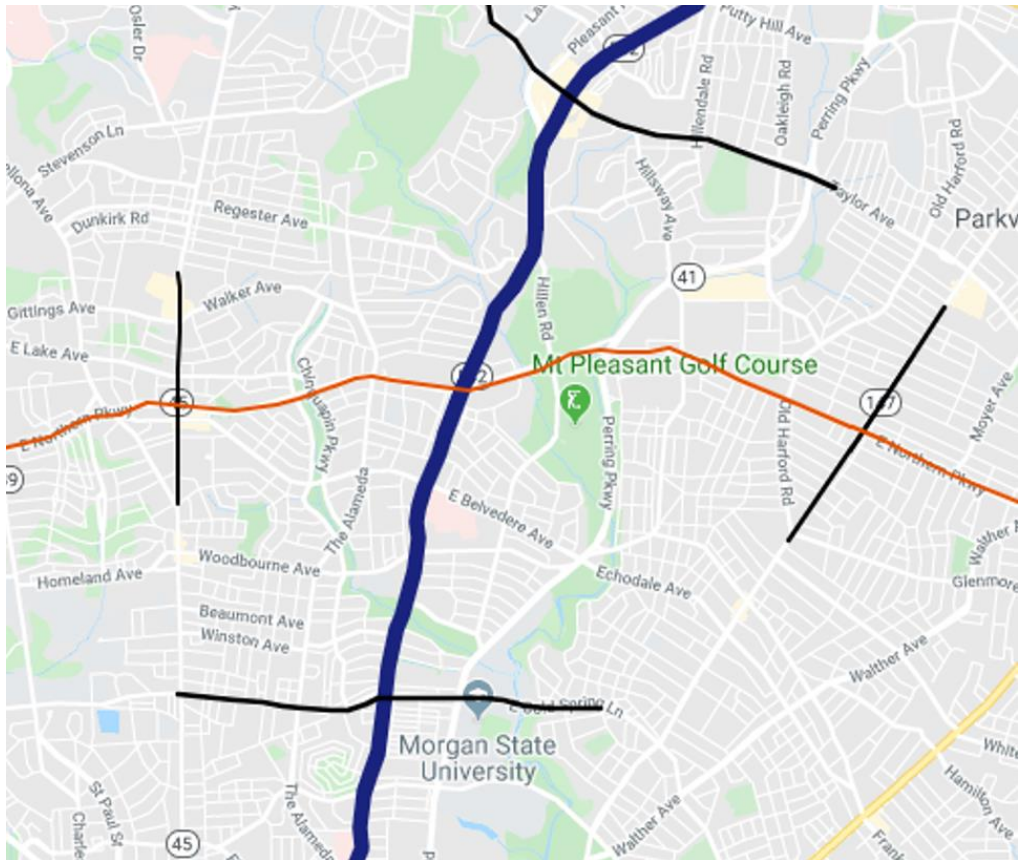
All participants were asked to fill out two survey questionnaires. The first focused on the socioeconomic features of the participants such as age, gender, work status, educational level, income level, and household size. The other survey was conducted after the driving experiment and addressed the usefulness and ease of the speed guidance provided as well as participants' experience with simulator sickness, if any.

#### *Driving Simulator*

This study implemented the previously developed HEV Eco-CACC-I controller (here called the ESC system) in a full-scale 3D driving simulator with VR-Design Studio software provided by Forum8 Company to study drivers' behavior in the vicinity of a signalized intersection in the presence of speed guidance. The hardware of the driving simulator resembles a real car including the cockpit, ignition key, automatic transmission, acceleration, brake pedals, steering wheel, three surrounding monitors (for front and rear, right and left views), safety seat belt, wiper, and hazard button, as shown in Figure 14. VR-Design Studio software can view the surrounding landscape with 3D buildings, vehicles, trees, etc., and allows the visual examination of alternative project options. The software can collect driver speed, acceleration, and location data and includes some connected vehicle capabilities. The software can create networks with real-world features such as traffic signals, road markings, and intersections, under realistic driving scenes. It is also possible to create different scenarios under various traffic and weather conditions. The simulated study area is presented in Figure 15, in which the blue line represents the three-lane road and the orange line represents the one-lane road.



