Final Report

Developing and Testing an ECO-Cooperative Adaptive Cruise Control System for Buses

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16. Abstract

Studies over the past decade have shown that eco-driving systems which provide speed advisories to drivers/vehicles using data received via vehicle-to-infrastructure and vehicle-to-vehicle communications can help improve traffic mobility and reduce vehicle energy and emission levels. This study extends the Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system previously developed for light duty vehicles to heavy duty vehicles (diesel and hybrid electric buses). First, the energy consumption models for diesel and hybrid buses are discussed and the field data collected by Blacksburg Transit are used to calibrate bus models. Thereafter, the bus Eco-CACC system is developed by incorporating the vehicle dynamic model and energy consumption model for buses. The developed Eco-CACC system has manual and automated modes to control buses. The manual Eco-CACC mode was tested by participants using driving simulators at Morgan State University under various scenarios that included different types of information. In addition, the automated bus Eco-CACC system was tested using the INTEGRATION microscopic simulation software to quantify the system-wide impacts of the proposed system under various traffic demand and vehicle types. The test results demonstrated that the proposed system could improve transit operations by reducing delay and helping transit agencies save on energy costs, resulting in an improved transit level of service, increased ridership, and improved traffic mobility.

17. Key Words: eco driving, Eco-Cooperative Adaptive Cruise Control, diesel and hybrid buses, signalized intersection, driving simulator, microscopic traffic simulation.

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Abstract

Studies over the past decade have shown that eco-driving systems which provide speed advisories to drivers/vehicles using data received via vehicle-to-infrastructure and vehicle-to-vehicle communications can help improve traffic mobility and reduce vehicle energy and emission levels. This study extends the Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system previously developed for light duty vehicles to heavy duty vehicles (diesel and hybrid electric buses). First, the energy consumption models for diesel and hybrid buses were investigated and the field data collected by Blacksburg Transit were used to calibrate bus models. Thereafter, the bus Eco-CACC system, with both manual and automated bus control modes, was developed by incorporating the vehicle dynamic model and energy consumption model for buses. The manual Eco-CACC mode was tested by participants using driving simulators at Morgan State University under various scenarios that included different types of information. In addition, the automated bus Eco-CACC system was tested using INTEGRATION microscopic simulation software to quantify the Eco-CACC's system-wide impacts under various traffic demand and vehicle types. The test results demonstrated that the proposed system could improve transit operations by reducing delay and helping transit agencies save on energy costs, resulting in an improved transit level of service, increased ridership, and improved traffic mobility.

1. Introduction

The Environmental Protection Agency (EPA) identifies the United States transportation sector as one of several sources of environmental problems caused by human activity [1]. The U.S. plays an outsized role, with research showing that 45% of the world's automotive CO2 emissions come from U.S. automobiles [2]. The transportation sector is the main producer of greenhouse gas emissions due to internal combustion engines' pollutant emissions. Researchers have considered technological solutions, such as eco-driving, to address this problem. Eco-driving reduces excessive fuel consumption and greenhouse emissions by adjusting or enhancing such driver behaviors as maintaining a steady speed, avoiding heavy acceleration and deceleration, anticipating the traffic flow ahead, and minimizing idling time [3], [4]. Several countries have implemented eco-driving and demonstrated its results in increasing driving efficiency; depending on the type of vehicle, fuel consumption savings can be up to 30% [5]. For example, Hornung (2004) found that fuel consumption decreased by 17% after implementing eco-driving among a group of 79 participants using a driving simulator [6]. In addition, the results of the field test and real world experience from a widespread eco-driving project in Europe showed an average of 5%–10% savings in fuel [7]. Implementing an eco-driving system that displays such information as average fuel efficiency and instantaneous acceleration results in a short-term reduction in fuel consumption [8]. Research on eco-driving has confirmed reductions in fuel consumption [9] and emissions [9], [10]. The results of one study show a 10%–15% fuel economy improvement using an eco-driving system that incorporates the signals and traffic from the network, calculates the steady speed for drivers, and advises them of the recommended speed [11].

At signalized intersections, drivers must decide whether to proceed or stop at the yellow light based on the estimated time-to-arrival at the intersection, which results in hard braking, acceleration/deceleration and idling maneuvers that are largely responsible for wasted energy [12]. An effective method to address this is advising drivers of a recommended eco-speed in real time in the vicinity of the signalized intersection without compromising travel time, safety, or drivers' riding comfort. The result of a study using a driving simulator showed that faster but shorter acceleration/deceleration is more fuel efficient than milder but longer acceleration/deceleration when compared within the same time span [11], [13].

Driving styles have a different impact on fuel consumption and emissions. For example, aggressive driving—such as speeding, changing lanes regularly, and turning without signaling—increases fuel consumption by more than 30%, while conservative driving decreases fuel consumption and emissions [14], [15], [16]. The results of a study by J. N. Barkenbus confirmed that eco-driving could reduce fuel consumption by 5%–15%, lessen greenhouse gas emissions, improve road safety, and reduce accident rates [4]. Studies show several advantages of eco-driving: providing safety by improving the driving capabilities [17]; decreasing environmental issues via reduced greenhouse emissions, CO2, local harmful emissions, and noise; more economic driving due to reduced fuel consumption and maintenance costs [18]; and creating social responsibility by reducing stress during driving and increasing both driver and passenger comfort [5]. The effects of eco-driving on bus emissions show 2% fuel savings [19]. Another eco-driving study reported an average decrease of 10% for bus emissions [20].

Eco-driving guidance is transmitted to drivers in different ways, which can include visual messages, auditory messages, or via an in-vehicle assistance system. Most studies implemented visual messages and very few used other types of assistance. In this respect, Tulusan et al. (2012) provided eco-driving guidance by displaying the most efficient average speed, depending on the vehicle type, to a sample of 50 corporate car drivers, and concluded that fuel efficiency improved significantly using such guidance [21]. One driving study compared an eco-driving assist system promoting eco-driving to no system use, using a driving simulator that measured 5 days of driving behavior. The results showed higher eco-driving scores with an assist system [22]. In another study, the advisory message was displayed to the driver, the recommended action was transmitted both audibly and visually, and the explanation was provided visually to the driver [23]. In a study by D. Niu and J. Sun, vehicles received speed advice at certain times or distance intervals [24].

In research conducted by Y. Zhao et al., a recommended speed was displayed to control the speed of the approaching vehicle in a pre-timed controller signalized intersection [25]. Using a driving simulator, the eco-driving support system provided real-time voice prompts and instant CO2 emissions cues to drivers, taking into consideration non-eco-driving behavior, including quick acceleration, rapid deceleration, engine revolutions at a high level, too fast or unstable speed on freeways, and idling for a longer time [26]. Another study tested 12 systems with differences in eco-driving support modality and design styles using a driving simulator [27]. In other studies, the visual presentation of the eco-driving information was displayed intermittently and continuously

[28], [29]. In research conducted by M. Staubach et al., system recommendations were transmitted to drivers via visual display and a haptic force-feedback signal on the acceleration pedal [30]. In yet another study, eco-driving guidance was provided by visual, haptic, and coupled visual-haptic assistance [31].

Another system included a haptic force feedback system, a haptic stiffness feedback system, and a visual display, which delivered guidance related to the current accelerator position and the change in pedal position every second to improve fuel economy. The driver could not control the operation of the system, and it remained activated for the entire drive. System advice focused on guiding drivers in their transition between speeds rather than their speed selection [32]. The result of eco-driving using the driving simulator revealed that not only is eco-driving effective at improving fuel efficiency but that it also reduces driver's physical fatigue [33]. One simulator study assessed both visual and haptic eco-driving feedback systems based on hill driving [34]. Another eco-driving method managed speed and acceleration while driving in order to decrease fuel consumption and vehicle emissions. The offered methodology provided recommended speeds to drivers, showing a reduction of 10%–20% in fuel consumption and CO2 emissions with no adverse effect on overall travel time [9]. Another study compared the result of eco-driving with no eco-driving system in a hybrid electric vehicle (HEV) and interviewed 46 drivers for a multi-week trial [35]. A study with 30 participants using a driving simulator assessed an eco-driving support system that gave recommendations to participants concerning fuel efficiency, gear shifting and acceleration/deceleration behavior using a visual display and a haptic force-feedback signal on the acceleration pedal [36]. Y. K. Joo and J.-E. R. Lee investigated the use of an in-vehicle voice agent to promote eco-driving [37]. Another study used an eco-driving smartphone application called DriveGain in a driving simulator, concluding that using such a support tool reduced fuel consumption by 16% [38].

