Field Testing of Eco-Speed Control Using V2I Communication

CVI UTC

CONNECTED VEHICLE/INFRASTRUCTURE UNIVERSITY TRANSPORTATION CENTER (CVI-UTC)

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Field Testing of Eco-Speed Control Using V2I Communication

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Disclaimer

Connected Vehicle/Infrastructure UTC

The mission statement of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) is to conduct research that will advance surface transportation through the application of innovative research and using connected-vehicle and infrastructure technologies to improve safety, state of good repair, economic competitiveness, livable communities, and environmental sustainability.

The goals of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) are:

- Increased understanding and awareness of transportation issues
- Improved body of knowledge
- Improved processes, techniques and skills in addressing transportation issues
- Enlarged pool of trained transportation professionals
- Greater adoption of new technology

Abstract

This research focused on the development of an Eco-Cooperative Adaptive Cruise Control (Eco-CACC) System and addressed the implementation issues associated with applying it in the field. The Eco-CACC system computes and recommends a fuel-efficient speed based on Signal Phasing and Timing (SPaT) data received from the traffic signal controller via vehicle-to-infrastructure (V2I) communication. The computed speed profile can either be broadcast as an audio alert to the driver to manually control the vehicle, or, implemented in an automated vehicle (AV) to automatically control the vehicle. The proposed system addresses all possible scenarios, algorithmically, that a driver may encounter when approaching a signalized intersection. Additionally, from an implementation standpoint, the research addresses the challenges associated with communication latency, data errors, real-time computation, and ride smoothness. The system was tested on the Virginia Smart Road Connected Vehicle Test Bed in Blacksburg, VA. Four scenarios were tested for each participant: a base driving scenario, where no speed profile data was communicated; a scenario in which the driver was provided with a "time to red light" countdown; a manual Eco-CACC scenario where the driver was instructed to follow a recommended speed profile given via audio alert; and finally, an automated Eco-CACC scenario where the AV system controlled the vehicle's longitudinal motion. The field test included 32 participants, and each participant completed 64 trips to pass through a signalized intersection for different combinations of signal timing and road grades. The analyzed results demonstrate the benefits of the Eco-CACC system in assisting vehicles to drive smoothly in the vicinity of intersections, thereby reducing fuel consumption levels and travel times. Compared to an uninformed baseline drive, the longitudinally automated Eco-CACC system controlled vehicle drive resulted in savings in fuel consumption levels and travel times of approximately 37.8% and 9.3%, respectively.

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Background

The United States is one of the world's prime petroleum consumers, burning more than 22% of the total petroleum refined on the planet. The transportation sector consumes, by itself, nearly three-quarters of this product and the U.S. is, consequently, ranked as the second largest carbon emitter in the world. The surface transportation sector is faced with important related challenges, including the availability of fuel to power vehicles and the emission of greenhouse gases. It is therefore important to reduce petroleum consumption and make surface transportation more efficient and sustainable [1].

With the development of information and communication technology, connectivity between vehicles, and between vehicles and transportation infrastructure, is now possible. For instance, information about signal phasing and timing (SPaT) as well as location and speed of vehicles could be easily transmitted and exploited for any application. The advanced communication power in connected vehicles (CVs) ensures a high information update rate, which enables researchers to develop connected transportation systems meeting safety, economic, and efficiency challenges [2]. Studies have shown that vehicle fuel consumption levels near signalized intersections are dramatically increased due to vehicles' deceleration and acceleration [3, 4]. Over the past decades, many studies have focused on changing traffic signal timing to optimize vehicles' delay and fuel demand levels [5, 6]. More recently, researchers have attempted to use CVs and infrastructure technologies to develop eco-driving strategies that are more fuel-efficient. The concept of eco-driving is to provide, in real-time, recommendations to drivers so that vehicle maneuvers can be adjusted accordingly to reduce fuel consumption and emission levels [7-9].

One such application is Eco-Speed Control (ESC), which was developed to optimize individual vehicle fuel consumption by recommending a fuel-efficient trajectory using advanced information from surrounding vehicles and upcoming signalized intersections [10]. Researchers have developed various ESC algorithms in recent years. Malakorn and Park proposed a cooperative adaptive cruise control system using SPaT information to minimize absolute acceleration levels of vehicles and reduce fuel consumption levels [11]. Kamalanathsharma and Rakha developed a dynamic programming-based fuel-optimization strategy using recursive path-finding principles, and evaluated the developed strategy using an agent-based modeling approach [12]. Asadi and Vahidi proposed a schedule optimization algorithm to allocate "green-windows" for vehicles to pass through a series of consecutive signalized intersections [13]. Guan and Frey further extended the work in [13] to generate a brake-specific fuel consumption map, which enables optimization of gear ratios, and uses dynamic programming to find the optimum solution [14].

Most ESC algorithms are developed and tested in a traffic simulation environment where vehicles are forced to follow the recommended speed as calculated by the ESC algorithms. However, there are a number of problems not treated in simulation software that need to be addressed in order to implement ESC systems in the field, such as communication latency, system malfunction, data collection error, driver perception/reaction delay, driver distraction resulting from following posted recommended speed, etc. A few existing studies have investigated the potentials of implementing ESC in the field. For instance, Barth and Xia developed a dynamic eco-driving system and conducted a field test on arterial roads [15-17]. However, vehicle fuel consumption was not explicitly considered in their algorithm objective function. Instead, their algorithm attempted to optimize vehicle acceleration/deceleration profiles to minimize the total tractive power demand and the idling time so that the fuel consumption levels were also reduced [17]. Munoz-Organero and Magana developed an expert system to reduce fuel consumption by calculating optimal deceleration patterns and minimizing the use of braking. The system was implemented on Android mobile devices and field-tested using five different vehicle brands and nine drivers [18]. However, fuel consumption was not explicitly considered in their objective function either. Rather, the algorithm provided the optimum solution for drivers to release the accelerator pedal and assumed it to result in a reduction of fuel consumption.

The research presented in this report details the development of an Eco-CACC system that computes and recommends a fuel-efficient speed profile in a CV environment. The objective function of the proposed ESC algorithm was the explicit minimization of the total fuel consumption required to travel from some distance upstream of the intersection to a distance downstream of the intersection. In addition, various constraints were constructed using the relationship between vehicle speed, acceleration, deceleration, and traveled distance. Dynamic programming was used to discretize the solution space and solve the optimization problem to compute the optimum speed profile. The system was tested on the Virginia Smart Road Connected Vehicle Test Bed. Four scenarios were tested for each participant: a baseline driving scenario where no speed profile data was communicated; a scenario that provided drivers with an audible red light countdown (“time to red light”); a manual Eco-CACC scenario where the driver was instructed to follow a recommended speed profile presented via audio alert; and finally, an automated Eco-CACC scenario that controlled the vehicle longitudinally to follow the speed profile. The field test included 32 participants, and each participant completed 64 trips to pass through a signalized intersection under different combinations of signal timing and road grades. The analyzed results demonstrate the benefits of the Eco-CACC system in assisting vehicles to drive smoothly in the vicinity of intersections and thereby reduce fuel consumption levels. Compared to the baseline driving scenario, the longitudinally automated Eco-CACC system controlled vehicle resulted in savings in fuel consumption levels and travel times in the range of 37.8% and 9.3%, respectively.

Methodology

Definitions and Assumptions

Given that both upstream and downstream vehicle speed profiles are considered in the ESC algorithm, it was necessary to define a control region in the vicinity of signalized intersections.

Taking the communication range of Dedicated Short Range Communications (DSRC) into account, the ESC algorithm was activated at a distance of d_{up} upstream of the intersection to a distance of d_{down} downstream of the intersection. Note that the distance was calculated from the vehicle's location to the intersection stop line. The value of d_{down} was defined to ensure that the vehicle had enough downstream distance to accelerate from zero mph to the speed limit at a low throttle level (i.e., 0.3). This ensured that all computations were made along a fixed distance of travel.

The ESC algorithm described in this report computes the optimum vehicle speed profile starting from upstream to downstream of a signalized intersection by incorporating vehicle dynamics and fuel consumption models. It should be noted that the impacts from neighboring vehicles, such as car-following and/or lane-changing behavior, were not considered in the algorithm tested in this report. However, the impact of these factors was tested in a traffic simulation environment [1, 12, 19-22]. As such, the tested algorithm treats ESC under light traffic conditions. The developed ESC algorithm could be refined for more complicated traffic conditions by considering the calculated optimum speed profile as the variable speed limit as demonstrated in [22]. Consequently, a general solution of ESC can be achieved by constraining the vehicle speed by the variable speed limit produced by the algorithm as well as other common traffic flow constraints, such as car following model, gap acceptance, collision avoidance, etc.

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 were considered in developing the ESC strategies:

- **Case 1:** vehicle is able to pass through the intersection during the green phase without decelerating (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 keep that speed to pass through the intersection during the green phase.

The two cases above describe the vehicle's optimum trajectory in order to minimize fuel consumption while traversing the intersection. After passing the stop line, the vehicle tries 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 works by both Kamalanathsharma and Xia [1, 15]. Figure 1 demonstrates the optimum speed profile when a vehicle passes a signalized intersection, and the ESC algorithm helps identify the best acceleration and deceleration levels. The sample speed profiles (initial speed u_1 and u_2) for case 1 are highlighted in blue, and the sample speed profile (initial speed u_3) for case 2 is represented in maroon. The road speed limit is denoted as u_f. Note that the samples of case 1 and 2 in Figure 1 happen at the red phase when the vehicle passes the upstream distance d_{up}. The same classification of case 1 and 2 also exists for the green phase. For the sake of simplicity in explaining the proposed ESC algorithm, an initial red phase is assumed for the following sections.

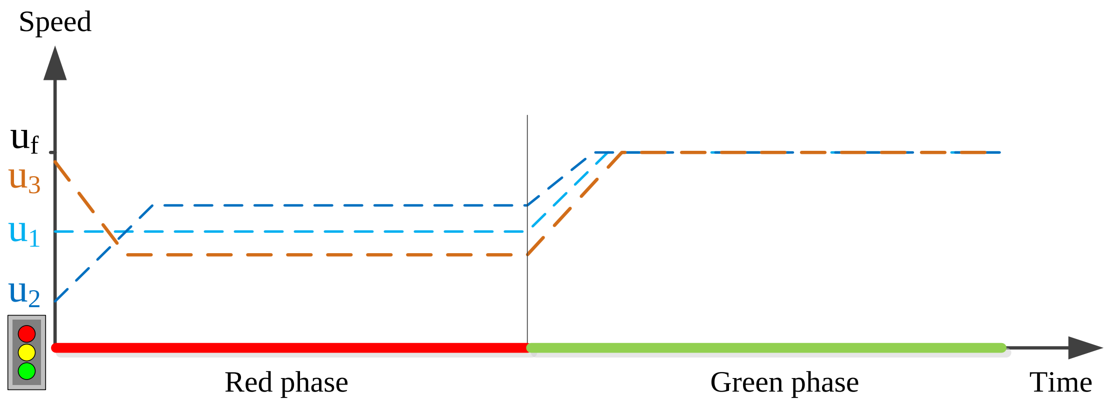


Figure 1: Samples of optimum speed profile when vehicle approaches a signalized intersection.

Fuel Consumption and Vehicle Dynamics Models

In the proposed ESC algorithm, deceleration is assumed constant for case 2. In case 1, vehicle acceleration follows the vehicle dynamics model developed in [23]. 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 [1], a constant throttle level of 0.6 is assumed in the vehicle dynamic model to simplify the ESC algorithm calculations 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 (0) to (0).

$$v(t + \Delta t) = v(t) + 3.6\frac{F(t) - R(t)}{m}\Delta t \quad (0)$$

$$F = \min\left(3600 f_p \beta h_d \frac{P}{v}, m_{ta} g \mu\right) \quad (0)$$

$$R = \frac{\rho}{25.92} C_d C_h A_f v^2 + mg\frac{c_{r0}}{1000}\left(c_{r1} v + c_{r2}\right) + mgG \quad (0)$$

where

- F is the vehicle tractive effort;
- R represents the resultant of the resistance forces, including aerodynamic, rolling and grade resistance forces;
- f_p is the driver throttle input [0,1] (unitless);
- β is the gear reduction factor (unitless), and this factor is set to 1.0 for light-duty vehicles;

- η_d is the driveline efficiency (unitless); P is the vehicle power (kW);
- m_{ta} is the mass of the vehicle on the tractive axle (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).

A fuel consumption model is needed in the ESC algorithm to calculate fuel consumption using vehicle speed data. The VT-CPFM-1 was selected due to its simplicity, accuracy, and ease of calibration [24]. The selected fuel model utilizes instantaneous power as an input variable and can be easily calibrated using publicly available fuel economy data (e.g., Environmental Protection Agency-published city and highway gas mileage). Thus, the calibration of model parameters does not require gathering any vehicle-specific data. The VT-CPFM-1 is formulated as presented by Equations 4 and 5.

$$FC(t) = \begin{cases} \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t); & P(t) \geq 0 \\ \alpha_0; & P(t) < 0 \end{cases} \, . \tag{0}$$

$$P(t) = \left(\frac{R(t) + 1.04ma(t)}{3600\eta_d} \right) v(t) \, . \tag{0}$$

Where α_0, α_1 and α_2 are the model parameters that can be calibrated for a particular vehicle, and the details of calibration steps can be found in [24]; $P(t)$ is the instantaneous total power (kW); $a(t)$ is the acceleration at instant t, which can be calculated by consecutive time speed values; $v(t)$ is the velocity at instant t; and $R(t)$ is the resistance force on the vehicle as given by Equation (0).