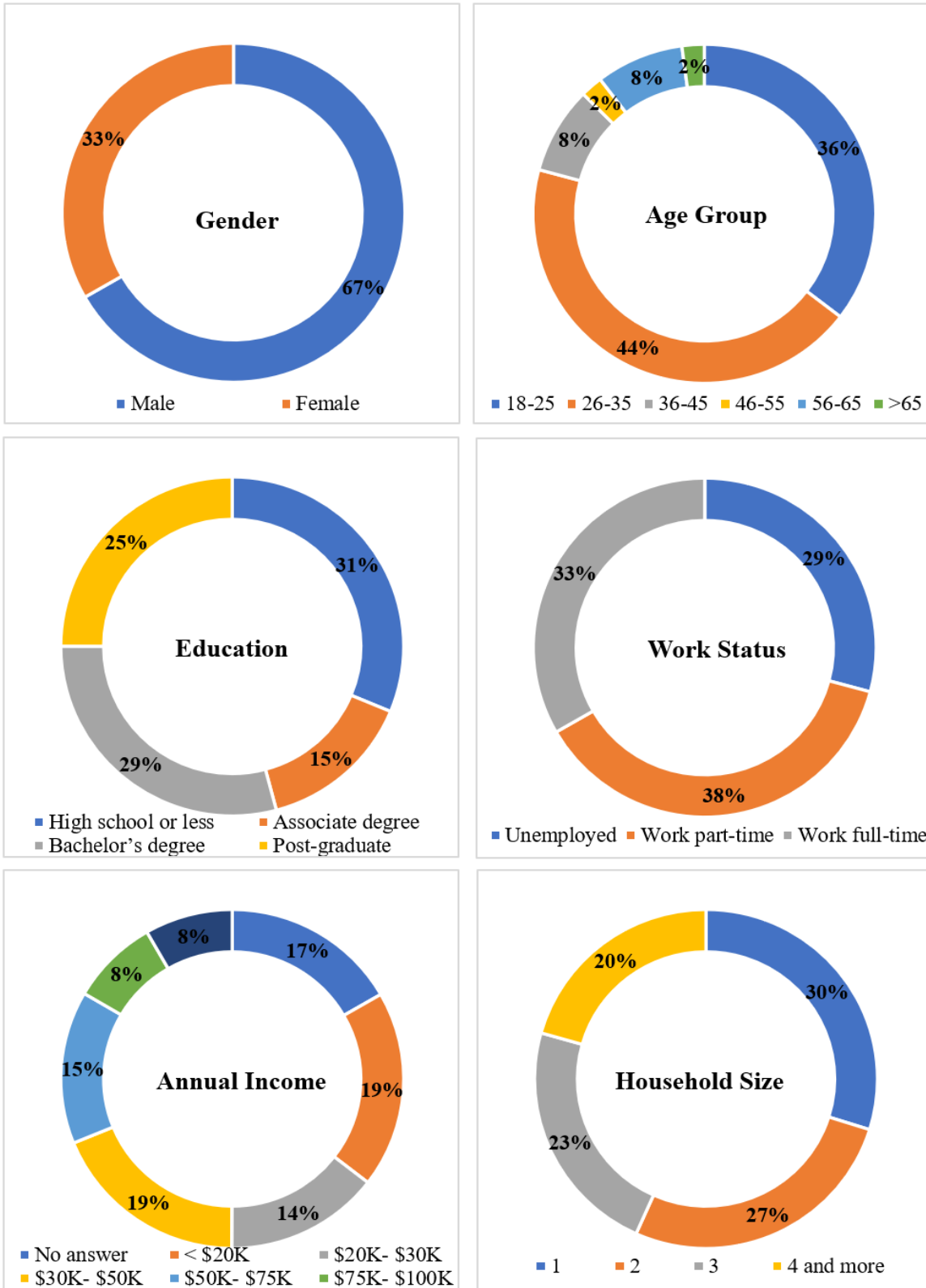
**Figure 14: Driving simulator.**



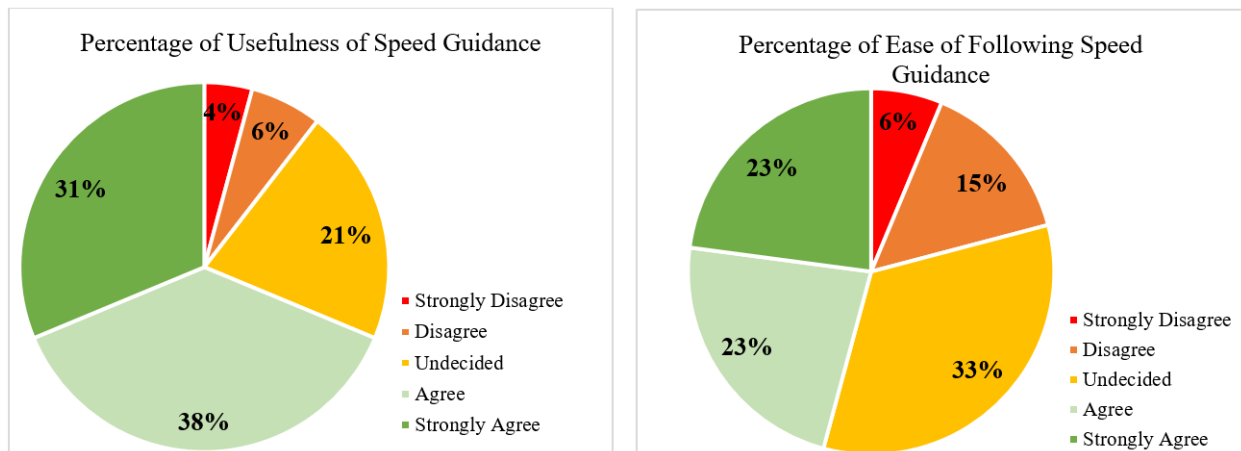
**Figure 15: Simulated study area.**

#### **4.4 Data Analysis and Test Results**

Descriptive statistics were obtained from pre-survey questionnaire data regarding participant characteristics. Among the 48 participants, 66.7% were male and 33.3% were female. The age range of participants was between 18 and 65 years, 43.8% of which were in the age group of 26 to 35 years (Figure 16). Also, the descriptive analysis of the post-surveys showed that 69% of participants agreed about the usefulness of recommended speed guidance via voice, and 46% of participants agreed about the ease of following such guidance, as shown in Figure 17.



**Figure 16: Descriptive analysis of participants' socioeconomic characteristics.**



**Figure 17: Participants' attitude regarding usefulness and ease of speed guidance system.**

To find the percentage of drivers who followed the recommended speed in different types of scenarios, the authors used descriptive analyses and analysis of variance (ANOVA). The results are summarized in Table 3, which indicates that 69% of participants followed the recommended speed voice guidance in scenario 2 (no traffic, uphill, 1 lane), the highest percentage of compliance, and 38% of the participants followed such guidance in scenario 7 (mild traffic, downhill, three lanes), which was the lowest percentage of compliance compared to the other ESC scenarios. The significantly lower compliance percentages of scenarios 6 and 7 compared to the other scenarios might be related to the number of lanes as these two scenarios have three lanes, while the other scenarios (2 to 5) have one lane. Also, the results show that there is a significant difference in compliance in different ESC scenarios.