A research study evaluating in-vehicle eco-driving support system provided auditory, visual, and vibrotactile impetuses to deter harsh accelerations and encourage fuel efficiency [39]. A driving simulator study with 27 participants used the anticipatory advanced driver assistance system to evaluate the reduction of each driver's fuel consumption, which was achieved by anticipating road situations and improving reaction time. [40].

A car equipped with GERICO, a new onboard system designed to reduce fuel consumption and CO2 emissions, was tested with 40 participants. Different types of information, including navigation, assistance, advice, and a warning, were displayed to drivers. Auditory information was also provided to the driver. The result showed a 16% reduction in fuel consumption [41]. Another study examined the reduction of fuel consumption rates achieved by presenting eco-driving information among a vehicle group in cooperative driving with a simulation of V2V communication. The authors concluded that sharing information about fuel consumption to the vehicles following an eco-driving vehicle was effective for the reduction of fuel consumption rates among the vehicle group [42].

Visual advice—including that regarding upcoming events like traffic signs or red traffic lights near a virtual road, as well as point to point navigation advice presented to drivers—is part of an advanced driver assistance system, which also reduces driver-related fuel consumption [43]. In a study by F. Yin et al. using a driving simulator, the driver was given a haptic velocity guidance assistance system and visual display of the ideal velocity information, and the effectiveness of the system was verified [44].

Although in-vehicle eco-driving support systems reduce emissions and save fuel, they may also distract drivers, particularly when the recommended guidance is provided via display presentation [45]. One study used the Advanced Driving Simulator to determine distraction due to reading an eco-driving message [46]. Another study evaluated drivers' distraction as a result of using a smart driving aid when information was presented to them on a colorful screen placed to the left of the steering wheel, concluding that if the assistance system was designed properly, it would not distract drivers [47].

As the literature shows, most studies have focused only on LDVs, disregarding heavy duty vehicles (HDVs) when designing eco-driving systems. Considering the improved mobility and reduced energy/emissions, using a bus eco-driving system may greatly benefit the multi-modal transportation network, illustrating the need to develop an eco-driving system for buses. Compared to LDVs, HDVs such as buses have poor fuel efficiency, especially in stop-and-go traffic conditions, due to their large curb weights and sizes. Considering that an energy consumption model is an important component for computing the optimum control solution in eco-driving, the main difficulty in designing eco-driving systems for buses is that the energy consumption models for buses are hard to develop and calibrate. This is especially true for hybrid electric buses that combine fuel and electric power with regenerative braking control. Moreover, the energy management strategy for the hybrid electric bus is complicated, as the power system continuously switches between series hybrid and parallel hybrid systems under different driving conditions.

A few studies have attempted to develop eco-driving systems to save fuel and emissions when buses pass signalized intersections. Zhang et al. proposed a bus eco-driving system by adjusting vehicle speed profile and the dwell time at bus stations to ensure that buses can smoothly pass downstream of signalized intersections [48]. A MATLAB simulated environment was used to validate the benefit of the proposed system, showing a savings of 5.5% in emissions. Another similar approach was developed by Bagherian et al. to minimize the number of bus stops at intersections to reduce the amount of transit fuel consumption in urban areas [49]. According to the predicted bus arrival time to the upcoming intersection and the corresponding signal timings, the bus speed and the dwell time were adjusted so that the bus could drive smoothly to approach the intersection. The fuel consumption savings was achieved by moving complete vehicle stops at signalized intersections to bus stations, thereby reducing the total number of stops and also removing accelerations and decelerations at intersections. The proposed method was implemented into VISSIM microsimulation software and the test results showed up to 15% savings in bus fuel consumption at intersections. Both studies tried to reduce bus stoppages at intersections by adjusting bus dwell time at upstream stations. However, these approaches may not work well for signalized intersections without, or far away from, neighboring bus stations.

To tackle the aforementioned issues, this study developed a bus eco-driving system called Eco-CACC for buses. First, the energy consumption models for diesel and hybrid buses were investigated and the field data collected by Blacksburg Transit were used to calibrate bus models. Thereafter, the bus Eco-CACC system, with both manual and automated bus control modes, was developed by incorporating the vehicle dynamic model and energy consumption model for buses. The manual Eco-CACC mode was tested by participants using driving simulators at Morgan State University under various scenarios that included different types of information. In addition, the automated bus Eco-CACC system was tested using INTEGRATION microscopic simulation software to quantify the Eco-CACC's system-wide impacts under various traffic demand and vehicle types. The test results demonstrated that the proposed system could improve transit operations by reducing delay and helping transit agencies save on energy costs, resulting in an improved transit level of service, increased ridership, and improved traffic mobility.

2. Develop Eco-CACC for Buses

2.1 Definitions and Assumptions

The Eco-CACC system described in this paper computes the optimum vehicle speed profile from upstream to downstream of a signalized intersection, by incorporating vehicle dynamics and energy consumption models for buses. Given that both upstream and downstream vehicle speed profiles are considered in the Eco-CACC system, a control region in the vicinity of signalized intersections should be defined. Considering the communication range of Dedicated Short Range Communications, the Eco-CACC system is activated at a distance of d_{up} upstream of the intersection to a distance of d_{down} downstream of the intersection. The distance is calculated from the vehicle's location relative to the intersection stop line. The value of d_{down} is defined to ensure that the vehicle has enough downstream distance to accelerate from zero speed 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.

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, as shown as below, were considered to develop the Eco-CACC system.

- Case 1: vehicle is able to pass the intersection on green phase without deceleration (either keeping a constant speed or accelerating to a higher speed and then keeping that speed).
- Case 2: vehicle needs to decelerate to a lower speed, and then keeps that speed to pass the intersection on green phase.

The two cases above describe the vehicle's optimum trajectory in order to minimize energy consumption while traversing the intersection. After the vehicle passes the stop line, it attempts to reach the speed limit, which describes the vehicle's maneuver downstream of the intersection. More details of optimum speed profiles during various situations are discussed in [50, 51]. Figure 1 demonstrates the optimum speed profile when the vehicle passes a signalized intersection. The Eco-CACC system helps 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 case 1 and 2 samples in Figure 1 happen at the red phase when the vehicle passes the upstream distance d_{up}. The same classification of case 1 and 2 also exist for the green phase. Considering the simplicity of the proposed Eco-CACC system, the initial red phase is assumed for the following sections.

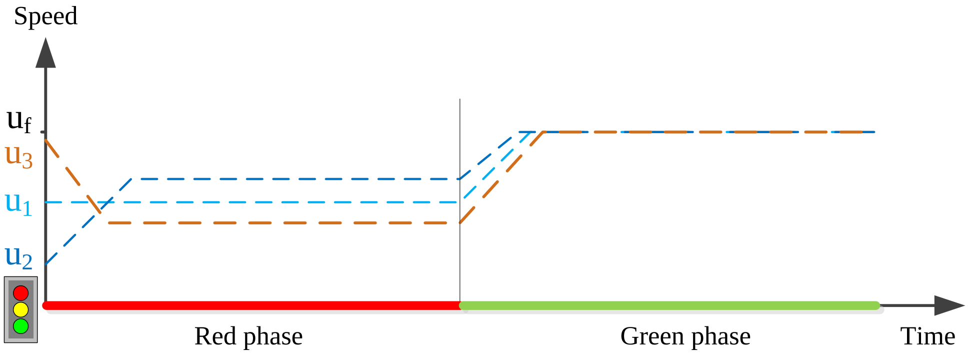


Figure 1: Samples of optimum speed profile when vehicle approaches a signalized intersection.