Eco-Speed Control Algorithm

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

Case 1:

The vehicle can pass the intersection during a green phase without decelerating. In order to obtain the maximum average speed to reduce fuel consumption, the cruise speed during the red phase is defined as shown by Equation (0). If u_c is equal to the 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 (0) to (0). 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 fuel consumption from upstream d_{up} to downstream d_{down}.

$$u_c = \min\left(\frac{d_{up}}{t_r}, u_f\right). \qquad (0)$$

Case 2:

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

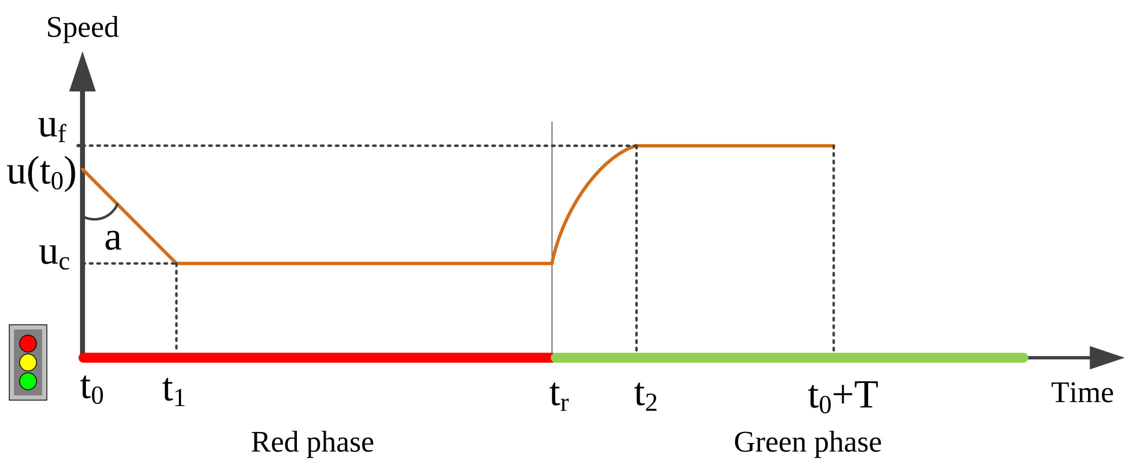


Figure 2: Optimum speed profile.

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

$$\min \int_{t_0}^{t_0+T} FC\left(u(t)\right) \cdot dt. \qquad (0)$$

where *FC(*)* denotes the calculated fuel consumption at instant *t* (Equation (0)) with vehicle speed *u(t)*. The constraints can be constructed by the relationships among speed, acceleration, deceleration, and distance as shown below:

s.t.

$$u(t):\begin{cases} u(t)=u(t_0)-at; & t_0 \le t \le t_1 \\ u(t)=u_c; & t_1 < t \le t_r \\ u(t+\Delta t)=u(t)+3.6\dfrac{F(f_p)-R(u(t))}{m}\Delta t; & t_r < t \le t_2 \\ u(t)=u_f; & t_2 < t \le t_0+T \end{cases} \quad . \tag{0}$$

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

In Equation (0), the functions *F(*)* and *R(*)* represent the vehicle tractive effort and resistance force as computed by Equations (0) and (0), respectively. According to the relationships in Equations (0) and (0), the deceleration a and throttle level f_p are the only unknown variables. It is important to note that the maximum deceleration level is limited to 5.9 m/s^2 (comfortable deceleration threshold felt by a driver). In addition, the throttle level is set to range from 0.4 to 0.8, given that the optimum throttle level is usually around 0.6 [1]. Dynamic programming (DP) is used to solve the problem by listing all the combinations of deceleration and throttle values and calculating the corresponding fuel consumption levels; the minimum calculated fuel consumption level gives the optimum parameters [1, 14].

Implementation of ESC into an Eco-CACC System

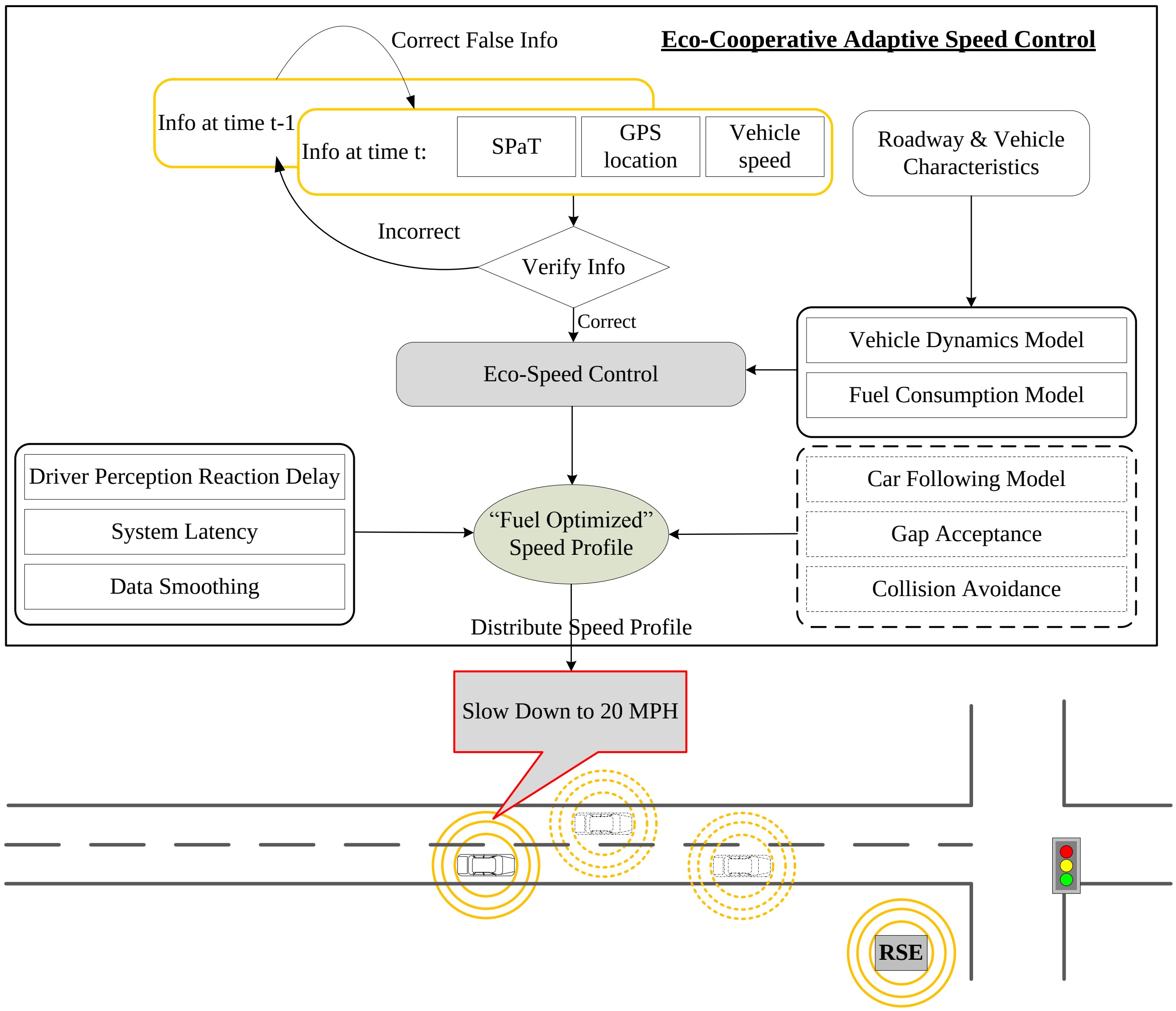


Figure 3: Illustration of the Eco-CACC system.

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

Considering the practical situation, Figure 3 provides an illustration showing the implementation of ESC into an Eco-CACC System. When the vehicle enters the Eco-CACC range at the intersection, the vehicle receives SPaT information from roadside equipment (RSE). At the same time, the vehicle onboard unit collects vehicle speed and GPS location data. Those data are the input information for ESC. Note that all the input information should be verified to avoid false information due to device malfunction or measurement error. Any false information can be updated using the information from the previous time interval. In addition to these time-dependent data, some constant data for the roadway and vehicle characteristics are also needed for the Eco-CACC, since they are used in the vehicle dynamics and fuel consumption models. Using the developed ESC algorithm described in the previous section, the "fuel optimized" speed profile can be obtained. If there are no surrounding vehicles on the road (the conditions of the test described in this paper), only constraints such as driver perception/reaction delay, system latency and data smoothing are considered when extracting the target speed from the speed profile. Otherwise, the impacts of other vehicles should be considered as well, which will mean more constraints, including car following model, gap acceptance, collision avoidance, etc. Eventually, the speed profile can be computed and distributed to the vehicle control system. In the developed Eco-CACC system, the computed speed profile can either be broadcast as an audio alert to the driver to manually control the vehicle's speed, or be implemented into the automated vehicle (AV) system to automatically control the vehicle's speed. The performance of the Eco-CACC system was validated in the field test of this study and is discussed in the following sections.

Field Test

Test Environment Setup

The Virginia Smart Road Connected Vehicle Test Bed facility was used to test the benefits of the proposed Eco-CACC system. The Virginia Smart Road is a 3.5 km (2.2 mile) stretch of road with turn-around loops at either end. The layout of the test road is illustrated in Figure 4. The road near the signalized intersection is a two-lane highway (one-lane for each direction). The four-way signalized intersection is located in the center of the figure. The road vertical grades for the downhill and uphill direction are approximately 3%. The stop lines for both directions are marked in red on the center of the figure. The Eco-CACC was activated when the testing vehicle was at 250 meters upstream of the stop bar and was deactivated when the testing vehicle was at 180 meters downstream of the stop line. Thus, the values of d_{up} and d_{down} are 250 and 180 meters, respectively. The speed limit of the testing facility is 40 mph. In order to have a fair comparison across different runs, it was determined that vehicles should drive at 40 mph when entering and leaving the range of the system. Thus, two cones were placed at 250 meters upstream (the first cone) and 180 meters downstream (the second cone) of the intersection in each direction, so there were four cones total. Drivers were asked to drive at 40 mph to pass the cones.

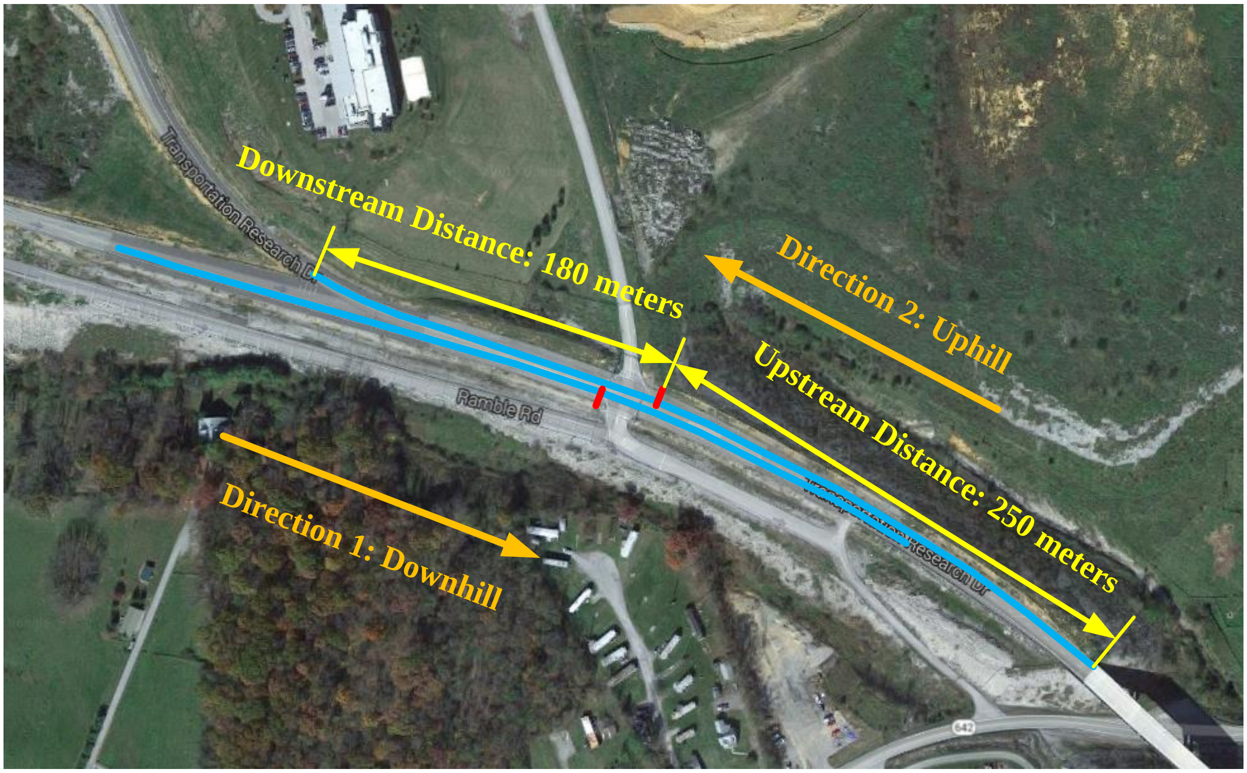


Figure 4: Layout of the field test portion of the Virginia Smart Road.

