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Article

Developing and Field Testing a Green Light Optimal Speed Advisory System for Buses

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Abstract: This paper develops a Green Light Optimal Speed Advisory (GLOSA) system for buses (B-GLOSA). The proposed B-GLOSA system is implemented on diesel buses, and field tested to validate and quantify the potential real-world benefits. The developed system includes a simple and easy to calibrate fuel consumption model that computes instantaneous diesel bus fuel consumption rates. The bus fuel consumption model, a vehicle dynamics model, the traffic signal timings, and the relationship between vehicle speed and distance to the intersection are used to construct an optimization problem. A moving-horizon dynamic programming problem solved using the A-star algorithm is used to compute the energy-optimized vehicle trajectory through signalized intersections. The Virginia Smart Road test facility was used to conduct the field test on 30 participants. Each participant drove three scenarios including a base case uninformed drive, an informed drive with signal timing information communicated to the driver, and an informed drive with the recommended speed computed by the B-GLOSA system. The field test investigated the performance of using the developed B-GLOSA system considering different impact factors, including road grades and red indication offsets, using a split-split-plot experimental design. The test results demonstrated that the proposed B-GLOSA system can produce smoother bus trajectories through signalized intersections producing fuel consumption and travel time savings. Specifically, compared to the uninformed drive, the B-GLOSA system produces fuel and travel time savings of 22.1% and 6.1% on average, respectively.

Keywords: eco-driving; GLOSA; signalized intersection; diesel bus; eco-cooperative adaptive cruise control; fuel consumption model; field test

1. Introduction

Previous studies have shown that the fuel consumption rates are dramatically increased when vehicles approach signalized intersections, which is caused by vehicle acceleration and deceleration maneuvers [1, 2]. Meanwhile, knowledge of traffic signal phase and timing (SPaT) has been proven to benefit the energy use of vehicles by reducing stop-and-go maneuvers and idling time at signalized intersections [3]. With the development of information and communication technology, the advanced communication power in a connected vehicle (CV) environment ensures a very high update rate of information can be provided to vehicles. For example, SPaT information, vehicle speed, surrounding vehicle locations can be shared using vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. Such information can greatly help transportation scientists to develop and implement connected traffic systems to enhance traffic safety, efficiency, and economy. Recently, numerous researchers have attempted to develop various eco-driving algorithms using the technologies of connected and/or automated vehicles and connected infrastructures. These eco-driving strategies are aimed to provide speed guidance in real-time to vehicles so that vehicle acceleration/deceleration can be adjusted accordingly to save fuel and greenhouse gas (GHG) emissions while traversing signalized intersections [4-6].

Various eco-driving strategies have been developed by researchers in the past decade. For instance, a cooperative adaptive cruise control system is developed using traffic signal data to minimize vehicle acceleration rates and fuel consumption [7]. Another study in [8] develops a vehicle fuel-optimal algorithm by using dynamic programming and recursive shortest path finding techniques. The developed algorithm is tested in a simulation environment using an agent-based model. In addition, a vehicle trajectory optimization strategy is proposed in [9] to search the green window so that vehicles can use this window to traverse multiple signalized intersections. Another extension study in [10] develops a similar approach by allocating a brake-specific fuel rate map for optimizing vehicle gear ratios, and they also use dynamic programming to search for the optimal solution.

However, the studies in this field are mainly focused on developing eco-driving algorithms for Light Duty Vehicles (LDVs). Compared to LDVs, heavy duty vehicles (HDVs) (e.g., buses) have poor fuel consumption efficiency due to heavy curb weights and sizes, especially travel in stop-and-go traffic in the vicinity of signalized intersections. Considering that energy consumption models are the key factor in 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. A few studies attempted to develop eco-driving systems to reduce fuel and emission levels along traffic signalized corridors. A bus eco-driving system is proposed in [11] by adjusting the vehicle speed profile and the dwell time at bus stops to ensure that buses can smoothly pass downstream signalized intersections. A MATLAB simulated environment has been used to validate the benefit of the proposed system and show a saving of 5.5% emissions. Another similar approach is developed in [12] to minimize the frequency of complete stops by buses at signalized intersections to reduce transit vehicle fuel consumption in cities. 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 can drive smoothly to approach the intersection. The fuel savings were achieved by moving vehicle complete stops at signalized intersections to bus stops, thus reducing the total number of stops and removing accelerations and decelerations at intersections. The proposed method was implemented in the VISSIM microsimulation software and the test results presented up to 15% savings in bus fuel consumption at intersections. Both studies tried to reduce bus stopping at intersections by adjusting bus dwell times at upstream bus stations. However, these approaches may not work well for signalized intersections without or far away from neighboring bus stations.