In the proposed Eco-CACC system, deceleration is assumed constant for case 2. In case 1, the vehicle acceleration follows the vehicle dynamics model developed in [52]. 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 [51], a constant throttle level of 0.6 is assumed in the vehicle dynamic model to simplify the calculations in the Eco-CACC system for case 1. In case 2, the throttle level ranges between 0.4 to 0.8, and the optimum throttle level can be located by the minimum fuel consumption level. The vehicle dynamics model is summarized by Equations (1) to (3).

$$u(t+\Delta t) = u(t) + \frac{F(t)-R(t)}{m}\Delta t \tag{1}$$

$$F = \min\left(3600 f_p \beta \eta_D \frac{P_{max}}{u}, m_{ta} g \mu\right) \tag{2}$$

$$R = \frac{\rho}{25.92} \mathrm{C}_d \mathrm{C}_h \mathrm{A}_f u(t)^2 + mg\frac{c_{ro}}{1000}\left(c_{r1} u(t) + c_{r2}\right) + mgR_g \tag{3}$$

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 LDVs; 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 (kg); g is the gravitational acceleration (9.8067 m/s^2); μ is the coefficient of road adhesion (unitless); ρ is the air density at sea level and a temperature of 15°C (1.2256 kg/m^3); 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^2); 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).

2.2 Eco-CACC 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 signal without decelerating. In order to travel at the maximum average speed to reduce fuel consumption, the cruise speed during the red phase is defined as shown in Equation (4). 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 (1) to (3). 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}.

$$u_c = min\left(\frac{d_{up}}{t_r}, u_f\right) \tag{4}$$

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 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 below. The vehicle's speed profile for case 2 is illustrated in Figure 2.

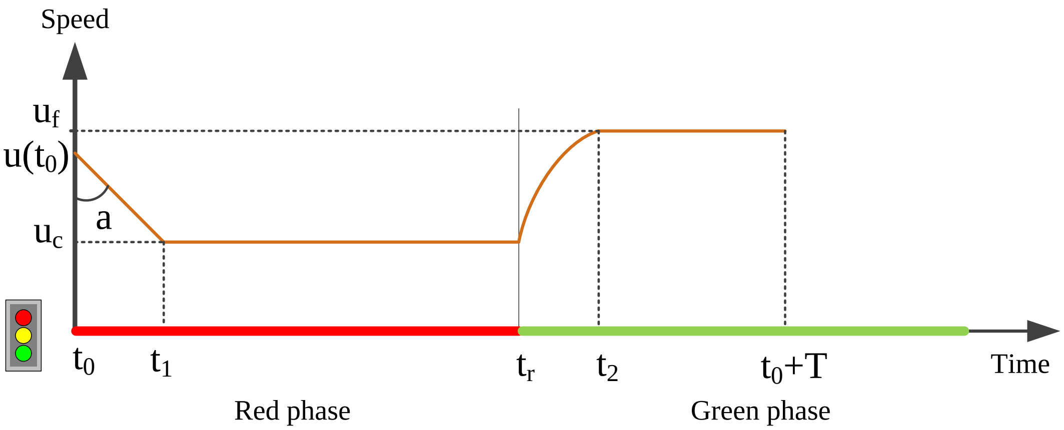


Figure 2: Optimum speed profile in case 2.

Assume a vehicle arrives d_{up} at time t_0 and passes d_{down} at time t_0+T, the cruise speed during the red phase is u_c, and the objection function is the total energy consumption level given by:

$$min \int_{t_0}^{t_0+T} EC\big(u(t)\big) \cdot dt \tag{5}$$

where *EC(*)* denotes the calculated fuel consumption at instant *t* (Equation **Error! Reference source not found.**) with vehicle speed *u(t)*. The constraints can be constructed by the relationships between speed, acceleration, deceleration, and distance as shown below:

$$u(t): \begin{cases} u(t) = u(t_0) - at & t_0 \le t \le t_1 \\ u(t) = u_c & t_1 < t \le t_r \\ u(t+\Delta t) = u(t) + \frac{F(f_p) - R(u(t))}{m} \Delta t & t_r < t \le t_2 \\ u(t) = u_f & t_2 < t \le t_0 + T \end{cases} \tag{6}$$

$$\begin{gathered} u(t_0) \cdot t - \frac{1}{2} a t^2 + u_c(t_r - t_1) = d_{up} \\ u_c = u(t_0) - a(t_1 - t_0) \\ \int_{t_r}^{t_2} u(t)\, dt + u_f(t_0 + T - t_2) = d_{down} \\ u(t_2) = u_f \\ a_{min} < a \le a_{max} \\ f_{min} \le f_p \le f_{max} \\ u_c > 0 \end{gathered} \tag{7}$$

In Equation 8, the functions *F(*)* and *R(*)* represent the vehicle tractive effort and resistance force as computed by Equations (2) and (3), respectively. According to the relationships in Equations (6) and **Error! Reference source not found.**, the deceleration a and throttle level f_p are the only unknown variables. Note that the maximum deceleration level is limited to 5.9 m/s^2 (comfortable deceleration threshold for average drivers). 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 [51]. Dynamic programming 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 [51, 53]. The developed Eco-CACC system has manual and automated modes to control buses. The manual Eco-CACC mode was tested by participants using driving simulators at MSU under various scenarios that included different types of information. The automated bus Eco-CACC system was tested using INTEGRATION microscopic simulation software to quantify the system-wide impacts of the proposed system under various traffic demand and vehicle types.

2.3 Energy Consumption Model for Buses

A simple energy consumption model for diesel buses was developed and calibrated in [54, 55]. The framework of the Virginia Tech Comprehensive Power-based Fuel Consumption Model (VT-CPFM), which was originally developed for LDVs, was used to develop the energy model for diesel buses, as presented in Equation 8. The vehicle power used in the bus energy model can be computed as Equation 9.

$$EC_{bus}(t)\colon \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2, & P(t) \geq 0 \\ a_0 & P(t) < 0 \end{cases} \tag{8}$$

$$P(t) = \left(\frac{R(t) + \left(1 + \lambda + 0.0025\xi u(t)^2\right) m a(t)}{3600\eta_d}\right) \cdot u(t) \tag{9}$$

Where $EC_{bus}(t)$ denotes the instantaneous energy consumption rate for a diesel bus; α_0, α_1 and α_2 are vehicle-specific model coefficients that should be calibrated for each vehicle; λ is the mass factor accounting for rotational masses, where a value of 0.1 is used for HDVs [56]; ξ is the term related to gear ratio, which is assumed to be zero due to the lack of gear data; $a(t)$ is the instantaneous acceleration level; $R(t)$ is the resistance force on the vehicle as given by Equation (4).