**Table 3: Descriptive and ANOVA results for speed guidance following behavior by different ESC scenarios.**

Scenarios	Mean Percentage	Std. Deviation	Std. Error	F	Sig.
2	69%	0.097	0.014	55.896	0.000
3	68%	0.101	0.015		
4	60%	0.126	0.018		
5	61%	0.129	0.019		
6	41%	0.116	0.017		
7	38%	0.149	0.022		

We also investigated the “following the recommendation” behavior of the participants based on their gender and age; the results in Table 4 show that females were more successful in following the recommended speed than males in the same age group, except for the age group 26 to 35, in which males followed the guidance more than females. For example, 54% of males in the age group of 18 to 25 were able to follow the recommended speed guidance, while 65% of females in the same age group followed the guidance. As Table 5 shows, the fuel consumption for females was less compared to males from the same age group. As shown in Tables 4 and 5, there is a significant difference in the guidance-following behavior and fuel consumption by gender and age group classification.

**Table 4: ANOVA results for following speed guidance.**

Dependent Variable	Gender	Age Groups	Percentage	Std. Deviation	F	Sig.
Following Percentage	Male	18-25	54%	0.156	5.839	0.000
		26-35	57%	0.172		
		36-45	50%	0.184		
		46-55	62%	0.18		
		56-65	67%	0.163		
	Female	18-25	65%	0.136		
		26-35	52%	0.184		
		36-45	51%	0.121		
		46-55	70%	0.197		
		56-65	59%	0.12		

**Table 5: ANOVA results for fuel consumption.**

<b>Dependent Variable</b>	<b>Gender</b>	<b>Age Groups</b>	<b>Mean</b>	<b>Std. Deviation</b>	<b>F</b>	<b>Sig.</b>
Fuel Consumption (km/L)	Male	18-25	3.084	6.413	4.204	0.000
		26-35	2.989	6.253		
		36-45	2.334	6.154		
		56-65	2.962	5.942		
		>65	0.453	0.654		
	Female	18-25	2.728	7.158		
		26-35	0.721	1.859		
		36-45	0.468	0.616		
		46-55	0.374	0.548		
		56-65	0.446	0.572		

In addition, we performed an ANOVA test to find the reduction in fuel consumption due to following the recommended speed guidance in comparison to the base scenario and the countdown scenario. The results in Table 6 demonstrate that the average fuel savings in the ESC scenarios is 32% when compared to the base scenario. Fuel consumption in the countdown scenarios is only 1.9% less than that in the base scenario. Such a result confirmed the effectiveness of the application of an ESC system in HEVs to save energy.

**Table 6: ANOVA analysis of fuel consumption by scenario.**

<b>Scenarios Types</b>	<b>Mean (km/L)</b>	<b>Std. Deviation</b>	<b>Std. Error</b>	<b>F</b>	<b>Sig.</b>
Base Scenario	3.443	10.019	24	8.71	0.04
ESC Scenario	2.343	4.484	47		
Countdown Scenario	3.378	5.307	47		



## 5. Conclusions

This research develops an Eco-CACC controller for HEVs to pass multiple signalized intersections with energy-optimized speed profiles. The research extends the Eco-CACC-I system previously developed by the research team on ICEVs to HEVs. The constraints of energy model and vehicle dynamics for HEVs are used to develop two HEV Eco-CACC-I controllers for a single intersection and multiple intersections, respectively. The developed HEV Eco-CACC-I controllers include two modes: automated and manual, for vehicles with or without an automated control system. The automated mode was implemented into microscopic traffic simulation software so that CAVs can directly follow the energy-optimized speed profile. Simulation tests using the INTEGRATION software validated the performances of the proposed controllers under the impact of signal timing, speed limit, and road grade. The simulation tests also demonstrated the improved benefits of using the proposed HEV Eco-CACC-I controllers in a traffic network with multiple intersections. Compared to the single intersection-optimized controller, the test results illustrate that the HEV Eco-CACC-I MS controller produces a smoother optimized-trajectory for a vehicle to pass multiple intersections and thus further improve energy consumption. The results under various traffic demand levels demonstrate that the HEV Eco-CACC-I MS controller produces an average energy savings of 10%, which outperforms the Eco-CACC-I 1S controller with 5.2% average energy savings. Lastly, the manual model of the proposed HEV Eco-CACC controllers was implemented in a driving simulator at Morgan State University so that drivers in connected vehicles (non-automated driving) can follow the recommended speed advisories. Data collected by the driving simulator with 48 participants demonstrated that the speed advisories calculated by the proposed controller can help drivers drive smoothly and save fuel while passing signalized intersections.