Moreover, the developed eco-driving algorithms have been primarily tested in traffic simulations that make numerous simplified assumptions that may deem them unrealistic. For instance, simulations typically assume that drivers can accurately and instantly follow the speed advisories, eco-driving systems run perfectly without providing erroneous information, latencies and loss of data in communication are neglected, traffic signal timing information are known precisely, etc. Consequently, field tests are very important to explore the benefits of eco-driving systems on real roads. Recently, the Virginia Tech Transportation Institute developed an eco-driving system entitled GLOSA that includes two modes of operation, namely; a manual mode for CVs and an automated mode for connected-automated vehicles (CAVs) [13-15]. Drivers follow recommended speed advisories that are provided via audio alerts in the manual GLOSA system. Alternatively, CAVs use longitudinally automated control to follow the optimum speed profile that is computed by the GLOSA system. The field tests demonstrated that the manual and automated modes of GLOSA produce fuel savings of 28% and 38% on average, respectively. A similar eco-driving system called GlidePath was developed and tested at the Turner Fairbank Highway Research Center, which also can be used for CVs and CAVs [16]. A few more similar eco-driving systems were developed in other countries such as the Green Light

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Optimal Speed Advisory System (GLOSA) in Europe [17]. However, those studies only used LDVs to design and test the eco-driving systems, without the consideration of HDVs such as diesel buses.

To tackle the abovementioned issues, this study proposes a bus eco-driving system by expanding the LDV GLOSA system we previously developed to buses. In the proposed system, a fuel consumption model for diesel buses is used to compute instantaneous fuel consumption rates, since this model is easy to calibrate using easy-to-access bus data. The bus consumption model, vehicle dynamics model, traffic signal timings, and the vehicle speed and distance relationship are used to construct an optimization problem. A moving-horizon dynamic programming using an A-star minimum path algorithm is used to solve the optimization problem and calculate the energy-optimized vehicle trajectory to assist buses traverse signalized intersections. The proposed B-GLOSA system was implemented on diesel buses, and a controlled field test was conducted to quantify the potential real-world benefits of using the proposed system. The test results demonstrate that the developed B-GLOSA system for buses produces average fuel and travel time savings of 22.1% and 6.1%, respectively.

The remainder of this paper is organized as follows. The proposed B-GLOSA system is described. This is followed by a description of the field test environment and the experimental design. Thereafter, the quantitative performance analysis is conducted to present the quantitative benefits of using the B-GLOSA. The last section provides conclusions of this study and recommendations for future research.

2. Methodology

We modified the GLOSA system previously developed for LDVs to work for buses. More details of the LDV GLOSA system is provided demonstrated in [13, 14]. In order to solve the optimization problem in the proposed B-GLOSA system, the bus fuel consumption model is a key component to calculate and compare the trip fuel consumption level for the speed profile in each possible solution. The diesel bus fuel consumption model developed in [18, 19] was selected to use here by considering two reasons: 1) this fuel model only needs instantaneous speed data as input to compute fuel consumption; 2) the model calibrate is very easy without the need of vehicle power or engine data. The B-GLOSA system and fuel model for buses are described as below.

2.1. B-GLOSA System

Given that the dedicated short range communication systems have a limited range of sending and receiving communication data, the bus GLOSA is assumed to work within a range near the signalized intersection from the intersection upstream location d_{up} of to the downstream location of d_{down}. It should be noted that both d_{up} and d_{down} are computed based on the distance to the intersection stop bar. Here, the intersection downstream location d_{down} is defined to ensure that buses passed through intersections with low speeds have enough distance to accelerate to the roadway speed limit, if the downstream traffic condition is uncongested. A bus generally has two options to approach a signalized intersection – 1) deceleration is needed; 2) deceleration is not needed. Therefore, the GLOSA algorithms for these two options are developed in this section. More detailed discussions of the options for vehicle to pass signalized intersections are presented in [20, 21].

In case 1, vehicles don't need to decelerate to approach the signalized intersection. This happens when the traffic signal has enough green time (or the red time is very short) for vehicles to pass the stop bar. In this case, the vehicle either keep the initial speed (the speed passing the location of d_{up}) or accelerate to a speed u_c and then keep driving with that constant speed to pass intersection. The cruise speed is calculated in Equation (1). Here, t_r denotes the remaining red indication time when vehicle arrives d_{up} upstream of the intersection. If the initial vehicle speed is equal to u_c, the vehicle can use the same initial speed to pass the intersection. Otherwise, the vehicle needs to follow the bus engine

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physical model – vehicle dynamics model denoted in Equations (2~4) and accelerate to the speed u_c to pass the intersection. Here, a vehicle dynamics model developed in [22] is used to capture the behavior of acceleration maneuver.

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

$$u(t+\Delta t) = u(t) + \frac{F(t)-R(t)}{m}\Delta t \tag{2}$$

$$F = \min\left(3600 f_p \beta \eta_d \frac{P}{u}, m_{ta} g \mu\right) \tag{3}$$

$$R = \frac{\rho}{25.92} C_d C_h A_f u^2 + mg\frac{c_{r0}}{1000}(c_{r1}u + c_{r2}) + mgG \tag{4}$$

where F represents the tractive effort in the vehicle dynamics model; R denotes the combination of aerodynamic, grade and rolling resistance forces; β denotes the reduction factor of gear; f_p represents the throttle level ranging between 0 and 1; η_d denotes the efficiency of driveline; m_{ta} represents the mass along the tractive axle (kilogram); P denotes the power of engine (kilowatt); μ is the road adhesion coefficient parameter; g represents the gravitational acceleration value (9.8067 meter per second^2); ρ denotes the air density under a temperature of 15 °C and sea level (1.2256 kilogram per meter^3); C_h represents the correction factor of altitude; C_d denotes the coefficient of vehicle drag; m represents the vehicle mass (kilogram); and G denotes the grade of roadway; A_f represents the frontal area of vehicle (meter^2); c_{r0} c_{r1} and c_{r2} denote the rolling resistance constant values.