An energy consumption model for a HEV was developed in [57]. This model estimates the instantaneous energy consumption rates of an HEV using instantaneous vehicle operational input variables, including instantaneous vehicle speed, acceleration and roadway grade, which can be easily obtained from GPS devices or smartphones. The data from a 2010 Toyota Prius were collected and analyzed to generate the following HEV energy consumption behaviors. First, the fuel consumption level is proportionally related to both vehicle power and speed; second, the HEV is operated in battery electric vehicle (BEV) mode during negative power; third, the HEV utilizes only electric power when vehicle 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 model if vehicle drives at a constant speed and the speed is lower than a specific value (v_b). The equations of the HEV model are presented as below.

$$EC_{HEV}(t): \begin{cases} Energy_{BEV\_model} & for \begin{cases} P \le 0 \\ v < v_a \; and \; P < P_a \\ v \; is \; constant \; and \; v < v_b \end{cases} \\ a + bv(t) + cP(t) + dP(t)^2 & Por \begin{cases} P > 0 \; and \; v \ge v_a \\ v < v_a \; and \; P \ge P_a \\ v \; isn't \; constant \; or \; v \ge v_b \end{cases} \end{cases} \tag{10}$$

Where $EC_{HEV}(t)$ denotes the instantaneous energy consumption rate for an HEV; $Energy_{BEV\_model}$ represents the energy consumption model for a BEV. Statistical analysis of the data collected from 2010 Toyota Prius found that v_a is 32 km/h, v_b is 72 km/h, and P_a is 10kW.

However, the study in [57] only investigated the energy data from LDVs. There is no evidence proving that this model also works for HDVs such as hybrid buses. With the help of Blacksburg Transit, a 40-foot hybrid electric bus was used to collect the bus data, which included fuel consumption and speed. We used the collected bus data to investigate whether the LDV HEV model could also be used for hybrid buses. The plots of bus speed and fuel consumption level are presented as below. However, the hybrid bus data don't have the same behaviors as light-duty HEVs. The fuel rate only goes to zero when the vehicle completely stops. From the data curve, it is impossible to determine when the hybrid bus uses battery power instead of fuel. Therefore, the HEV model for LDV cannot be used here to estimate the hybrid buses' energy consumption. According to Blacksburg Transit fuel usage data, there is no obvious difference in using a diesel or hybrid bus on the same bus route. Further, the battery capacity in hybrid buses is generally quite low and the electric power engine is not very powerful compared to the fuel-powered engine. Therefore, the change in battery level is minor compared to fuel consumption. Thus, the same method used to develop the energy consumption model for diesel buses can also be used to develop the energy model for hybrid buses.

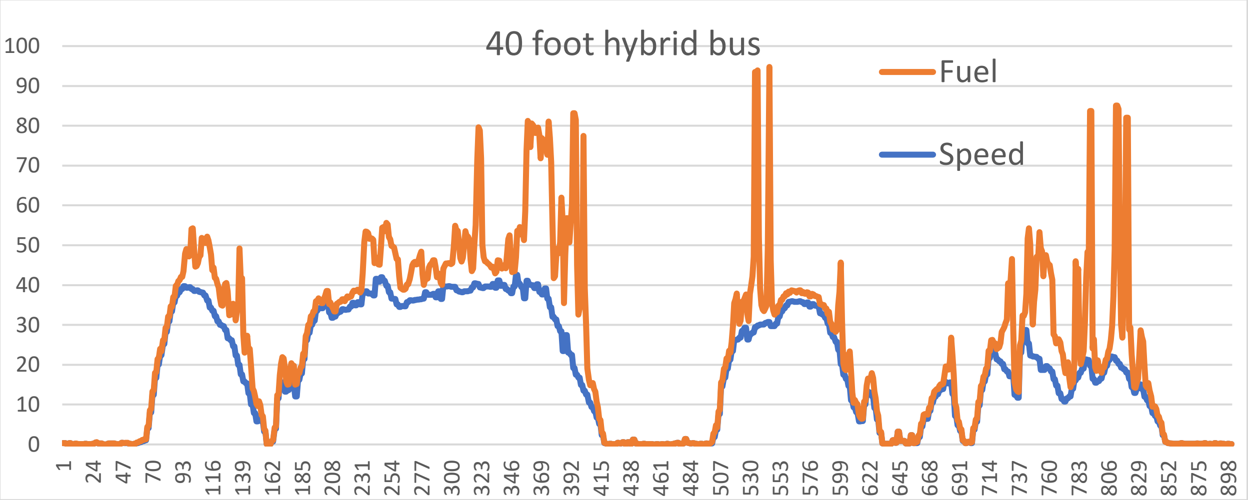
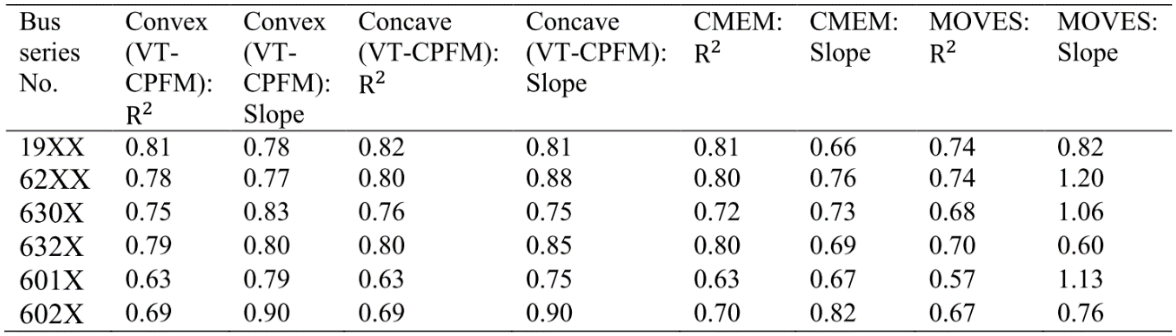


Figure 3: The plots of vehicle speed and fuel consumption.

A regression-based approach was developed in [54] to calibrate the VT-CPFM model for buses. Mass field data, including instantaneous vehicle speed, fuel consumption rate, latitude, longitude, and altitude were collected by test driving the buses around the town of Blacksburg, VA. In order to cover a wide range of real-world driving conditions, the test driving routes consisted of two roadway sections: US 460 business (highway with a speed limit of 65 mph) and local streets (with speed limits from 25 mph to 45 mph). The collected data were divided into two data sets for the test bus. The first data set was used for calibration purposes and included 60% to 70% percent of all data collected for the test bus; the remaining data set was used for model validation. The bus energy models were calibrated using general linear regression to estimate the values of parameters α_0, α_1 and, α_2 in Equation 8. The best model fitting results indicated that the concave models produced the least errors to field measured data [54]. However, there was an issue that the concave models may produce unrealistic driving recommendations. More specifically, the negative second-order parameter in the concave model resulted in mild growth of fuel consumption with the increase of vehicle power. This means that heavier vehicles or vehicles on steeper roads will use a higher cruise speed to minimize fuel consumption, which is not consistent with real-world findings.

Table 1: Comparison of model performance



Bus series No.	Convex (VT-CPFM): R^2	Convex (VT-CPFM): Slope	Concave (VT-CPFM): R^2	Concave (VT-CPFM): Slope	CMEM: R^2	CMEM: Slope	MOVES: R^2	MOVES: Slope
19XX	0.81	0.78	0.82	0.81	0.81	0.66	0.74	0.82
62XX	0.78	0.77	0.80	0.88	0.80	0.76	0.74	1.20
630X	0.75	0.83	0.76	0.75	0.72	0.73	0.68	1.06
632X	0.79	0.80	0.80	0.85	0.80	0.69	0.70	0.60
601X	0.63	0.79	0.63	0.75	0.63	0.67	0.57	1.13
602X	0.69	0.90	0.69	0.90	0.70	0.82	0.67	0.76

Considering the issue with concave models, bus energy consumption models should be constrained to be a convex function of engine power. In order to develop convex energy consumption models for buses, the order of magnitude of the second-order parameter was selected within the range of 1E-05 to 1E-11. Eventually, the parameter of 1E-08 was calculated as the optimal value by considering the tradeoff between model accuracy and the degree of convexity. The model fitting results demonstrate the estimated values for α_0, α_1, and α_2 are 1.66E-03, 8.68E-05, and 1.00E-08 for a diesel bus with a series number of 19XX, and the corresponding values for a hybrid bus with a series number of 601X are 1.00E-03, 5.18E-05, and 1.00E-08. The model validation was conducted by comparing the bus convex energy models with concave models, as well as other state-of-art and state-of-practice models such as CMEM and MOVES. The model comparison results, presented in Table 1, demonstrate that the convex models produce similar estimation accuracy to other methods, with the benefit of avoiding conflicts with physical laws. The model validation results, illustrated in Figure 4 and Figure 5, present that the diesel and hybrid bus models can produce accurate estimates to the measured data. Therefore, we used the convex bus models in the proposed Eco-CACC system to compute optimal trajectories for buses. More details about developing and validating convex energy consumption models for diesel and hybrid buses can be found in [55].