In order to test the Eco-CACC system in response to different signal timings, four different values for this variable were selected. This variable is hereafter referred to as "red phase offset," and represents the remaining red light time when the vehicle enters the test area by passing the first cone. The values selected for testing were 10, 15, 20, and 25 seconds. When the test vehicle was far away and moving towards the signalized intersection, the signal phase was red. The red phase offset was triggered when the testing vehicle arrived at a distance d_{up} upstream of the intersection, which meant that the remaining time for the red phase was the randomly preset value (either 10, 15, 20 or 25 seconds). The green phase was set as 25 seconds, which was long enough for the vehicle to pass the downstream distance d_{down}, even when the test vehicle experienced a complete stop on the stop line.

Four scenarios were included in the field test, including a baseline, where the driver received no information; a scenario during which the driver was provided with a red light countdown; a scenario where the driver was provided with recommended target speed delivered via audio alert; and finally, a scenario employing the longitudinally automated Eco-CACC system.

Scenario 1 (S1): Baseline – uninformed drive.

The driver approached the intersection with no information about signal phase or target speed, and had to maintain a vehicle speed of 40 mph when passing from the first cone to the second cone.

Scenario 2 (S2): Informed drive – driver was provided a "time to next signal indication change" audio alert.

The driver could use the audio alert information to adjust the vehicle speed to pass through the intersection, and had to maintain a vehicle speed of 40 mph when passing from the first to the second cone.

Scenario 3 (S3): Informed drive – driver was provided a "target speed," which was calculated by the proposed ESC algorithm (Manual Eco-CACC System).

The driver had to maintain a vehicle speed of 40 mph when passing the first cone. Then an audio alert with the target speed was provided and the driver attempted to control the vehicle speed by following the target speed to the best of his/her ability.

Scenario 4 (S4): Automated drive – the vehicle automatically controlled acceleration and braking by following the target speed calculated by the proposed algorithm (Automated Eco-CACC System).

The driver had to maintain a vehicle speed of 40 mph when passing the first cone. Then the driver heard an "Engage" audio alert to indicate the automated control was activated. When the vehicle passed the second cone, the driver heard a "Dismiss" audio alert to indicate the automated control was deactivated. Note that the driver had to control the steering wheel at all times.

The VTTI automated vehicle used for testing was a 2014 Cadillac SRX equipped with an onboard unit for V2V and V2I communication. The manufacturer specifications for this vehicle were used to calibrate the fuel consumption model (Equation (0)); the calibration procedure can be found in [24]. This vehicle had the ability to drive autonomously by following the optimum speed profile produced by the developed ESC algorithm. This automated drive mode was tested in scenario 4 during the field test. Two options for communicating the target speed were designed for use in the test vehicle: a monitor display as shown in Figure 5 and an audio system. Many studies have shown that drivers can be highly distracted by visual displays in their natural driving environment [25, 26], and therefore the audio system was selected for scenarios 2 and 3 of this study. The ESC algorithm was coded to the Eco-CACC system in the test vehicle using C/C++. The optimum speed profile and target speed were calculated every 0.1 second (10 hertz) to ensure the system could be used for real-time applications. In scenarios 2 and 3, since the average driver perception/reaction time is approximately 1.5 seconds and the latency in the communication system is around 0.5 seconds, the sound system was set to provide audio information to the driver at 2-second intervals. In scenario 4, the automated Eco-CACC system followed the target speed by every 0.1 second.

Figure 5: Test vehicle and equipment.

The field test included 32 participants, and each participant completed 64 trips to pass through the signalized intersection under different combinations of signal timings and road grades. The pre-defined signal timing table is presented in Table 1, which shows that that each scenario included 16 runs and each participant randomly repeated the four red phase offset values two times each for each direction. It should be noted that only the data from d_{up} and d_{down} were extracted during each trip. Eventually, 2,048 trips were collected to analyze the system's performance under different scenarios.

Table 1: Pre-defined Signal Timing Table

Run Index	Scenario 1 (second)	Scenario 2 (second)	Scenario 3 (second)	Scenario 4 (second)	Direction
1	25	15	15	25	uphill
2	25	25	25	20	downhill
3	10	25	25	20	uphill
4	15	25	10	20	downhill
5	15	10	25	25	uphill
6	10	20	15	15	downhill
7	25	25	15	15	uphill
8	25	10	20	10	downhill
9	10	15	10	15	uphill
10	20	20	15	15	downhill
11	15	20	20	20	uphill
12	15	15	20	10	downhill
13	20	20	20	10	uphill
14	10	10	10	25	downhill
15	20	10	10	10	uphill
16	20	15	25	25	downhill

Test Results

The instantaneous fuel consumption, vehicle speed, and location data were collected during each trip to calculate the total fuel consumption level and the total travel time. Table 2 presents the average fuel consumption levels of four scenarios under different combinations of trip direction and red phase offset value. For the same trip direction and red phase offset value, the fuel consumption level consistently reduced from scenario 1 to 4, with scenario 4 always resulting in the least consumption of fuel; these findings are easily observed in Figure 6. The results of trip travel times in Figure 7 also show trends similar to the fuel consumption results. For the same trip direction and red phase offset value, the average trip travel time was consistently reduced from scenario 1 to 4, with scenario 4 generally resulting in the least travel time. Results also showed that both fuel consumption and travel time increased when red light offset increased, since longer red signal timing results in slower average vehicle speed and longer travel time for the vehicle to pass the signalized intersection. Considering the average road grade values are -3 degrees for the downhill direction and 3 degrees for the uphill direction, trips in the uphill direction resulted in much higher levels of fuel consumption compared to trips in the downhill direction. As the test results in Table 2 show, the uphill trips consumed, on average, 50% more fuel than downhill trips in the same scenario.

Table 2: Average Fuel Consumption

Direction	Red phase offset (second)	Scenario 1 (liter)	Scenario 2 (liter)	Scenario 3 (liter)	Scenario 4 (liter)
Downhill	10	0.034	0.020	0.020	0.019
	15	0.063	0.042	0.034	0.029
	20	0.070	0.070	0.053	0.040
	25	0.078	0.075	0.065	0.047
Uphill	10	0.077	0.055	0.053	0.053
	15	0.104	0.085	0.079	0.062
	20	0.116	0.103	0.091	0.085
	25	0.125	0.112	0.101	0.093

Table 3: Average Travel Time

Direction	Red phase offset (second)	Scenario 1 (second)	Scenario 2 (second)	Scenario 3 (second)	Scenario 4 (second)
Downhill	10	25.6	24.1	24.2	24.1
	15	29.9	28.3	26.8	26.6
	20	36.7	35.3	33.0	32.6
	25	42.3	41.1	39.4	38.9
Uphill	10	26.1	24.7	24.1	24.7
	15	30.2	29.1	27.4	26.4
	20	36.9	35.8	33.4	32.8
	25	42.7	41.5	39.7	39.1

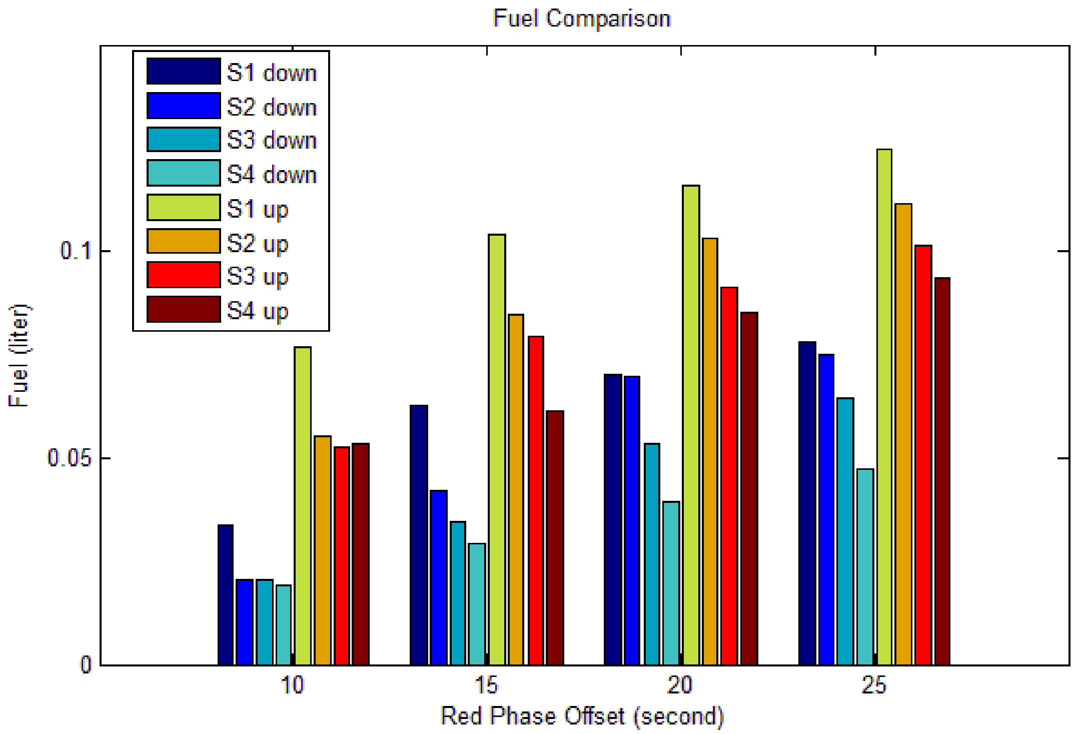


Figure 6: Average fuel consumption.

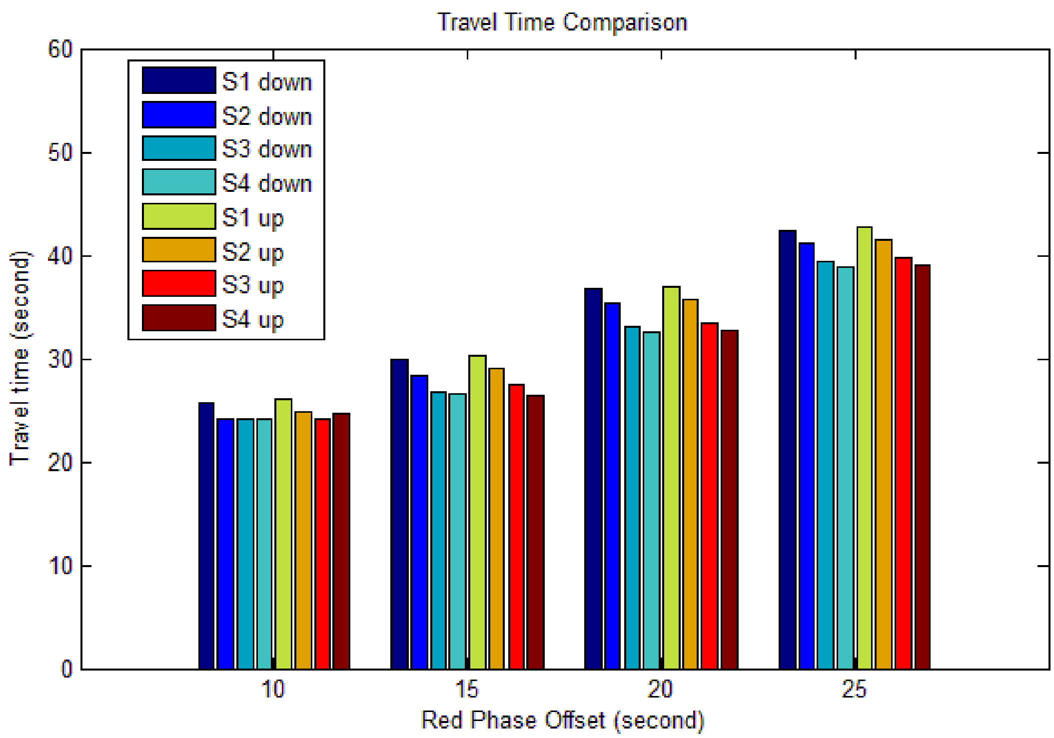


Figure 7: Average travel time.