## 6. References

- Aerde, M. V., & Rakha, H. (2007a). *INTEGRATION © Release 2.30 for Windows: User's Guide – Volume I: Fundamental Model Features*. M. Van Aerde & Assoc., Ltd., Blacksburg.
- Aerde, M. V., & Rakha, H. (2007b). *INTEGRATION © Release 2.30 for Windows: User's Guide – Volume II: Advanced Model Features*. M. Van Aerde & Assoc., Ltd., Blacksburg.
- Ahn, K., & Rakha, H. (2019). *A Simple Hybrid Electric Vehicle Fuel Consumption Model for Transportation Applications*. Retrieved from
- Almannaa, M. H., Chen, H., Rakha, H. A., Loulizi, A., & El-Shawarby, I. (2019). Field implementation and testing of an automated eco-cooperative adaptive cruise control system in the vicinity of signalized intersections. *Transportation Research Part D: Transport and Environment*, 67, 244-262.
- Asadi, B., & Vahidi, A. (2011). Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time. *Control Systems Technology, IEEE Transactions on*, 19(3), 707-714.
- Barth, M., & Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. *Transportation Research Record: Journal of the Transportation Research Board*(2058), 163-171.
- Barth, M., & Boriboonsomsin, K. (2009). Energy and emissions impacts of a freeway-based dynamic eco-driving system. *Transportation Research Part D: Transport and Environment*, 14(6), 400-410.
- Boubaker, S., Rehim, F., & Kalboussi, A. (2013). *Estimating energy consumption of hybrid electric vehicle and gasoline classical vehicle*. Paper presented at the 2013 International Conference on Advanced Logistics and Transport.
- Chen, H., & Rakha, H. (2019). *DEVELOPING A TRAFFIC SIGNAL ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL SYSTEM FOR BATTERY ELECTRIC VEHICLES*. Retrieved from
- Chen, H., & Rakha, H. A. (2020). Battery Electric Vehicle Eco-Cooperative Adaptive Cruise Control in the Vicinity of Signalized Intersections. *Energies*, 13(10), 2433.
- Chen, H., Rakha, H. A., Almannaa, M., Loulizi, A., & El-Shawarby, I. (2017). *Field Implementation of an Eco-cooperative Adaptive Cruise System at Signalized Intersections*. Paper presented at the 94th Annual Meeting Transportation Research Board, Washington D.C.
- De Nunzio, G., Wit, C. C., Moulin, P., & Di Domenico, D. (2016). Eco-driving in urban traffic networks using traffic signals information. *International Journal of Robust and Nonlinear Control*, 26(6), 1307-1324.
- Fadhloun, K., Rakha, H., Loulizi, A., & Abdelkefi, A. (2015). Vehicle dynamics model for estimating typical vehicle accelerations. *Transportation Research Record: Journal of the Transportation Research Board*(2491), 61-71.
- Fiori, C., Ahn, K., & Rakha, H. A. (2016). Power-based electric vehicle energy consumption model: Model development and validation. *Applied Energy*, 168, 257-268.