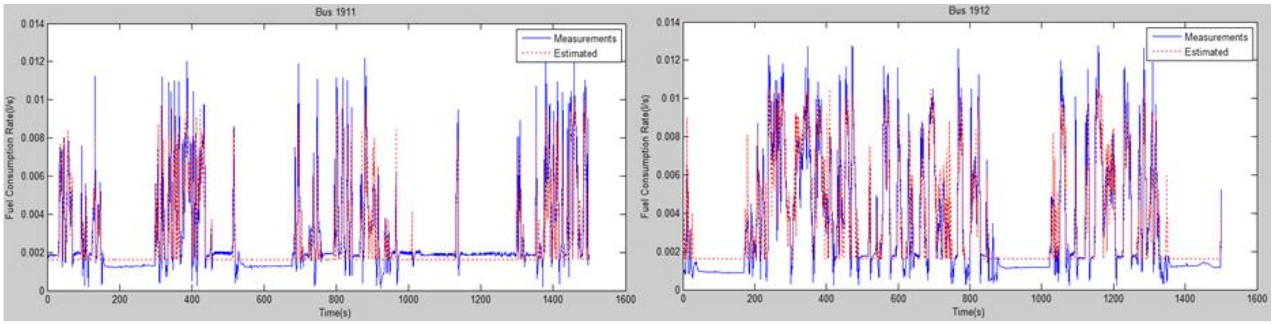


Figure 4: Model validation for diesel bus energy consumption model.

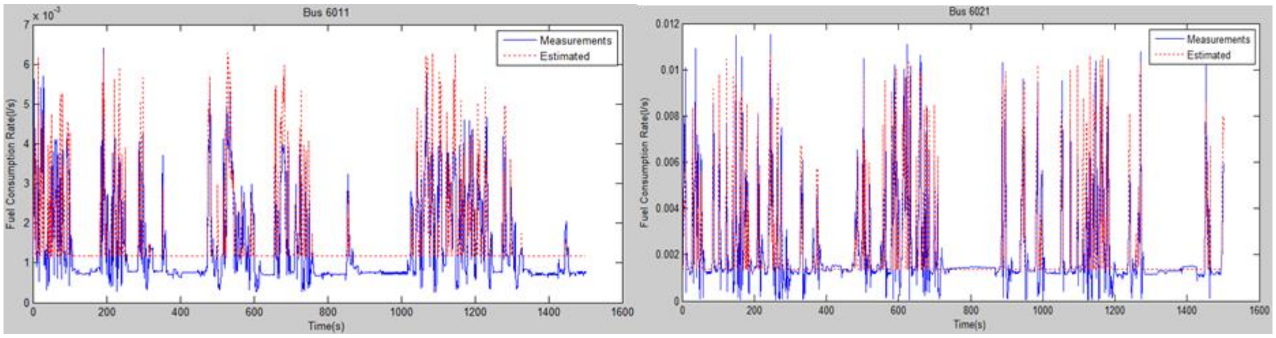


Figure 5: Model validation for hybrid bus energy consumption model.

3. Simulation Test

3.1 Simulation Environment

INTEGRATION, microscopic traffic simulation software developed over the past decade [58-61] was used to simulate the traffic network to test the proposed bus Eco-CACC system (See Figure 6). The INTEGRATION model is a trip-based microscopic traffic assignment, simulation, and optimization model that has the capability of modeling networks of up to 10,000 links and 500,000 vehicle departures. It can also run the simulation while tracking each individual vehicle’s movement every 0.1 second. With this level of resolution, INTEGRATION is capable of processing detailed analyses of lane-changing movements and shock wave propagations. The model updates vehicle speeds based on a user-specified steady-state speed-spacing relationship and the speed difference between the subject vehicle and the vehicle ahead of it, and speeds are calibrated using field loop detector data. A more detailed description of INTEGRATION is provided in [60, 61].

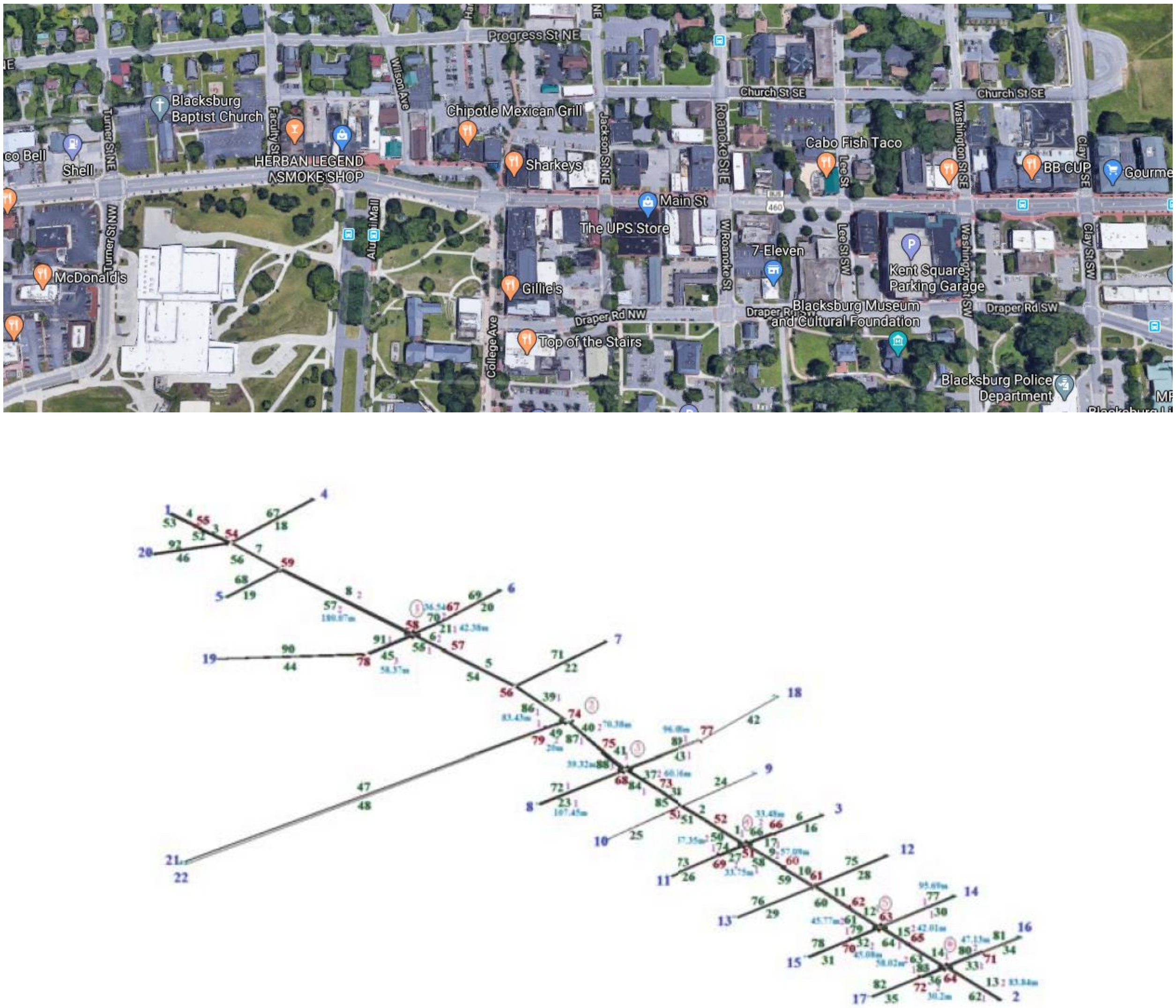


Figure 6: The simulated traffic network.