By considering scenario 1 to be the baseline scenario and then comparing the difference in fuel consumption and travel time in scenarios 2, 3 and 4, we can calculate the results, presented in Table 4, which show fuel consumption comparisons under different scenarios. The comparison results indicate that average fuel consumption levels in scenarios 2–4 are lower than the consumption levels in scenario 1, which means all other scenarios are helpful in reducing fuel consumption compared to the uninformed baseline drive. Compared to the baseline scenario, the average fuel savings for scenarios 2, 3, and 4 are 18.3%, 27.7%, and 37.8% respectively. When we compare the fuel consumption levels between scenario 1 and scenario 4, it is interesting to see that the 15-second red phase offset always corresponds to the maximum fuel saving for both downhill and uphill directions. This may be explained by the fact that the vehicle with the Eco-CACC system has the maximum speed difference when compared to the vehicle without ESC, under the 15-second red light value. The same results and trends can also be found in Table 5, which shows the comparison of travel time under different scenarios.

Table 4: Comparison of Fuel Consumption for Different Scenarios

Direction	Red phase offset (second)	Difference between S2 and S1 (%)	Difference between S3 and S1 (%)	Difference between S4 and S1 (%)
Downhill	10	-39.8	-39.4	-42.8
	15	-32.6	-45.0	-53.2
	20	-0.7	-23.9	-43.6
	25	-4.4	-17.5	-39.8
Uphill	10	-28.5	-31.7	-30.5
	15	-18.5	-23.9	-40.9
	20	-10.9	-21.5	-26.7
	25	-10.5	-18.7	-25.0
Average		**-18.3**	**-27.7**	**-37.8**

Table 5: Comparison of Travel Time for Different Scenarios

Direction	Red phase offset (second)	Difference between S2 and S1 (%)	Difference between S3 and S1 (%)	Difference between S4 and S1 (%)
Downhill	10	-5.9	-5.7	-5.9
	15	-5.4	-10.4	-11.3
	20	-3.9	-10.1	-11.3
	25	-3.0	-7.0	-8.1
Uphill	10	-5.3	-7.8	-5.4
	15	-3.6	-9.3	-12.7
	20	-3.0	-9.5	-11.1
	25	-2.8	-7.0	-8.4
Average		**-4.1**	**-8.3**	**-9.3**

The results and trends found by comparing the four scenarios can be easily observed in the following figures. Comparisons of fuel consumption in different scenarios for downhill and uphill directions are presented in Figure 8 and Figure 9. Comparisons of travel times in different scenarios for downhill and uphill directions are presented in Figure 10 and Figure 11. Compared to the first three scenarios, scenario 4 always corresponds to the lowest fuel consumption and travel time with the same combination of red phase offset and drive direction. The average results indicate that automated driving in scenario 4 saves 37.4% in fuel consumption and 8.6% in travel times, respectively.

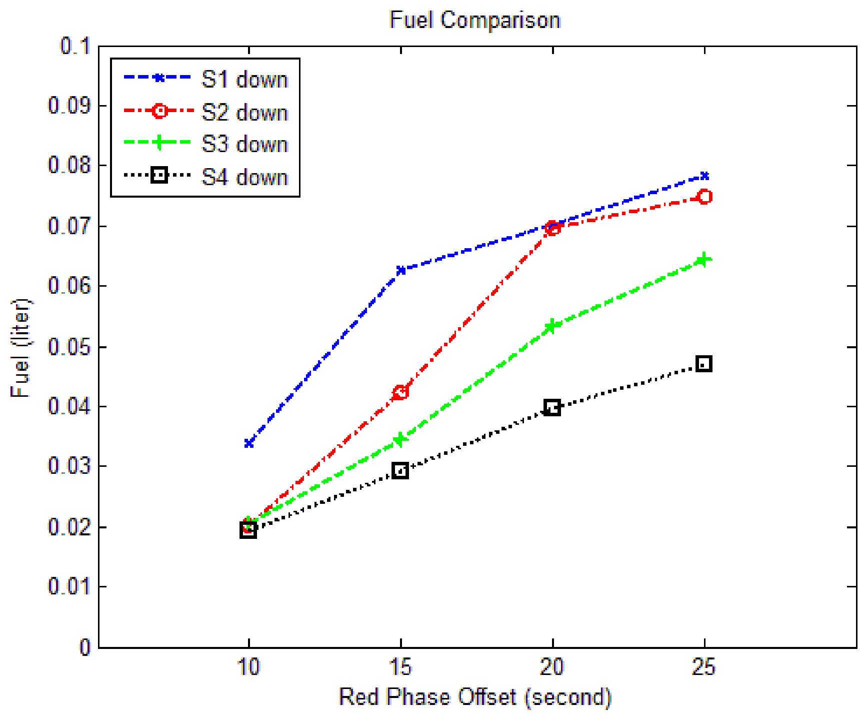


Figure 8: Comparison of fuel consumption for different scenarios for downhill direction.

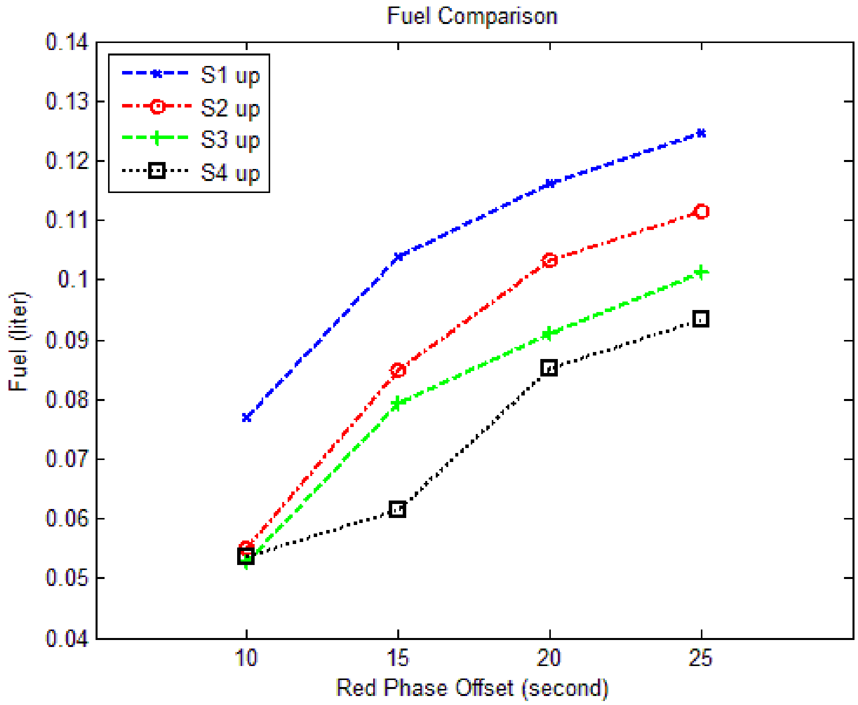


Figure 9: Comparison of fuel consumption for different scenarios for uphill direction.

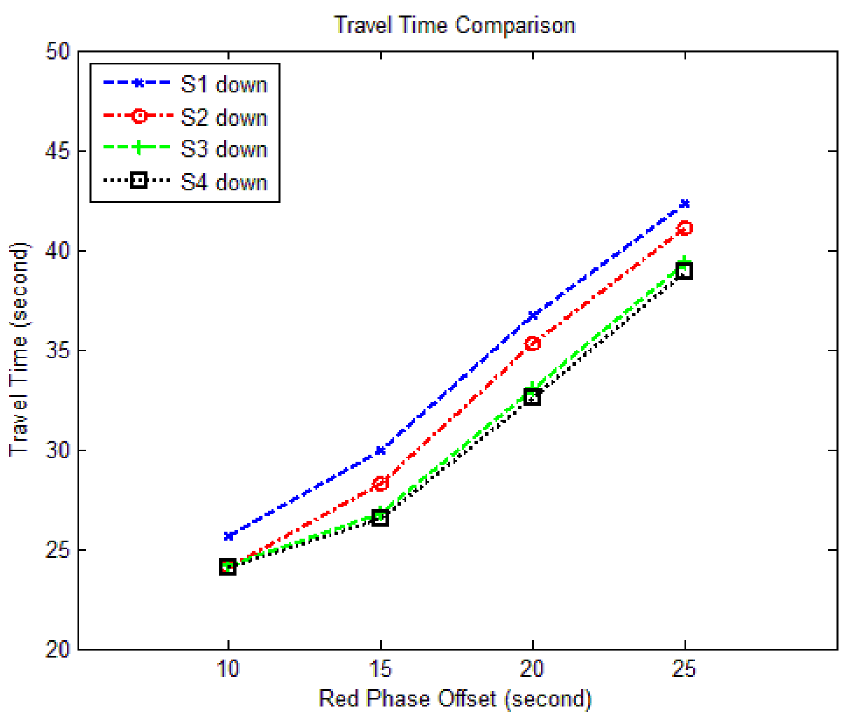


Figure 10: Comparison of travel time for different scenarios for downhill direction.

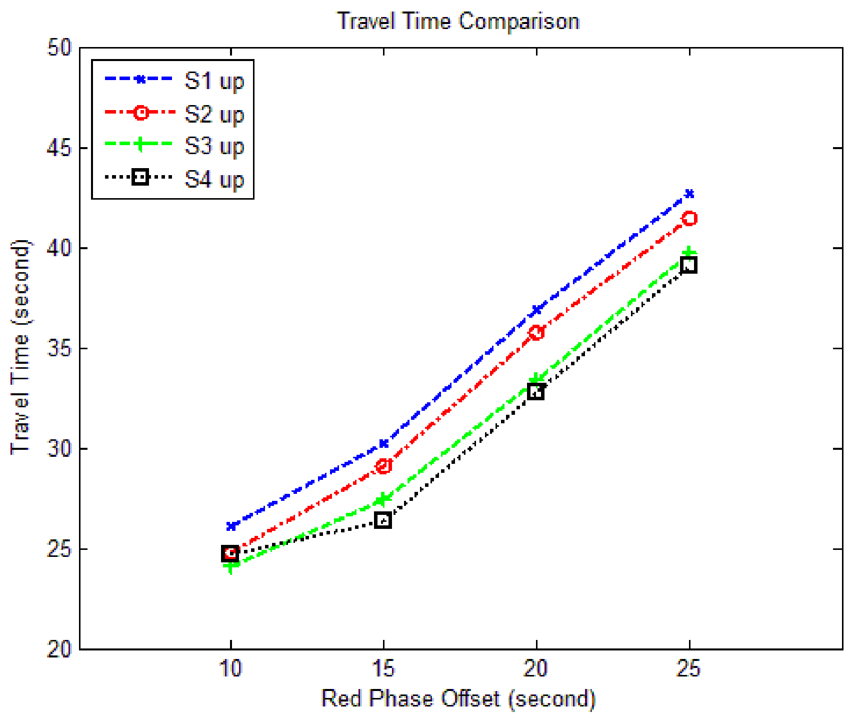
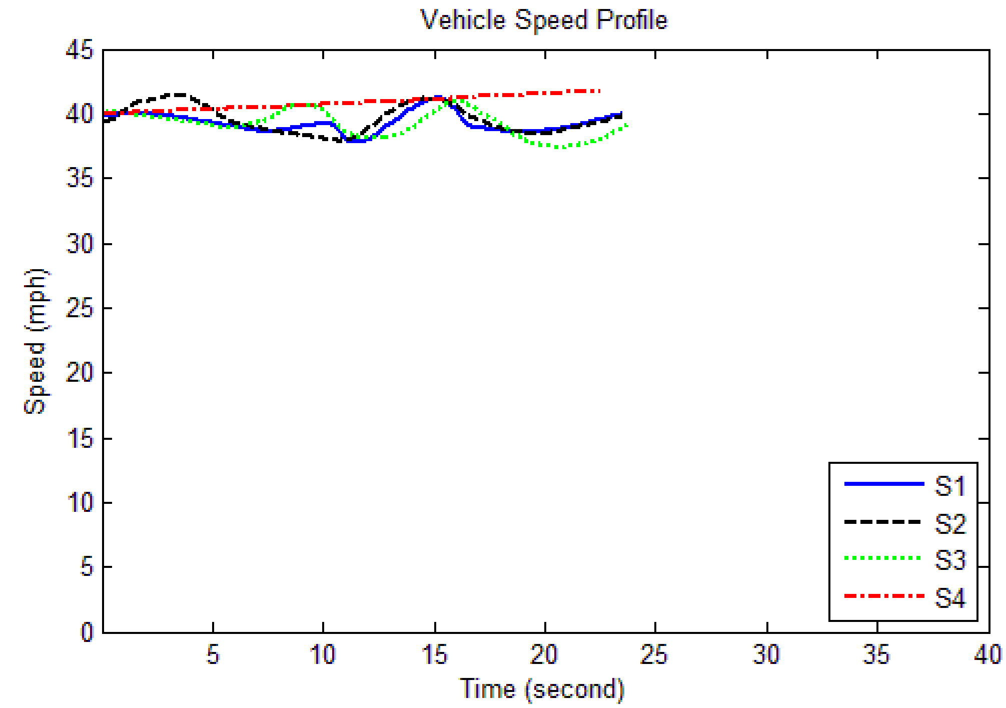


Figure 11: Comparison of travel time for different scenarios for uphill direction.