In case 2, vehicles need to decelerate and keep a lower constant speed to pass the signalized intersection. Figure 1 demonstrates the fuel-optimized vehicle speed profile. After the vehicle passes the location of d_{up}, with a speed of $u(t_0)$, the vehicle needs to reduce the speed to u_c by following the decelerate level of a, and then the vehicle maintains the cruise speed of u_c to approach the intersection. When this vehicle drives on the downstream road of the intersection, the vehicle needs to speed up from the cruise speed to u_f, and then keep this speed to pass the location of d_{down}. The fuel-optimized vehicle trajectory can be computed by solving the optimization problem as below. It should be noted that this optimization problem only has two unknown variables – the vehicle deceleration a and the throttle input f_p.

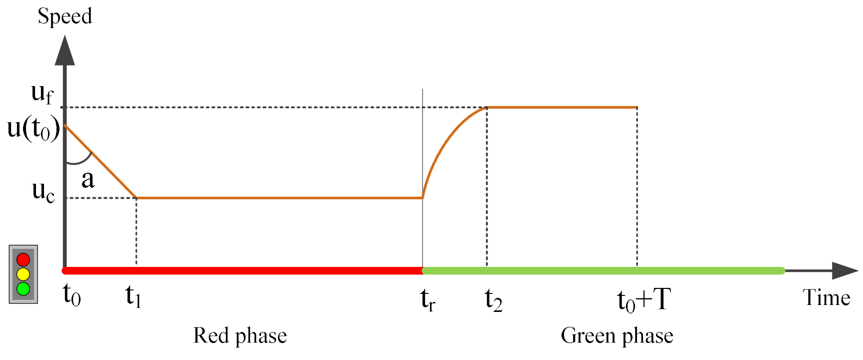

Figure 1. The fuel-optimized vehicle trajectory.

Here, we assume the vehicle arrives the upstream location (d_{up}) at the time of t_0, and then passes the downstream location (d_{down}) at the time of t_0+T. And the intersection upstream cruise speed is u_c. The objective function entails minimizing the total fuel consumption level as:

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

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where *FC(*)* denotes the fuel consumption at instant t. The constraints listed as below are developed according to the relationships between vehicle acceleration/deceleration level, velocity, and distance to the stop bar.

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

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

In Equation (6), the functions *F(*)* and *R(*)* denote the vehicle tractive force and resistances calculated in Equations (3) and (4), respectively. The variables a_{min} and a_{max} denote the minimum and maximum allowed acceleration levels to ensure driving comfort. And f_{min} and f_{max} represent the minimum and maximum throttle levels. According to the relationships in Equations (5~7), the deceleration a and throttle level f_p are the only unknown variables. A moving-horizon dynamic programming approach is implemented here to find the optimal solution of the optimization problem. In this way, all the combinations of deceleration and throttle levels are enumerated and the corresponding trip fuel consumption levels from upstream location d_{up} to downstream location d_{down} are computed. Therefore, the optimum parameters can be located according to the minimum fuel consumption level [10, 21]. Considering that the optimization solution needs to be calculated at a rapid frequency (e.g., 10 Hz) for real-time applications, an A-star algorithm is used here to expedite the computation speed [14]. The deceleration speed and the throttle level are considered as constant values in the A-star algorithm. Given that the optimal solution is re-calculated by the interval of every 0.1 second, the acceleration/deceleration and throttle levels can also be updated by every 0.1 second.

2.2. GLOSA for Buses

A simple bus fuel consumption model was developed and calibrated in [18, 19]. The framework of Virginia Tech Comprehensive Power-based Fuel Consumption Model (VT-CPFM), which was originally developed for LDVs, was used to develop the fuel model for buses as presented in Equation 8. The vehicle power used in the fuel model can be computed as Equation 9.

$$FC(t):\begin{cases} a_0 + a_1P(t) + a_2P(t)^2, & P(t) \ge 0 \\ a_0 & P(t) < 0 \end{cases} \tag{8}$$

$$P(t) = \left(\frac{R(t) + (1 + \lambda + 0.002\quad (t)^2)ma(t)}{3600\quad d}\right)\cdot u(t) \tag{9}$$

Where *FC(t)* denotes the instantaneous fuel consumption rate; α_0, α_1 and α_2 are the model coefficients for a specific vehicle type, which need to be calibrated for each vehicle; λ is the mass factor accounting for rotational masses, a value of 0.1 is used for HDVs [23]; 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 forces on the vehicle as given by Equation (4).