The arterial traffic network located in the heart of downtown of Blacksburg was simulated using INTEGRATION software. The network includes six signalized intersections on the main street. The origin-destination (O-D) demand matrices were generated using the QueensOD software based on traffic counts collected during the afternoon peak period (4~6 p.m.), at 15 minutes intervals, for the year 2012. Considering that the simulated network includes four bus routes and the interval for each bus on the same route is about 15 minutes, the estimated total number of buses was 32. In this way, the simulated network included two types of vehicles—hybrid buses and LDVs (sedans).

3.2 Test Results

The original O-D demand calibrated by traffic counts during the afternoon peak period was defined as 100% traffic demand. In order to test the performance of the bus Eco-CACC system under various traffic conditions (from light to heavy traffic volume), traffic demands of 25%, 50%, 75% and 100% were used in tests. In addition, the three scenarios shown below were considered during the tests.

- Base case: no Eco-CACC system
- Scenario 1: Eco-CACC system enabled for buses
- Scenario 2: Eco-CACC system enabled for all vehicles

Table 2: Simulation test results

OD Demand	**Test Scenario**	**Average Bus Energy Consumption (ml)**	**Average Vehicle Energy Consumption (ml)**	**Average Total Delay (sec)**
25% Demand	Base case	312.3	95.6	32.9
	Scenario 1	288.9	92.2	32.0
	Scenario 2	253.1	83.3	30.3
	Reduction 1	7.5%	3.6%	2.6%
	Reduction 2	12.4%	9.6%	5.4%
50% Demand	Base case	360.9	118.3	46.5
	Scenario 1	338.5	115.0	45.5
	Scenario 2	302.6	104.9	43.3
	Reduction 1	6.2%	2.8%	2.2%
	Reduction 2	10.6%	8.8%	4.7%
75% Demand	Base case	471.1	158.2	67.9
	Scenario 1	454.1	155.7	66.9
	Scenario 2	425.1	144.5	65.1
	Reduction 1	3.6%	1.6%	1.4%
	Reduction 2	6.4%	7.2%	2.8%
100% Demand	Base case	524.4	175.1	88.3
	Scenario 1	512.3	173.2	87.7
	Scenario 2	492.9	162.1	85.7
	Reduction 1	2.3%	1.1%	0.7%
	Reduction 2	3.8%	6.4%	2.3%

The average performances for buses only and all vehicles under various traffic demand and the three scenarios are summarized in Table 2. Note that reduction 1 represents the reduction for scenario 1 compared with the base case, and reduction 2 represents the reduction for scenario 2 compared with the base case. The test results demonstrate that the Eco-CACC system can efficiently reduce the average energy consumption for vehicles to pass signalized intersections in the traffic network. Compared with the base case, the average reductions of bus energy for scenario 1 are 7.5% for 20% traffic demand, 6.2% for 50% traffic demand, 3.6% for 75% demand, and 2.3% for 100% traffic demand. This means that the proposed bus Eco-CACC worked better under alight traffic load, since the intersection queue and multi-intersection impacts were not yet considered. In addition, while only the bus trajectories were optimized by Eco-CACC in scenario 1, the overall average vehicle energy consumption levels were also reduced, by 3.6%, 2.8%, 1.6%, and 1.1%, under various traffic demands. These reductions are due to the fact that the proposed Eco-CACC system helps buses to pass smoothly through intersections, allowing other vehicles following buses to drive smoothly, thus resulting in energy savings for average vehicles in the network. When all vehicles are controlled by the Eco-CACC system, energy consumption is further reduced in the traffic network. Compared with the base case, the average reductions in bus energy for scenario 1 were 12.4% for 20% traffic demand, 10.6% for 50% traffic demand, 6.4% for 75% demand, and 3.8% for 100% traffic demand. The average energy consumption and delay for an average vehicle was also further reduced. The average total delay reductions per vehicle under traffic demand from 25% to 100% were 5.4%, 4.7%, 2.8%, and 2.3%, respectively. The results in the following bar plots (Figure 7, Figure 8, Figure 9) clearly demonstrate that the benefits of using Eco-CACC for traffic network saving energy and delay.

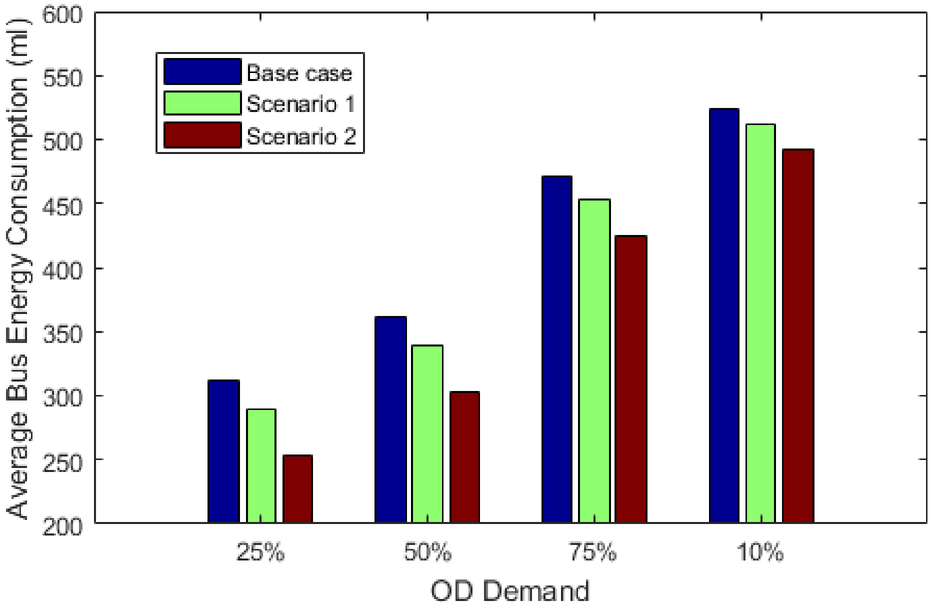


Figure 7: Average energy consumption per bus.

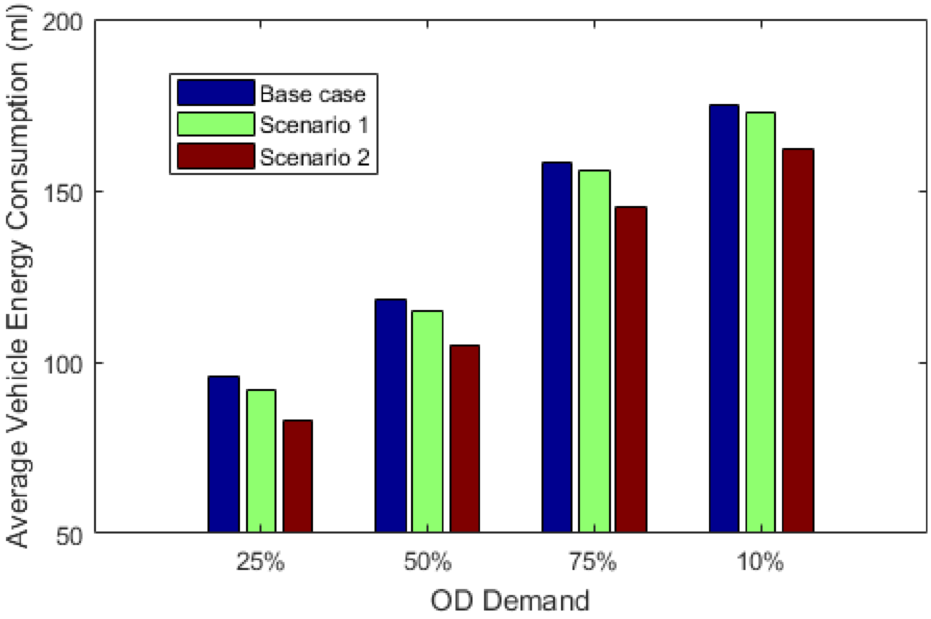


Figure 8: Average energy consumption per vehicle.