To investigate driver behavior and vehicle trajectories for different scenarios, examples for each combination of red phase offset, drive direction, and scenario are presented in the following figures. It should be noted that the automated vehicle could not perfectly follow the advisory speed calculated from the Eco-CACC system. For instance, the advisory speed in scenario 4 for 10 seconds of red light offset was a constant value of 40 mph. When the vehicle drove in the downhill direction in Figure 12, vehicle speed increased from 40 mph to 41.6 mph because of the positive gravity force; this speed discrepancy was so small that the automated control system did not engage the brake. When the vehicle drove in the uphill direction in Figure 13, vehicle speed initially dropped from 40 mph to 37.2 mph due to the negative gravity force, and the automated control system accelerated to reach 40 mph only after this initial drop in speed.



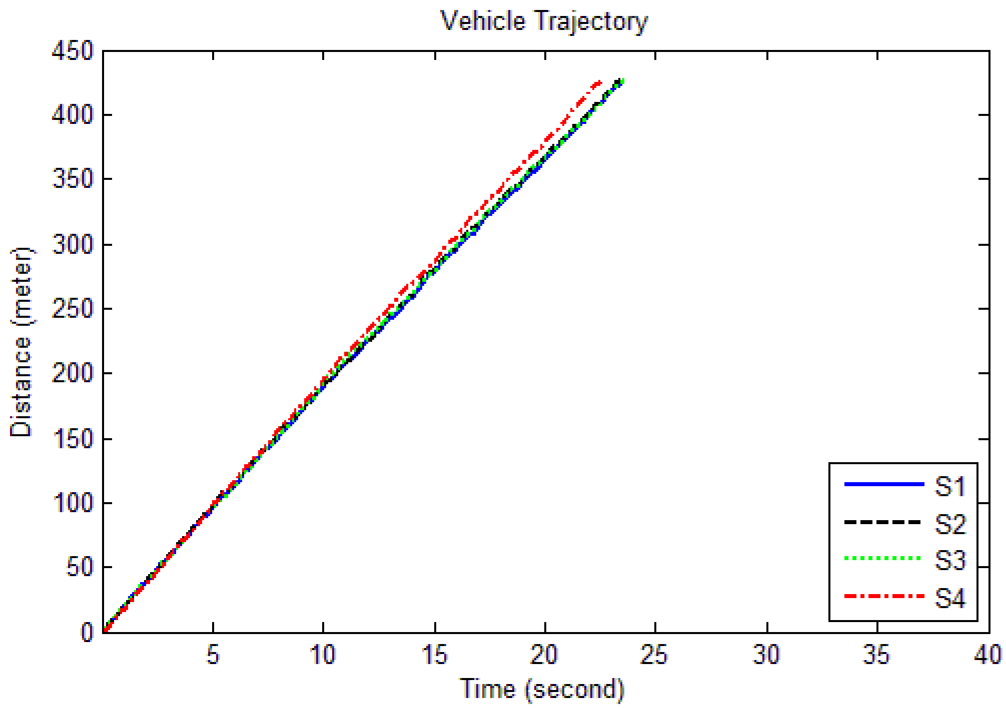


Figure 12: Example of vehicle speed profile and trajectory under red phase offset 10 seconds, downhill direction.

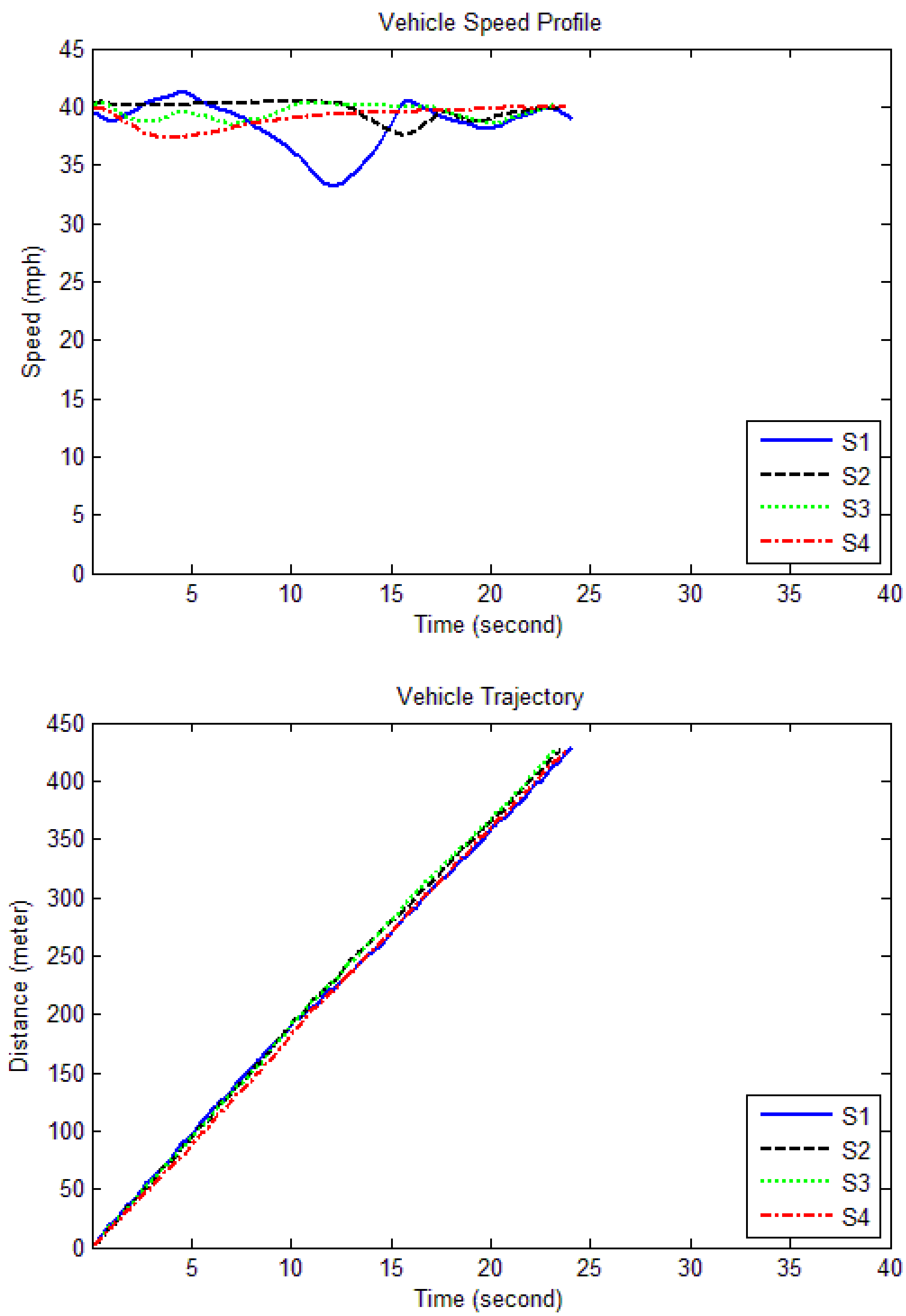


Figure 13: Example of vehicle speed profile and trajectory under red phase offset 10 seconds, uphill direction.

Figure 14 serves as a good example for explaining the differences in driver behavior and vehicle trajectories in each of the four scenarios. In scenario 1, the vehicle's speed was reduced to a complete stop at the intersection because of the red signal. In scenario 2, the countdown information helped the driver slowly decelerate to a complete stop with a moderate deceleration rate compared to scenario 1. In scenario 3, the driver tried to follow the target speed by reducing vehicle speed initially and then increasing speed to pass the intersection. In scenario 4, the vehicle speed reduced from 40 to 20 mph, and then maintained a speed of around 20 mph to approach and pass through the intersection. The speed curves indicate the vehicle didn't stop during scenarios 3 and 4, and that the average speeds during these scenarios were much higher than in the other two scenarios. The Eco-CACC system helped the test vehicle follow a smoothed speed profile with significantly less acceleration or deceleration maneuvers, thus allowing it to drive at a higher average speed to pass the intersection. The sample trips demonstrate the benefits of the Eco-CACC system in assisting drivers with smooth driving in the vicinity of intersections, leading to lower fuel consumption levels.

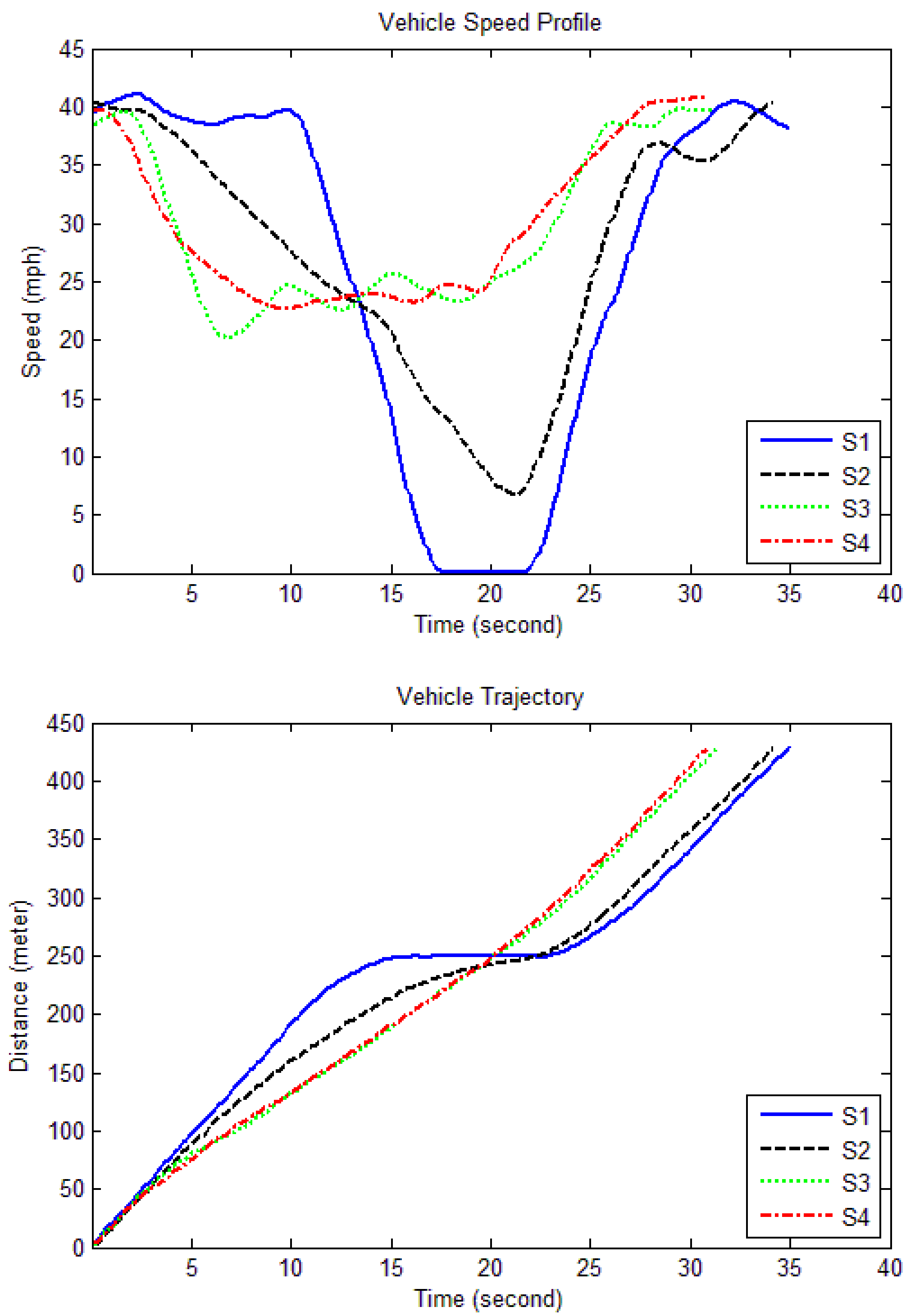


Figure 14: Example of vehicle speed profile and trajectory under red phase offset 20 seconds, uphill direction.

Post-Run Questionnaire Survey

After running the field test on the Virginia Smart Road Connected Vehicle Test Bed, each of the 32 participants was asked to complete a post-run questionnaire survey; survey results are discussed in this section. The first two questions are related to drivers' decision-making. Given that the automated control in scenario 4 doesn't require the driver to make a decision once the system is activated, this scenario is not included in the first two questions. According to the results shown in Figure 15, 72% of participants selected scenario 2 as their top choice with regard to improving the driver's ability to make a decision about how to proceed through intersection. Most participants felt that the signal timing information provided in scenario 2 was easy to understand and could make driving adjustments for accordingly, whereas the target speed in scenario 3 was very difficult to follow. According to Figure 16, 58% of participants selected scenario 2 as the top choice for helping them avoid completely stopping at the intersection. According to Figure 17, Figure 18 and Figure 19, the top choice with regard to "sav[ing] fuel consumption", "mak[ing] driving more comfortable" and "enhanc[ing] safety to drive through intersection" was scenario 4 (automated Eco-CACC); scenario 3 (manual Eco-CACC) was the last choice for those questions. Most participants felt that the manual Eco-CACC distracted their attention from the road environment since they had to focus on the odometer to adjust their vehicle speed according to the advisory speed. Interestingly, although 84% of participants thought scenario 3 was the worst case for reducing fuel consumption, data analysis results indicate that scenario 3 provides a 27.7% fuel savings compared to the uninformed baseline drive in scenario 1. According to Figure 20, an equal percentage of participants (around 43%) selected scenario 1 and 4 as the top choices regarding which "you would like to have in your car." Finally, as Figure 21 indicates, 91% of participants agreed, either strongly or slightly, that they would like to have the Eco-CACC system in their vehicle.