A regression-based approach was developed in [18] 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 with two roadway sections: US 460 business (highway with a speed limit of 65 mph) and local streets (with the speed limit from 25 mph to 45 mph). The collected data were divided into two data sets for the test bus. The first data set were used for calibration purpose, which include 60% to 70% percent of the entire data for the test bus, and the remaining data set were used for model validation. The regression-based model fitting can estimate the values of parameters α_0, α_1 and α_2 in Equation 8. The calibrated bus fuel model was compared with the measurement data and presented very good fitting accuracy as shown in Figure 2.

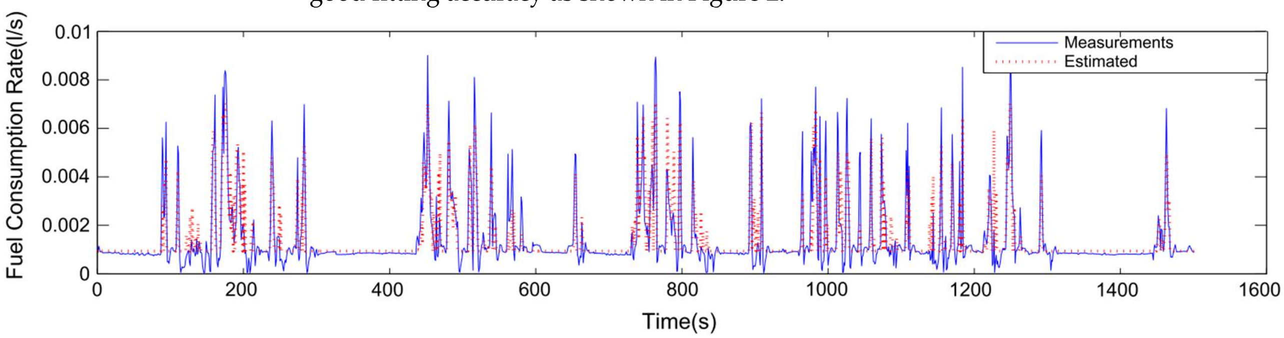

Figure 2. Model validation for bus fuel consumption model.

3. Case Study

3.1. Test Environment

The connected vehicle testbed located at the Virginia Tech Transportation Institute (VTTI)'s Smart Road was used to validate the performance of the proposed B-GLOSA system. The Smart Road at VTTI is a 3.5-kilometer (2.2-mile) roadway with turnaround loops at both ends. Wireless roadside equipment unites are installed at a spacing around 500~600 meters, which provides 5.9GHz of short range wireless communications between the infrastructure and vehicles. Two mobile roadside equipment sites are also available at the Smart Road. The Signal Phasing and Timing (SPaT) information at intersection can be remotely controlled by vehicle location or user input through wireless communication. The layout of the test road is illustrated in Figure 3. The upstream and downstream roadway connected by the signalized intersection is a surface roadway with two lanes, and each direction is a one lane road. Figure 3 shows that a four-way signalized intersection is located in the center. The roadway grades are approximately -3 percent for the downhill direction and +3 percent for the uphill direction. The stop lines for both directions are located on the signalized intersection. The B-GLOSA system is enabled when the bus is 200 meters upstream of the stop bar and is disabled when the bus is 200 meters downstream of the stop bar. Thus, both of d_{up} and d_{down} are equal to 200 meters. During the test drive in the uphill direction, the bus can accelerate up to 32~34 mph before merging to turnaround 1 if the bus was fully stopped at the intersection. Therefore, the speed limit was set as 30 mph. In order to have a fair comparison across different runs, buses attempted to drive at 30 mph before entering and after leaving the control range. Thus, two cones were placed at the 200 meters upstream (the first cone) and 200 meters downstream (the second cone) of the intersection for each direction, so in total there are four cones with drivers being asked to drive at 30 mph when passing the cones.

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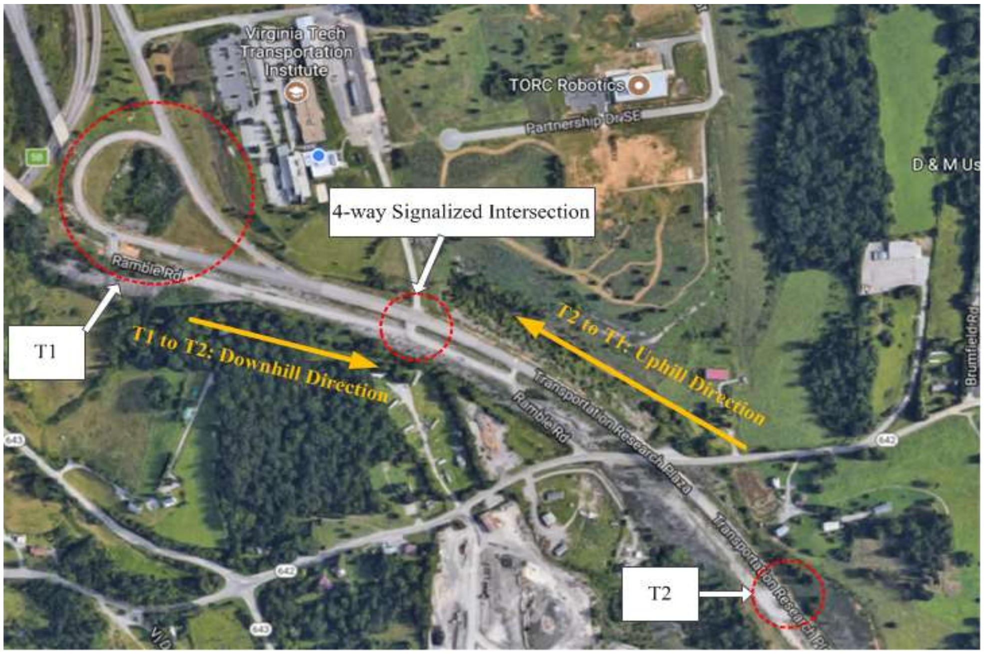