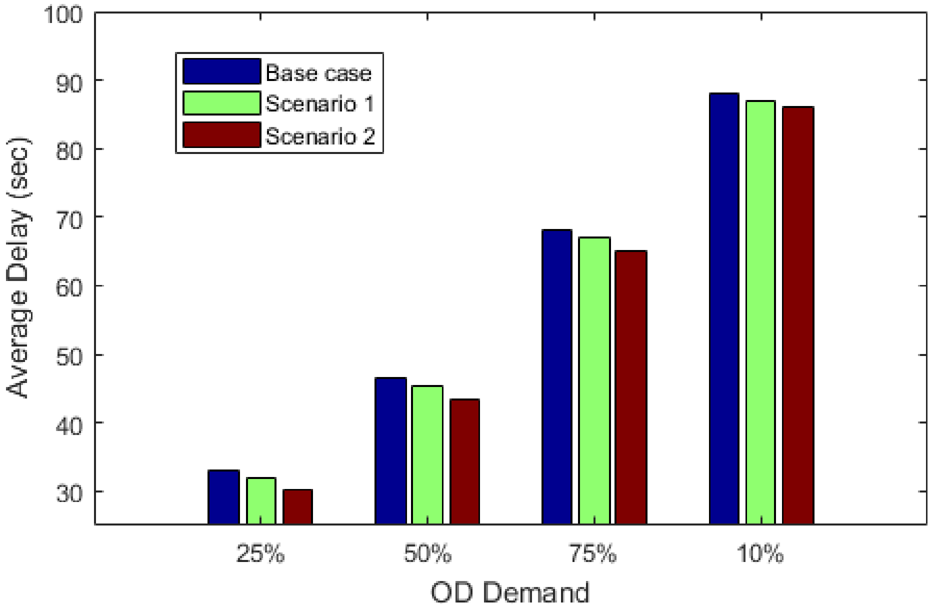


Figure 9: Average total delay per vehicle.

4. Driving Simulator Test

4.1 Participants and Designed Scenarios

Using online advertisements, flyers, and email invitations, 70 participants were recruited from MSU and the Baltimore metro area to drive nine different scenarios (Table 3). 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 eligibility and scheduled to drive in the simulator environment.

Participants had to have a valid driver's license and were compensated at $15 per hour for their study participation. Participants were asked to fill out a pre-survey questionnaire, drive in the different simulated scenarios, and then fill out the post-survey questionnaire after driving to see how their experience affected their driving behavior.

Table 3: Simulated scenarios' description

Scenario	Information Type	Traffic Type	Road Condition	Number of Lanes	Grade
1	No Information	No Traffic	Uphill	1 lane	0.03
2	No Information	No Traffic	Downhill	1 lane	-0.03
3	No Information	Mild Traffic	Uphill	3 lanes	0.03
4	No Information	Mild Traffic	Downhill	3 lanes	-0.03
5	Recommended Speed Voice	No Traffic	Uphill	1 lane	0.03
6	Recommended Speed Voice	No Traffic	Downhill	1 lane	-0.03
7	Recommended Speed Voice	Mild Traffic	Uphill	3 lanes	0.03
8	Recommended Speed Voice	Mild Traffic	Downhill	3 lanes	-0.03
9	Speed Change Voice	No Traffic	Uphill	1 lane	0.03

The nine scenarios included providing no information as a benchmark versus providing recommended speed via voice command or speed change (increase or decrease) via voice command. We differentiated uphill versus downhill (due to differences in emission) and no traffic versus mild traffic. The scenarios are explained in more detail in the next section.

4.2 Driving Performance

This study implemented an Eco-Speed-Control system in a full-scale 3D driving simulator with VR-Design Studio software provided by Forum8 Company (http://www.forum8.co.jp) 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 in order to compare that benchmark driving behavior with other types of Eco-Speed-Control guidance. Participants then drove different Eco-Speed-Control guidance scenarios using voice guidance on a midsize road network in the Baltimore metropolitan area that included three intersections with different road types (uphill and downhill). The driving data consisted of vehicle speed, distance to stop bar, traffic light phase, traffic light color and recommended speed for each scenario in 200 meters before and 200 meters after each intersection.

In the aforementioned Eco-Speed-Control area at each intersection, participants were given the recommended speed or speed change via voice; in recommended speed voice scenarios, the exact speed (e.g., 28 mph) was announced, while in change speed voice scenarios, participants heard statements like "increase speed," "decrease speed," and "no change." Participants were supposed to drive at 30 mph and change their speed in response to the information provided via Eco-Speed-

Control (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.

Before the start of the driving experiment, we suggested to the participants that they follow the provided guidance during their experiment in order to traverse the intersection without stopping, so as to reduce emissions. However, there was no instruction that they HAD to follow the guidance. Some participants followed the provided speed guidance while others did not. It took most participants a while to get accustomed to following at and adjusting to the recommended speed. All participants drove different scenarios and their speed behavior was analyzed for each scenario, including the scenario without information (base) and those scenarios with Eco-Speed-Control guidance.

4.3 Data Collection

Questionnaires

The questionnaires included participants' demographic information and their attitude and real-world driving behavior before the driving simulator experience (pre-survey) and their attitude after driving the simulator (post-survey). Observers gave participants the option of completing the questionnaire on their own or with the assistance of the observer.

Driving Simulator

Driving data, such as speed, acceleration, throttle, traffic signal color, and phase of the traffic signal, were collected in a fixed high-fidelity driving simulator. The driving simulator directly logged all the related data, had three 40-inch screens, and software (VR Design Studio) that renders realistic roads, signals, signs, models, and traffic (Figure 10). The study area was a medium sized road network of the Baltimore metropolitan area consisting of three signalized intersections.

Figure 10: Driving simulator.