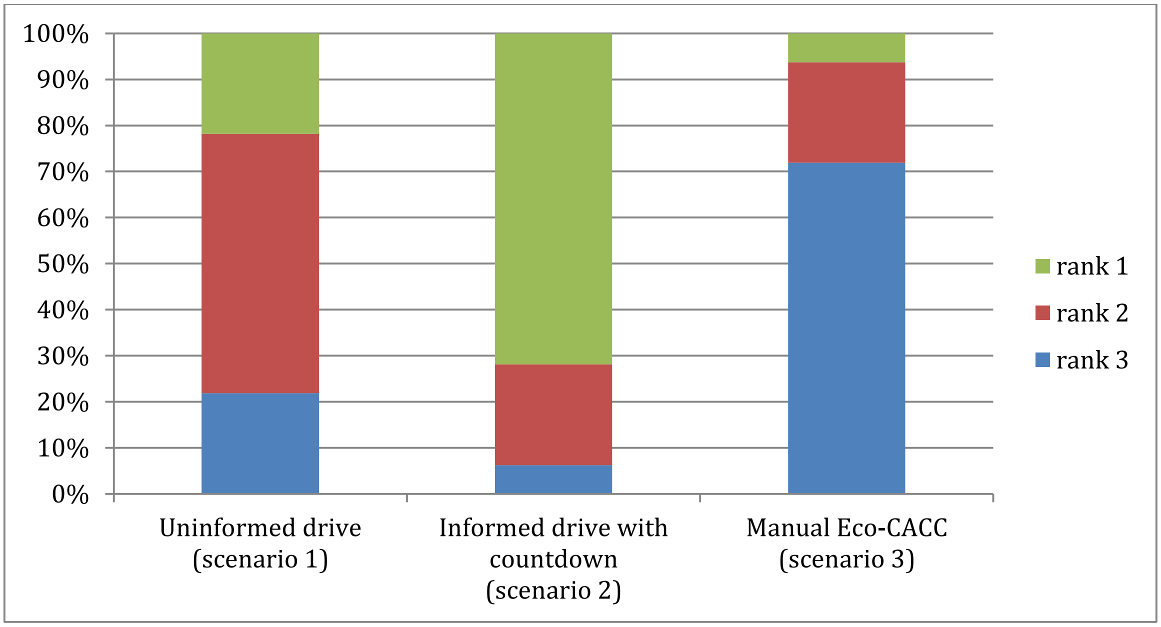


Figure 15: Ranking scenarios by "improve your ability to make decision on how to proceed through intersection."

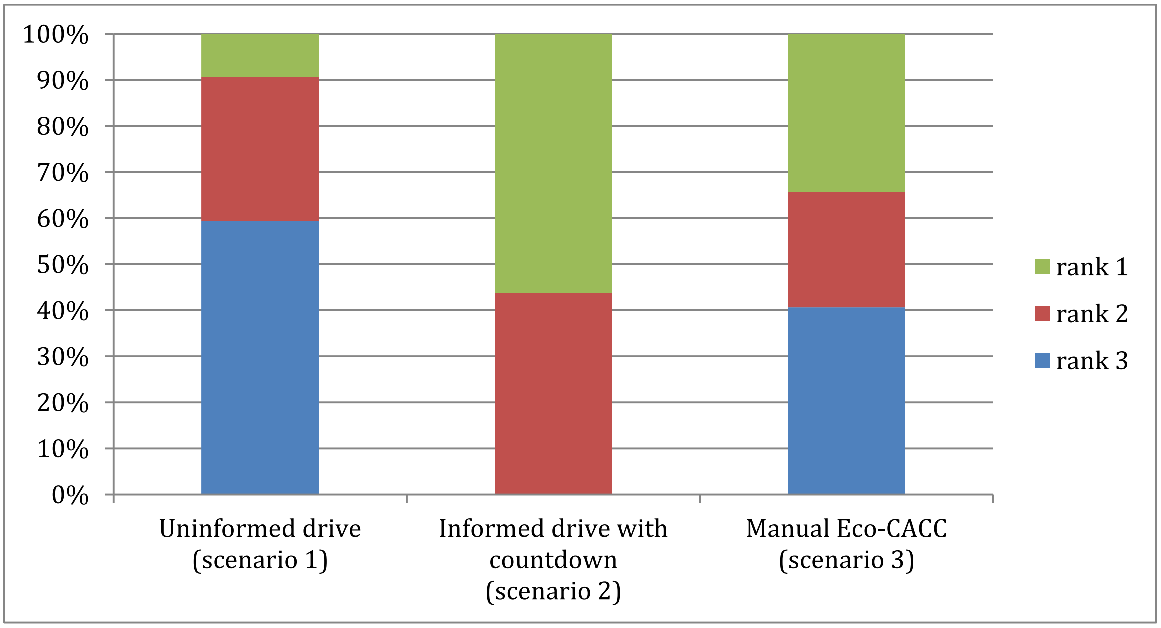


Figure 16: Ranking scenarios by "avoid completely stopping at intersection."

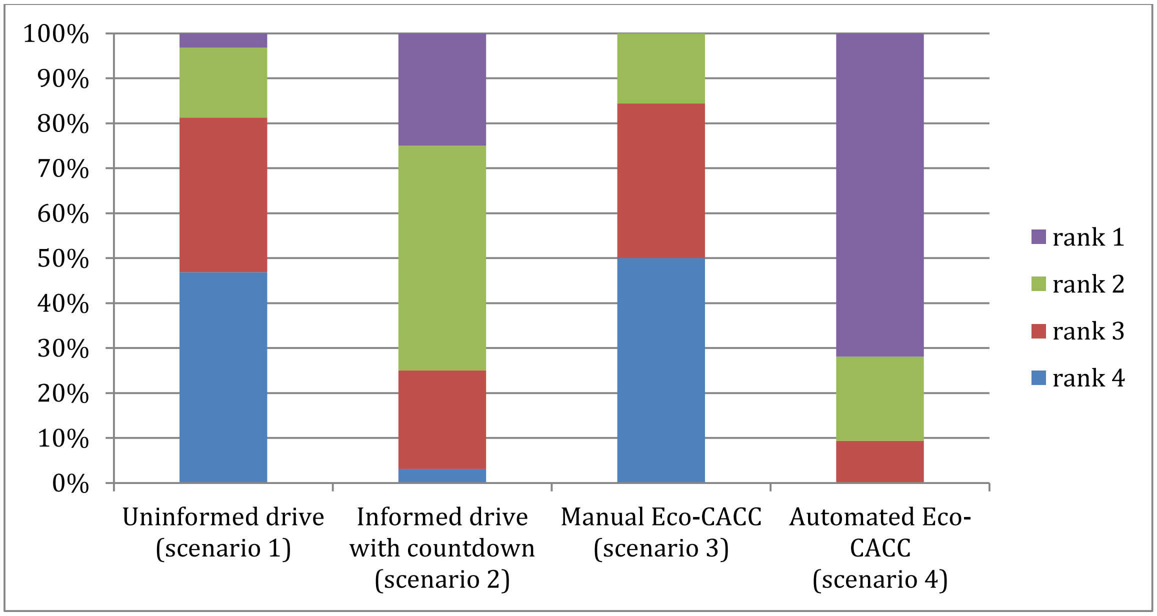


Figure 17: Ranking scenarios by "save fuel consumption."

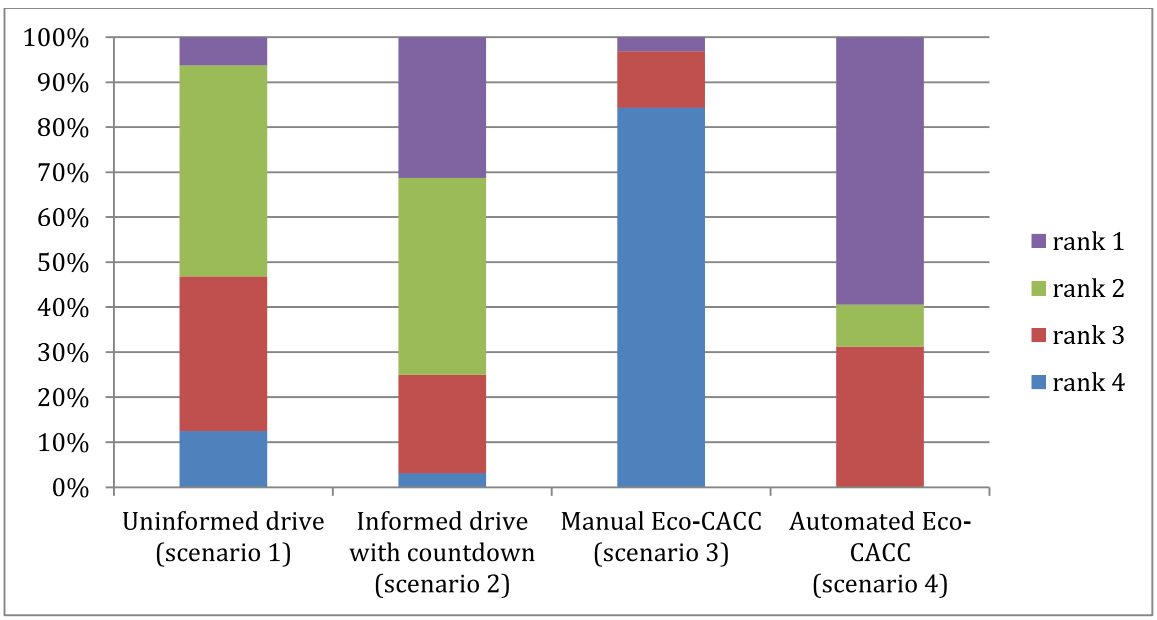


Figure 18: Ranking scenarios by "make driving more comfortable."

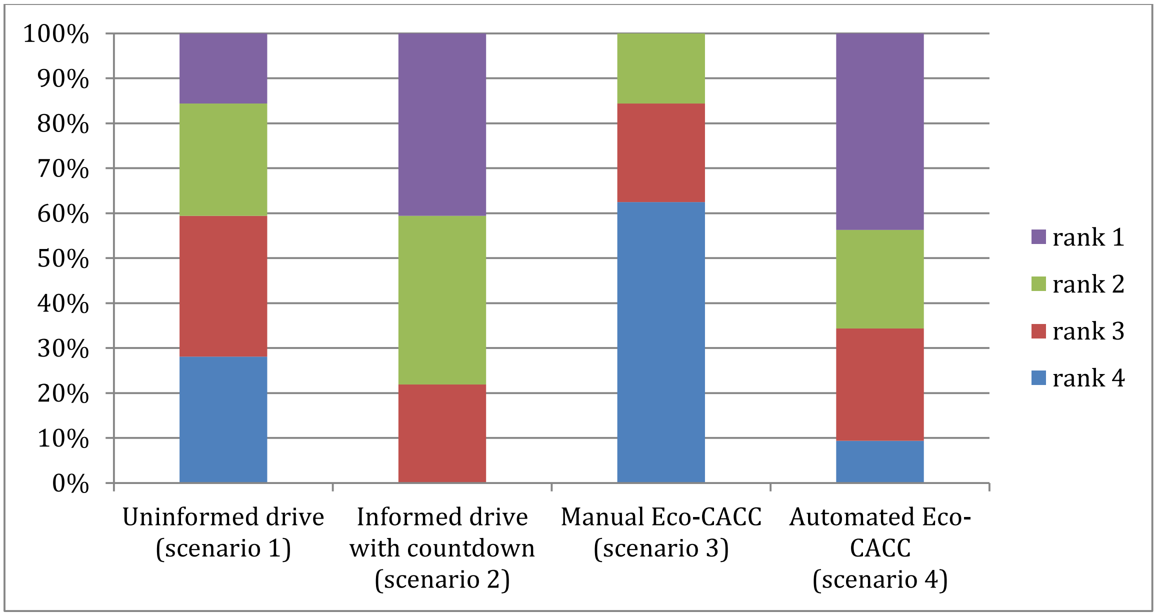


Figure 19: Ranking scenarios by "enhance safety to drive through intersection."