Figure 3. Layout of the test road (source: Google Maps).

In order to test the impact of different signal timing plans to the B-GLOSA system performance, four different signal timings were used during the test. Here, the variable is called "red offset", which represents the remaining red offset time when the vehicle enters the test area by passing the first cone. We used four combinations of red offsets, including 10, 15, 20 and 25 seconds. During the test, initially the testing bus is far away and driving to the downstream traffic signal, and the traffic signal shows a constant red indication. When the testing bus is passing the upstream location d_{up}, the countdown of the red offset (the remaining red indication time) is triggered by a random value from 10, 15, 20 or 25 seconds. Moreover, the upcoming green indication time is set as 25 seconds to ensure the bus can arrive at the downstream location even the bus is completely stopped at the signalized intersection.

In total, 30 participants were recruited to conduct the field test. All the participants were voluntarily recruited from BT bus drivers, since the test vehicle was a diesel bus provided by Blacksburg Transit (BT) and BT's policy required the bus can be only operated by BT bus drivers. Each participant was asked to conduct three different driving scenarios including: 1) scenario 1 – uninformed drive; 2) scenario 2 – informed drive with signal timing; 3) scenario 3 – informed drive with recommended speed. The field test was aimed to investigate the impacts of road grades and red offset timings on vehicle performances, and the details of experimental design and statistical analysis are described in the next section. Each participant drove the test bus 8 times for each driving direction, and red offset value for each repeated trip was randomly selected from 10, 10, 15, 15, 20, 20, 25, 25 seconds, which means each predefined red offset value is repeated twice. In addition, each participant was drove under 3 different scenarios described below, under dry road surface and day light conditions. In this way, each participant had 16 trips for each scenario (48 trips for 3 scenarios). The total trip number for 30 participants was 1440. Note that we only extracted the vehicle data for each trip by passing from the upstream location d_{up} to the downstream location d_{down}. Eventually, 1440 sets of trip information were collected as the raw data set to analyze the system performance in the field test.

- **Scenario 1 (S1) – Uninformed drive:**

The driver needs to operate the bus normally by following traffic signal indications, without any driving assistant systems.

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- **Scenario 2 (S2) – Informed drive with the provision of signal timing information:** The driver is provided, through audio information, when approaching the signalized intersection when the traffic signal will turn green. The audio information provides a countdown of signal timing to the next signal phase, which is used to assist the driver to operate the vehicle maneuver to traverse the intersection.
- **Scenario 3 (S3) – Informed drive with recommended speed (B-GLOSA):** The driver is provided with audio information with the recommended speed when approaching the signalized intersection. The driver is asked to try his/her best effort to follow the recommended speed and adjust the vehicle speed accordingly.

Figure 4. Hardware of vehicle onboard units in the bus GLOSA system.

A diesel-powered bus from BT was used in the field test, and the vehicle's onboard units of our developed bus GLOSA system were installed into the cabinet control box behind the driver's seat, as presented in Figure 4. The test bus was a 2014 New Flyer XD40 model with a 280-horsepower diesel engine. A differential GPS device was installed on the vehicle front top area to ensure the vehicle can receive accurate location information. A data acquisition system (DAS) customized by VTTI was installed in the control box, which collects GPS data, vehicle data, and SPaT and communicates with a portable laptop to compute recommended speed. All the test data were encrypted and stored in a hard drive disk, which were uploaded to VTTI data service after completing the test. An audio system was chosen for conveying the information in the cases of scenario 2 and 3 because previous researches [24, 25] have proven that visual display can be highly distracting for the driver. In order to ensure that the proposed system can be used for real-time applications, the B-GLOSA system computes the optimum speed profile at 10 Hz, which means the optimum speed is re-calculated every 0.1 seconds. The average driver's perception reaction time is considered as approximately 1.5 seconds. The communication system is tested, and we obtained around 0.5 seconds of latency. Hence, the audio system was preset to convey the information to the driver at intervals of 2 seconds.