- Guan, T., & Frey, C. W. (2013). *Predictive fuel efficiency optimization using traffic light timings and fuel consumption model*. Paper presented at the Intelligent Transportation Systems- (ITSC), 2013 16th International IEEE Conference on.
- Kamalanathsharma, R., & Rakha, H. (2014). Agent-Based Simulation of Ecospeed-Controlled Vehicles at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*(2427), 1-12.
- Kamalanathsharma, R. K. (2014). *Eco-Driving in the Vicinity of Roadway Intersections - Algorithmic Development, Modeling, and Testing*. (Doctor of Philosophy), Virginia Polytechnic Institute and State University.
- Li, X., Li, G., Pang, S.-S., Yang, X., & Tian, J. (2004). Signal timing of intersections using integrated optimization of traffic quality, emissions and fuel consumption: a note. *Transportation Research Part D: Transport and Environment*, 9(5), 401-407.
- Malakorn, K. J., & Park, B. (2010). *Assessment of mobility, energy, and environment impacts of IntelliDrive-based Cooperative Adaptive Cruise Control and Intelligent Traffic Signal control*. Paper presented at the Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on.
- Miyatake, M., Kuriyama, M., & Takeda, Y. (2011). *Theoretical study on eco-driving technique for an electric vehicle considering traffic signals*. Paper presented at the Power Electronics and Drive Systems (PEDS), 2011 IEEE Ninth International Conference on.
- Qi, X., Barth, M. J., Wu, G., Boriboonsomsin, K., & Wang, P. (2018). Energy Impact of Connected Eco-driving on Electric Vehicles *Road Vehicle Automation 4* (pp. 97-111): Springer.
- Rakha, H., Ahn, K., & Trani, A. (2003). Comparison of MOBILE5a, MOBILE6, VT-MICRO, and CMEM models for estimating hot-stabilized light-duty gasoline vehicle emissions. *Canadian Journal of Civil Engineering*, 30(6), 1010-1021.
- Saboohi, Y., & Farzaneh, H. (2008). Model for optimizing energy efficiency through controlling speed and gear ratio. *Energy Efficiency*, 1(1), 65-76.
- Saboohi, Y., & Farzaneh, H. (2009). Model for developing an eco-driving strategy of a passenger vehicle based on the least fuel consumption. *Applied Energy*, 86(10), 1925-1932.
- Statistics, B. o. T. (2019). Hybrid-Electric, Plug-in Hybrid-Electric and Electric Vehicle Sales. Retrieved from <https://www.bts.gov/content/gasoline-hybrid-and-electric-vehicle-sales>
- Stevanovic, A., Stevanovic, J., Zhang, K., & Batterman, S. (2009). Optimizing traffic control to reduce fuel consumption and vehicular emissions: Integrated approach with VISSIM, CMEM, and VISGAOST. *Transportation Research Record: Journal of the Transportation Research Board*(2128), 105-113.
- USDOT. (2015). Connected Vehicle Technology. Retrieved from [http://www.its.dot.gov/connected\\_vehicle/connected\\_vehicle\\_tech.htm](http://www.its.dot.gov/connected_vehicle/connected_vehicle_tech.htm)
- Wipke, K. B., Cuddy, M. R., & Burch, S. D. (1999). ADVISOR 2.1: A user-friendly advanced powertrain simulation using a combined backward/forward approach. *IEEE Transactions on Vehicular technology*, 48(6), 1751-1761.

- Wu, X., He, X., Yu, G., Harmandayan, A., & Wang, Y. (2015). Energy-optimal speed control for electric vehicles on signalized arterials. *IEEE Transactions on Intelligent Transportation Systems*, 16(5), 2786-2796.
- Yang, H., Almutairi, F., & Rakha, H. (2017). *Eco-cooperative adaptive cruise control at multiple signalized intersections*. Paper presented at the Transportation Research Board 96th Annual Meeting, Washington DC, United States.
- Yu, K., Yang, J., & Yamaguchi, D. (2015). Model predictive control for hybrid vehicle ecological driving using traffic signal and road slope information. *Control theory and technology*, 13(1), 17-28.
- Zhang, R., & Yao, E. (2015). Eco-driving at signalised intersections for electric vehicles. *IET Intelligent Transport Systems*, 9(5), 488-497.