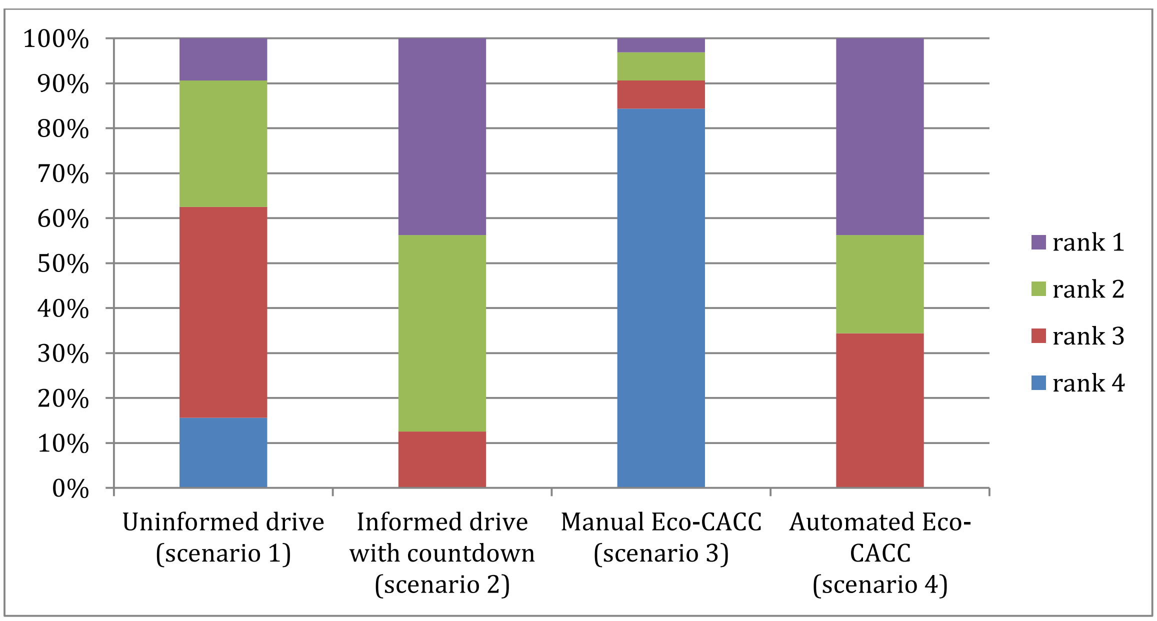


Figure 20: Ranking scenarios by "you would like to have in your car."

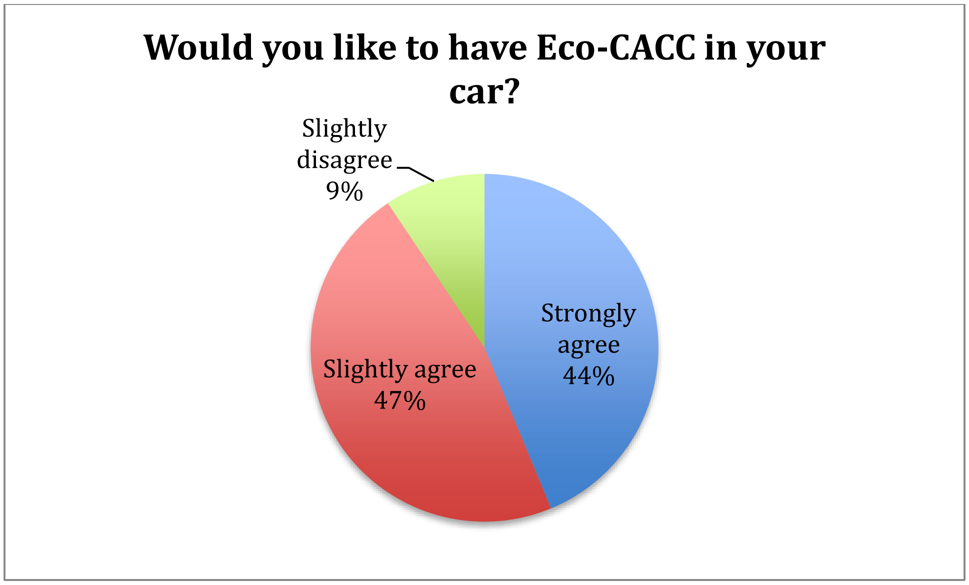


Figure 21: Percentage of responses to "would like to have Eco-CACC technology in the car?"

Conclusions and Recommendations

This research focused on the development of an ESC algorithm to compute a fuel-efficient speed profile in the vicinity of signalized intersections. The ESC algorithm was implemented in an Eco-CACC system installed in a VTTI automated vehicle. The Eco-CACC system could either broadcast, via audio alert, the computed speed profile to the driver so they could manually control the vehicle, or be implemented into the automated vehicle (AV) functionality to automatically control the vehicle. From an algorithmic standpoint, the proposed algorithm addressed all possible scenarios that a driver may encounter while approaching a signalized intersection. Additionally, from an implementation standpoint, the research addressed the challenges associated with communication latency, data errors, real-time computation, and ride smoothness.

The system was tested on the Virginia Smart Road Connected Vehicle Test Bed. Four scenarios were tested for each participant, including a baseline uniformed drive scenario, a scenario in which the driver was provided with a countdown to red light alert, a manual Eco-CACC scenario where the driver followed an audio recommended speed profile, and finally an automated Eco-CACC scenario in which the vehicle used longitudinally automated control to follow the speed profile. The field test included 32 participants, and each participant completed 64 trips to pass through a signalized intersection under a different combination of signal timing and road grades.

The analyzed results demonstrate the benefits of the ESC algorithm and system in assisting vehicles to drive smoothly in the vicinity of intersections and thereby reduce fuel consumption levels. Compared to the uninformed baseline drive, the longitudinally automated Eco-CACC system-controlled vehicle resulted in savings in fuel consumption and travel times in the range of 37.8% and 9.3%, respectively.

It has been noted that the impacts from neighboring vehicles were previously tested in a traffic simulation environment and were not considered in the algorithm tested in this report. The tested algorithm treated ESC under light traffic conditions. The developed ESC algorithm could be refined for more complicated traffic conditions by considering the calculated optimum speed profile as the variable speed limit.

Under future work, the ESC algorithms will be further improved by considering intersection queues. Given that only one signalized intersection is available at the Virginia Smart Road Connected Vehicle Test Bed, it is recommended that the Eco-CACC system be evaluated at additional test sites with multiple signalized intersections to validate performance. Different vehicle models are also recommended to test Eco-CACC system for the future research.

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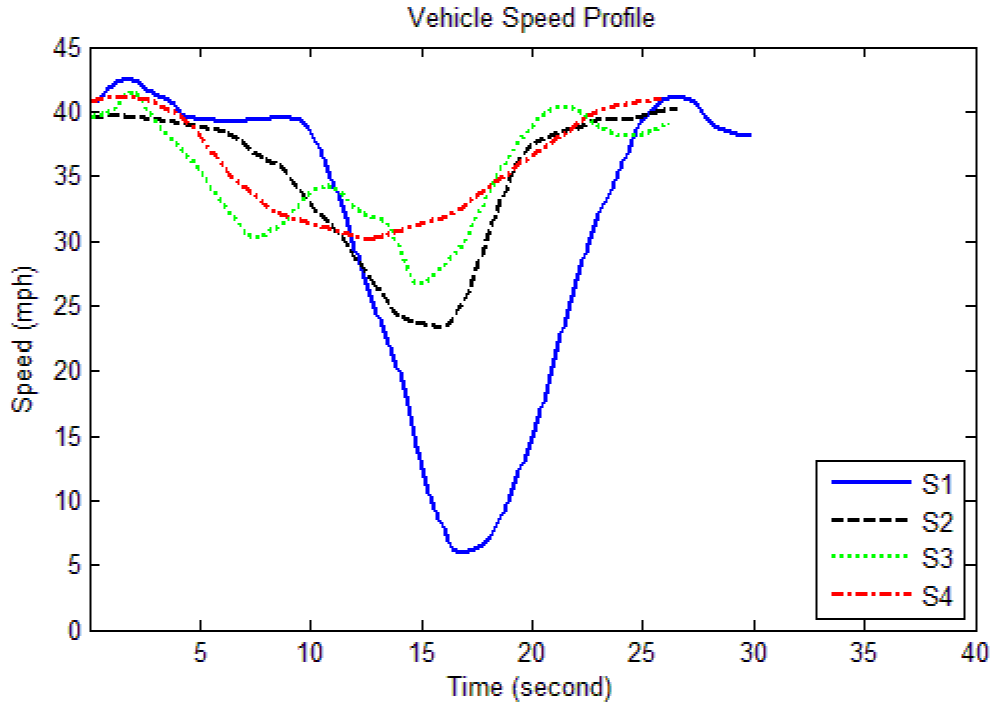
Appendix A. Additional Figures



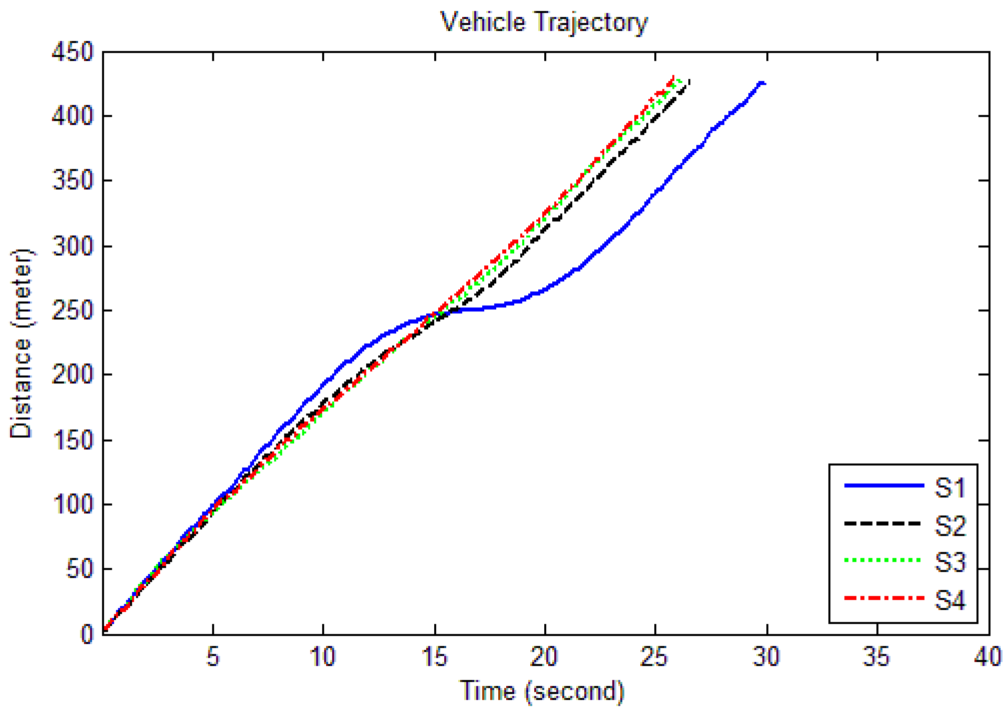


Figure 22: Example of vehicle speed profile and trajectory under red phase offset 15 seconds, downhill direction.

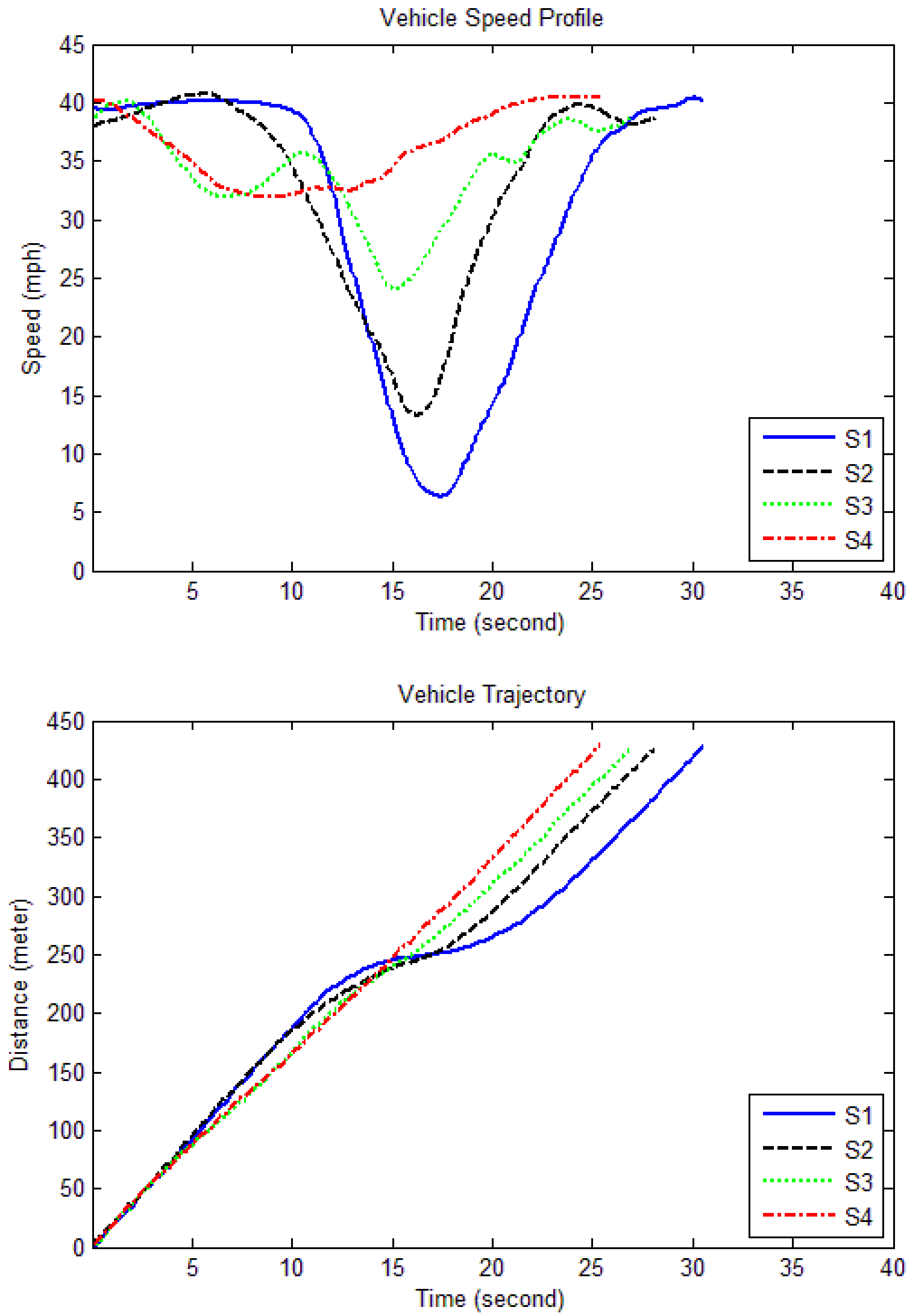


Figure 23: Example of vehicle speed profile and trajectory under red phase offset 15 seconds, uphill direction.