3.2. Experimental Design and Statistical Analysis

The case study attempts to investigate the impact of three factors – scenario, road grade and red indication offset on trip fuel consumption level and travel time. Different experimental design approaches were considered for planning this case study so that the data obtained can be analyzed to yield valid and objective conclusions. The simplest option is that each factor can be randomly assigned for each testing trip when a participant passes the signalized intersection from upstream to downstream. However, practically there are several reasons we cannot conduct the field test in this way. Firstly, we do not

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want a participant to start with scenario 3 before the other two scenarios, since it is highly probable that a participant's driving behavior for scenarios 1 or 2 will be changed after getting the experience of following the optimal speed profile in scenarios 3. Secondly, testing the same road grade in two consecutive trips is not effective from a cost and time perspective. Given that the test site is a loop road starting from turnaround 2 to 1 and eventually returning to turnaround 2, participants will need to drive two loops if we want to test two 3% (or -3%) runs. But participant will only need to drive one loop to test a 3% uphill run followed by a -3% downhill run. Therefore, two factors (scenario and road grade) cannot be randomized in this experiment. Specifically, each participant should start with scenario 1, followed by scenario 2, and lastly scenario 3. The road grade iterates through 3% uphill and -3% downhill by driving along the loop road. The only factor that can be randomized is the red indication offset at the instant the bus is 200 meters upstream of the intersection.

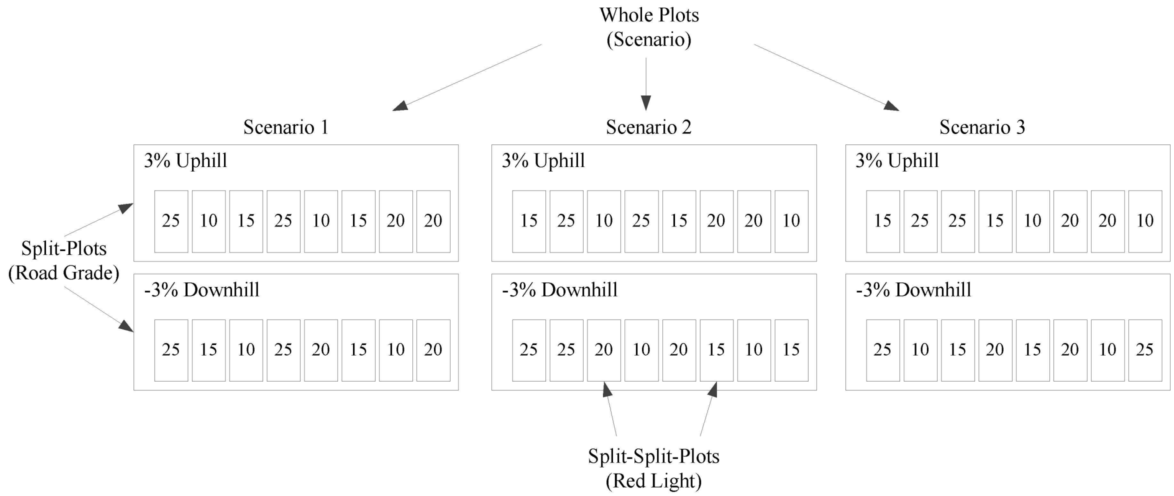

Figure 5. Structure of the split-split-plot design.

Considering the constraints that two factors are difficult to change, the split-split plot design was used in this study. The split-split plot design is a type of restricted randomization experimental design, which was originally proposed in the field of agriculture to make the experiment design easier and more cost and time effective [26]. The split-split-plot design in this study is a blocked experiment with three levels of experimental units as shown in Figure 5. The first level of the experimental units is the whole plot (scenario); the second level is the experimental units within the whole plot, called the split-plot (road grade); and the third level is the experimental units within the split-plot, called the split-split-plot (red indication offset). The red indication offset was the only factor that can be randomized without any effects on the experiment. Given that we had a limited participant pool and all the drivers were bus drivers from Blacksburg Transit, we did not recruit participants by gender or age groups. The participant effect (variation of driver behavior among participants) was considered as a random effect, so it was not used as a fixed effect factor.

The JMP statistical software was used to analyze the split-split plot experiment results. The results of fixed effect tests from the output of the Fit Mixed report are presented in Table 1, which includes the degrees of freedom, F ratio and p value from the ANOVA test. However, an ANOVA test can only tell if the results are significant overall. To further investigate which pairs of compositions from all the source factors have a significant difference, the Tukey Test (also called Tukey's Honest Significant Difference test) was used to compare all possible pairs of means [27]. For the response variable of fuel consumption, the test results indicated that S1 and S3 are significantly different for both uphill and downhill directions for various red indication offset values. Moreover, the differences

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between S1 and S2 are statistically significant except for driving towards downhill direction with 20 and 25 seconds offset. In addition, the results showed that S2 and S3 are significantly different except for the cases with a 10 second offset for both the uphill and downhill directions of travel.

Table 1. Results of fixed effect tests.