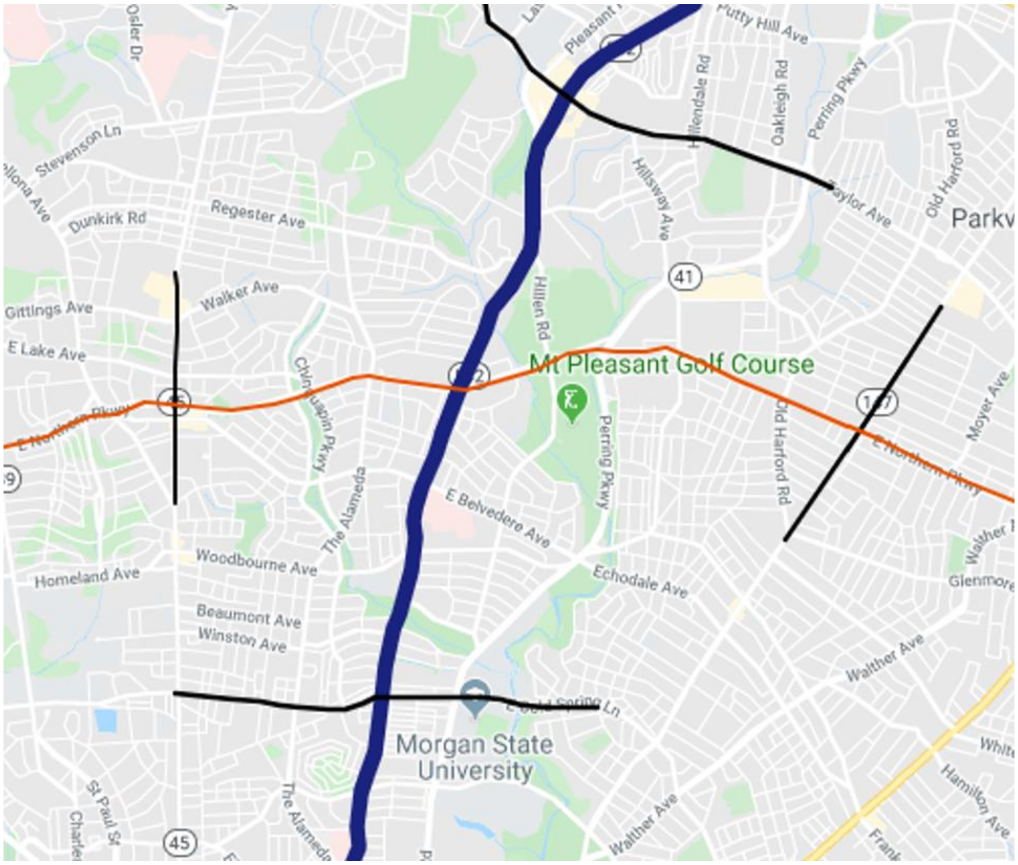


Figure 11: Simulated study area.

The Blue line is the 3-lane road and the orange line is the 1-lane road.

4.4 Data Analysis and Test Results

Descriptive statistics were obtained from pre-survey questionnaire data regarding participant characteristics. The participant pool consisted of 41.4% male subjects and 58.6% female subjects. Participants were 18 to 65 years old; 32.9% of these were 18 to 25 years old (Table 4).

Table 4 : Descriptive analysis

Variables		**Frequency**	**Percent**
Gender	Female	41	58.6
	Male	29	41.4
Age	18 to 25	23	32.9
	26 to 35	20	28.6
	36 to 45	8	11.4
	46 to 55	10	14.3
	56 to 65	9	12.8
Ethnicity	White	11	15.7
	Black or African American	47	67.1
	Asian	4	5.7
	Hispanic, Latino or Spanish Origin	2	2.9
	Other	6	8.6
	Total	70	100.0
Level of Education	High School or Less	13	18.6
	College Student	7	10.0
	Associate Degree	4	5.7
	Bachelor's Degree	17	24.3
	Graduate Degree	26	37.1
	Professional Degree	3	4.3
Employment Status	Unemployed	11	15.7
	Employed Part time	19	27.1
	Employed Full time	40	57.2
Driving License	I don't have a license	2	2.9
	Learner's Permit	6	8.6
	Permanent License for regular vehicle (class C)	59	84.3
	Permanent License for all types of vehicle (class A)	3	4.2
Type of Vehicle	Sedan	40	57.1
	Midsize SUV	11	15.7
	Large SUV	5	7.1

Variables		Frequency	Percent
	Hatchback	2	2.9
	Small Truck	3	4.3
	Crossover Large Truck	2	2.9
	Large Truck	6	8.6
	Other	1	1.4
Annual Household Income	Less than $20K	20	28.6
	$20K to $30K	9	12.9
	$30 to $50K	10	14.3
	$50 to $75K	13	18.6
	$75 to $100K	5	7.1
	More than $100K	13	18.5
Number of Adults	1	24	34.3
	2	28	40.0
	3	10	14.3
	4 and more	4	11.4
Number of Children	None	49	70.0
	1	14	20.0
	2	4	5.7
	More than 2	3	4.3

Table 5: T-test for following speed in two voice scenarios (uphill, no traffic, and one lane)

Variable		N	Mean	Std. Deviation	t	Sig. (2-tailed)
Follow Percentage	**Recommended Speed Voice**	206	0.6957	0.16118	-8.284	0.000
	Speed Change Voice	207	0.8070	0.10656	-8.276	0.000

In order to find the percentage of drivers who followed the recommended speed by different types of guidance, including “recommended speed voice” and “speed change voice,” we utilized a t-test. The results of the t-test (Table 5) show that 80% of participants followed the speed in the speed change voice scenario, while 69% of participants followed the speed in the recommended speed voice scenario.

As previously mentioned, we simulated three intersections in this study to find drivers’ following\speed behavior at coordinated signalized intersections. To find the following percentage at each intersection we applied analysis of variance (ANOVA) and post hoc analysis (using Tukey’s test) for each Eco-Speed-Control scenario. The results (Table 6) show that 64%

of participants followed the recommended speed in the first intersection voice scenarios and that the percentage of people following the recommended speed in the second and third intersections was higher than in the first intersection (Table 7).

Table 6: ANOVA results by intersection for following recommended speed in voice scenarios

	N	Mean	Std. Deviation	Std. Error	F	Sig.
First Intersection	274	0.648	0.238	0.014	18.788	0.000
Second Intersection	275	0.735	0.147	0.009		
Third Intersection	274	0.728	0.152	0.009		

Table 7: Tukey's test results by intersection for following recommended speed in voice scenarios

		Mean Difference (I-J)	Std. Error	Sig.
First Intersection	Second Intersection	-.08657*	0.01567	0.000
	Third Intersection	-.07942*	0.01568	0.000
Second Intersection	First Intersection	.08657*	0.01567	0.000
	Third Intersection	0.00714	0.01567	0.892
Third Intersection	First Intersection	.07942*	0.01568	0.000
	Second Intersection	-0.00714	0.01567	0.892

* The mean difference is significant at 0.05.

The ANOVA results of the following speed in change speed voice scenarios show that about 80% of participants followed the recommended speed change in different intersections and that there was no statistically significant difference among them.

Table 8: ANOVA results by intersection for following change speed recommendation in change speed voice scenarios.

	N	Mean	Std. Deviation	Std. Error	F	Sig.
First Intersection	69	0.8088	0.09744	0.01173	0.509	0.602
Second Intersection	69	0.8151	0.11090	0.01335		
Third Intersection	69	0.7971	0.11153	0.01343		

Table 9: Tukey's results by intersection for following change speed recommendation in change speed voice scenarios.

		Mean Difference (I-J)	Std. Error	Sig.
First Intersection	**Second Intersection**	-0.00629	0.01819	0.936
	Third Intersection	0.01178	0.01819	0.794
Second Intersection	**First Intersection**	0.00629	0.01819	0.936
	Third Intersection	0.01807	0.01819	0.582
Third Intersection	**First Intersection**	-0.01178	0.01819	0.794
	Second Intersection	-0.01807	0.01819	0.582

5. Conclusions

Studies over the past decade have shown that eco-driving systems that provide speed advisories to drivers/vehicles using V2I and V2V communications can help improve traffic mobility and reduce vehicle energy consumption and emission levels. However, most studies focus only on LDVs, omitting consideration of HDVs, when designing eco-driving systems. Given the potential for improved mobility and reduced energy/emissions that a bus eco-driving system might contribute to the multi-modal transportation network, the need to develop an eco-driving system for buses is clear. Compared to LDVs, HDVs such as buses have poor fuel efficiency, especially in stop-and-go traffic conditions, due to their large curb weights and sizes.

This study extends the Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system previously developed for LDVs to HDVs (diesel and hybrid electric buses). As described in this report, the energy consumption models for diesel and hybrid buses were investigated and field data collected by Blacksburg Transit was subsequently used to calibrate bus models. The bus Eco-CACC system, with both manual and automated control modes, was then developed by incorporating the vehicle dynamic and energy consumption models for buses. The manual Eco-CACC mode was tested by participants using driving simulators at MSU under various scenarios, including the provision of different types of information. In addition, the automated bus Eco-CACC was is tested using INTEGRATION microscopic simulation software to quantify Eco-CACC's system-wide impacts under various traffic demand and vehicle types. The test results demonstrated that the proposed system could improve transit operations by reducing delay and helping transit agencies save on energy costs, resulting in an improved transit level of service, increased ridership, and improved traffic mobility.

6. References

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