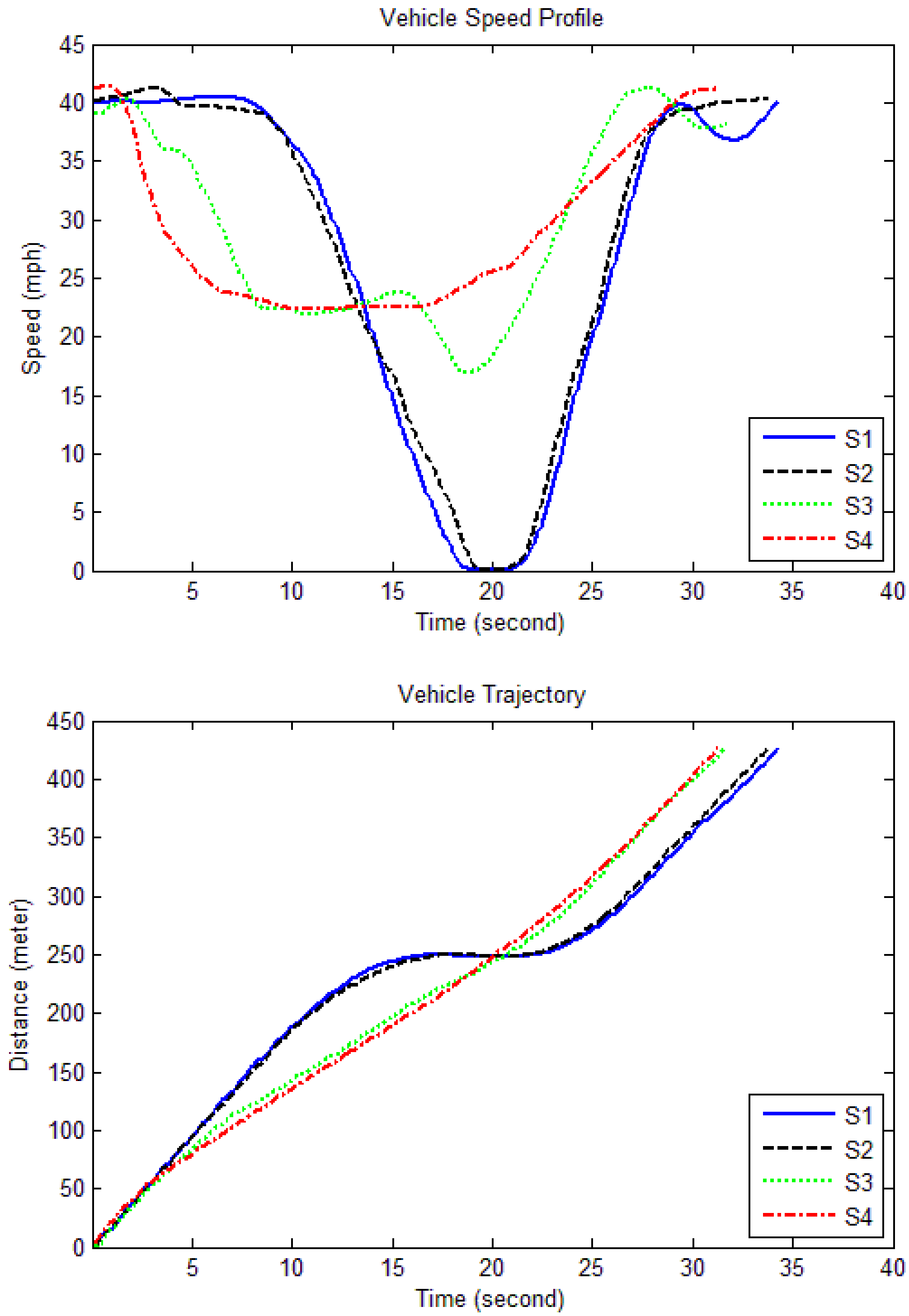


Figure 24: Example of vehicle speed profile and trajectory under red phase offset 20 seconds, downhill direction.

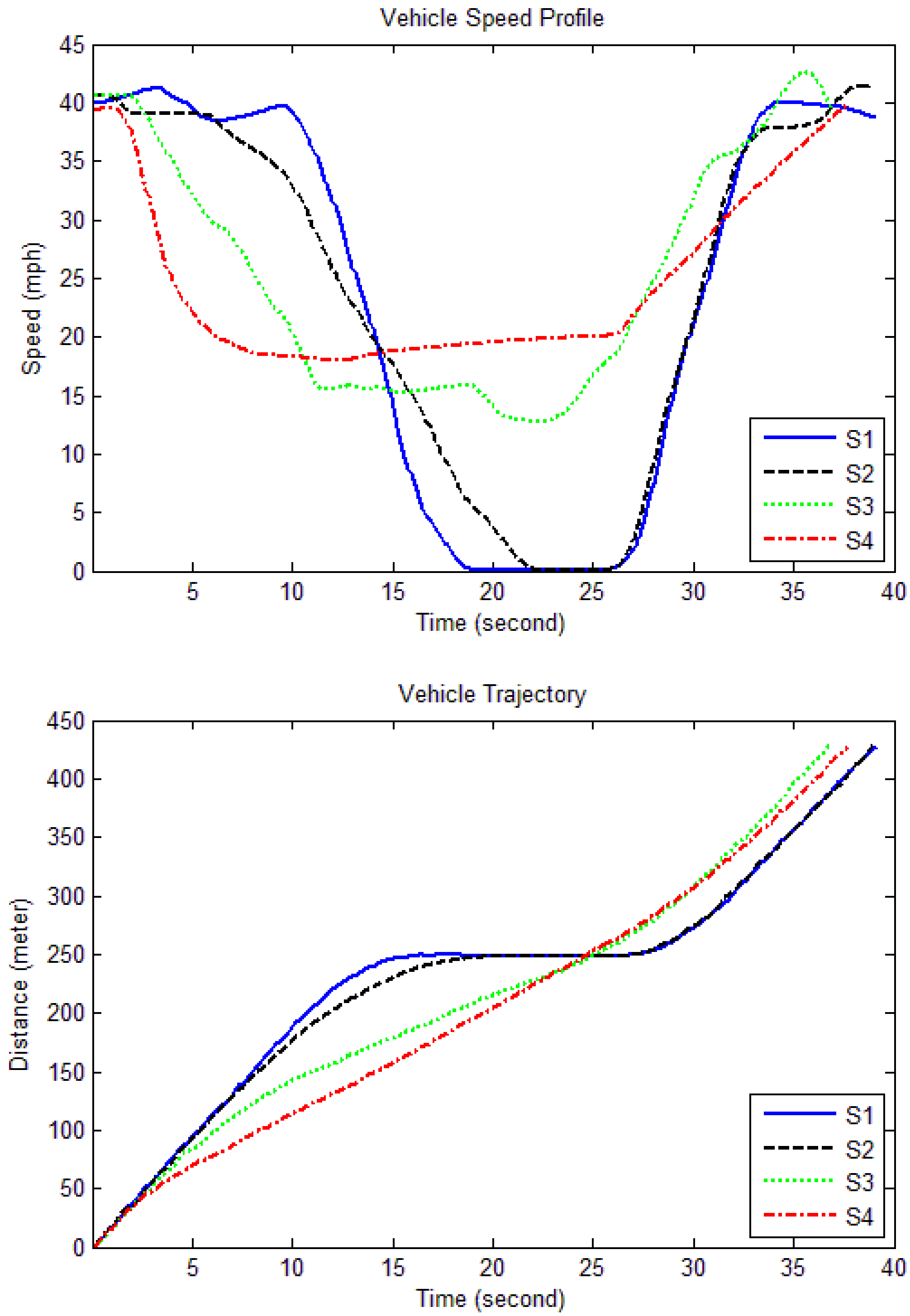


Figure 25: Example of vehicle speed profile and trajectory under red phase offset 25 seconds, downhill direction.

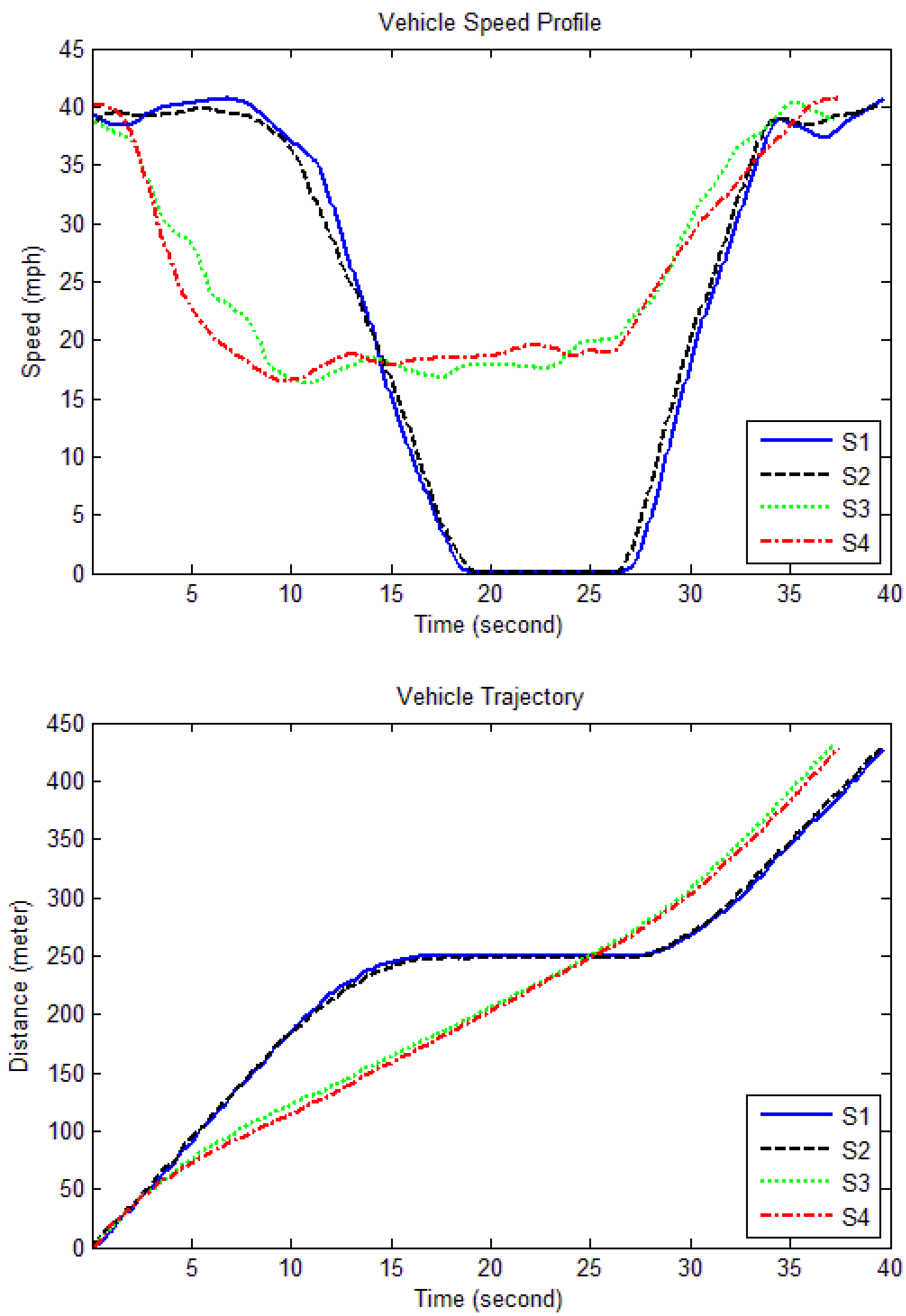


Figure 26: Example of vehicle speed profile and trajectory under red phase offset 25 seconds, uphill direction.