Response Variable	Source	DF	DFDen	F Ratio	*p* value
Fuel Consumption	Scenario	2	146	83.004	<.0001
	Red offset	3	1255	1182.769	<.0001
	Grade	1	175	7355.448	<.0001
	Scenario*Grade	2	175	10.658	0.1872
	Scenario*Red offset	6	1255	12.449	0.0685
	Red offset*Grade	3	1255	30.084	<.0001
	Scenario*Red offset*Grade	6	1255	8.796	0.1236
Travel Time	Scenario	2	146	660.503	<.0001
	Red offset	3	1255	8623.917	<.0001
	Grade	1	175	131.278	0.0853
	Scenario*Grade	2	175	13.477	0.0762
	Scenario*Red offset	6	1255	53.352	0.1082
	Red offset*Grade	3	1255	0.900	0.4849
	Scenario*Red offset*Grade	6	1255	3.029	0.6215

Compared to the Tukey Test results for the response variable of fuel consumption, using the response of travel during the test showed slightly different results. The differences between S1 and S3 are statistically significant except for the cases with a 10 second red indication offset for both uphill and downhill directions, as well as driving with 25 seconds red offset for uphill direction. Moreover, S1 and S2 are only significantly different under 15 and 20 seconds red offset for uphill direction. For uphill direction, the differences between S2 and S3 are statistically significant except for 10 seconds red offset. For downhill direction, the differences between S2 and S3 are statistically significant only driving under 15 seconds red offset. The test results demonstrated that the proposed B-GLOSA system produces significantly different fuel consumption performance compared with S1 and S2 in most cases, by consuming a similar (or less) travel times. The quantitative performance analysis of the field test is presented as below.

3.3. Quantitative Performance Analysis

The instantaneous fuel consumption, vehicle speed and location were collected during each trip to calculate the average fuel consumption and travel times. Table 2 presents the average fuel consumption levels for one trip (from 200 meters upstream to 200 meters downstream) for different scenarios (1, 2 and 3), road grade (3% and -3%) and red offset time (10, 15, 20, 25 seconds). Under the same road grade and red offset time, the fuel consumption levels continue to decrease from scenario 1 ~ 3 as presented in the left bar charts in Figure 6. Compared to scenario 1, scenario 2 consumed averagely 13.4% and 6.0% less fuel consumption for the downhill and uphill directions, respectively. Compared to scenario 1, scenario 3 consumed averagely 34.2% and 10.1% less fuel consumption for the downhill and uphill directions. Note that scenario 3 produced significant amount of fuel

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savings (2.55 times savings over scenario 2) under downhill direction. It should be noted that 15 seconds of red offset corresponds to the maximum fuel savings (49.1% and 15.1%) for scenario 3 under both uphill and downhill directions. This is resulted by the fact that the bus equipped with the proposed B-GLOSA system shows the maximum speed difference compared to the case of bus without B-GLOSA. Under the case of 15 seconds red offset, drivers will expect to stop when vehicle is very close to the intersection since the signal turns from red to green at the last moment. In scenario 1, drivers usually start to reduce speed quickly when vehicle is around 50 meters away from the intersection, which results in 10~15 mph vehicle speed at the start of green light. But in scenario 3, the B-GLOSA system will ask drivers to slow down to around 25 mph at beginning, which results in greater than 25 mph vehicle speed at the start of green light. Consequently, the average bus speed in scenario 3 was much higher than the speed in scenario 1 for the 15 seconds red interval offset, which resulted in the maximum savings of fuel in this case. It's also very interesting to see that the test bus under 3% uphill direction consumed 2 ~ 3 times of fuel compared to driving with similar speed under -3% downhill direction. In total, scenario 3 produced 22.1% of overall average fuel savings compared with scenario 1, and scenario 2 produced 9.7% of overall fuel savings. Such high fuel saving rates by scenario 3 proved that the proposed B-GLOSA system can efficiently save bus fuel in the vicinity of signalized intersections.

Table 2. Average Trip Fuel Consumption (FC) Levels.

Direction	Red offset (sec)	Scenario 1 FC (liter)	Scenario 2 FC (liter)	Scenario 3 FC (liter)	Difference between S2 and S1 (%)	Difference between S3 and S1 (%)
Downhill	10	0.102	0.072	0.056	-29.7%	-44.9%
	15	0.179	0.151	0.091	-15.3%	-49.1%
	20	0.217	0.202	0.161	-6.7%	-25.8%
	25	0.229	0.224	0.190	-2.1%	-16.8%
Uphill	10	0.369	0.356	0.354	-3.5%	-4.2%
	15	0.424	0.390	0.360	-8.0%	-15.1%
	20	0.451	0.419	0.399	-7.1%	-11.6%
	25	0.462	0.438	0.419	-5.3%	-9.3%
Downhill Average		0.182	0.162	0.125	-13.4%	-34.2%
Uphill Average		0.427	0.401	0.383	-6.0%	-10.1%
Total Average		0.304	0.282	0.254	-9.7%	-22.1%

Table 3 presents the average trip travel times under different scenarios, grades and red offset times. Under the same road grade and red offset time, the similar trend that travel times keep reducing from scenario 1 ~ 3 can be observed in the right bar charts in Figure 6, which means scenario 3 always produced the least fuel consumption levels and travel times. Compared to scenario 1, scenario 2 consumed averagely 2.5% and 3.0% less travel times for downhill and uphill directions, respectively. Compared to scenario 1, scenario 3 consumed averagely 6.9% and 5.3% less travel times for downhill and uphill directions, respectively. Note that travel times under uphill direction are not significantly different from downhill direction. In total, scenario 3 produced 6.1% of overall average travel time savings compared with scenario 1, and scenario 2 produced 2.8% of overall travel time savings. The test results in Table 1 and 2 proved that the proposed bus GLOSA system can efficiently reduce fuel savings while keeping a fairly amount of travel time savings at the same time.

Table 3. Average Trip Travel Times.

Direction	Red offset (sec)	Scenario 1 TT (sec)	Scenario 2 TT (sec)	Scenario 3 TT (sec)	Difference between S2 and S1 (%)	Difference between S3 and S1 (%)
Downhill	10	30.4	29.6	29.4	-2.9%	-3.3%
	15	34.1	33.1	30.6	-2.8%	-10.1%
	20	40.1	39.0	36.7	-2.9%	-8.5%
	25	45.7	45.1	43.1	-1.4%	-5.6%
Uphill	10	31.1	30.2	30.0	-2.9%	-3.5%
	15	35.5	34.3	32.0	-3.3%	-9.7%
	20	42.0	40.3	39.9	-3.9%	-5.0%
	25	47.3	46.4	46.0	-2.0%	-2.7%
Downhill Average		37.6	36.7	35.0	-2.5%	-6.9%
Uphill Average		39.0	37.8	37.0	-3.0%	-5.3%
Total Average		38.3	37.2	36.0	-2.8%	-6.1%

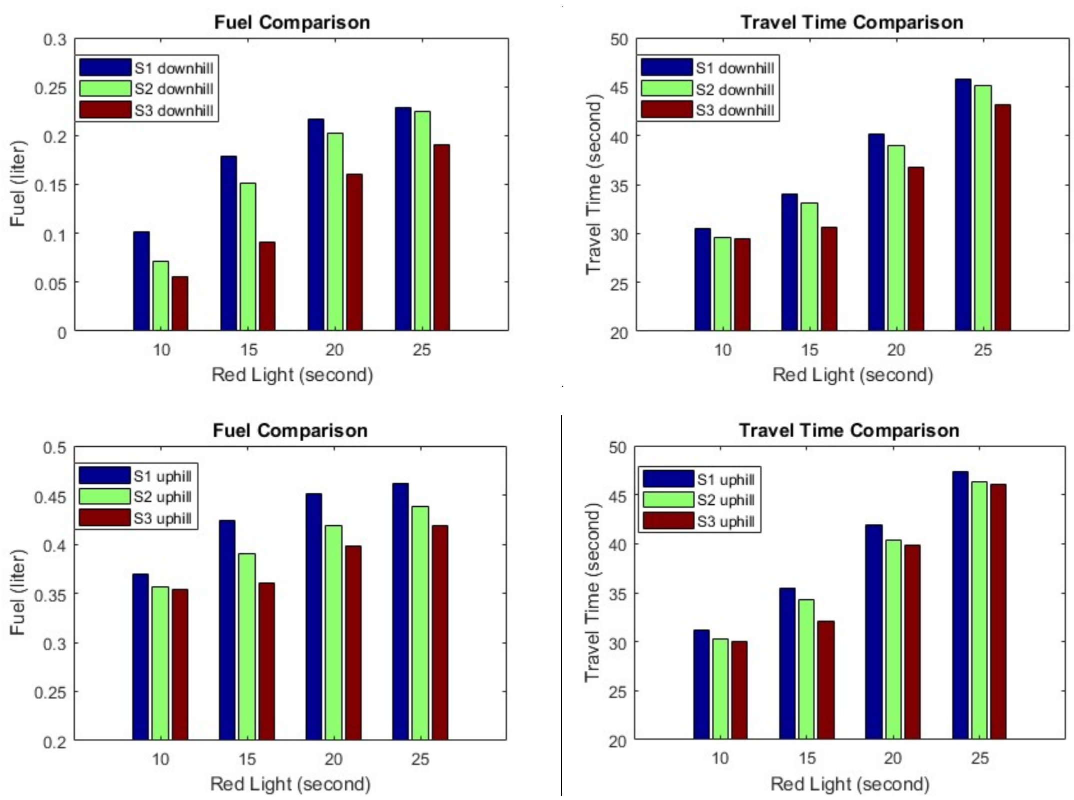

Figure 6. Compare test results for fuel levels and travel times.

Sample vehicle speed profiles of a selected participant for downhill direction under various red offset timings are presented in Figure 7. All speed profiles have the similar starting and ending speeds around 30 mph, so the comparison between different scenarios are fair since vehicle speed values in between were affected by the settings of uninformed or informed driving in each scenario. For scenario 1, it can be observed that vehicle resulted in completely stop for 20 and 25 seconds red offset. Scenario 2 also had a completely

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stop under 25 seconds red offset. Apparently, scenario 3 produced much smoother speed profiles compared with other scenarios. The sample speed profiles demonstrated the benefits of the bus GLOSA system by helping the bus to drive smoothly to pass signalized intersections and simultaneously reduce fuel consumption rates and travel times.

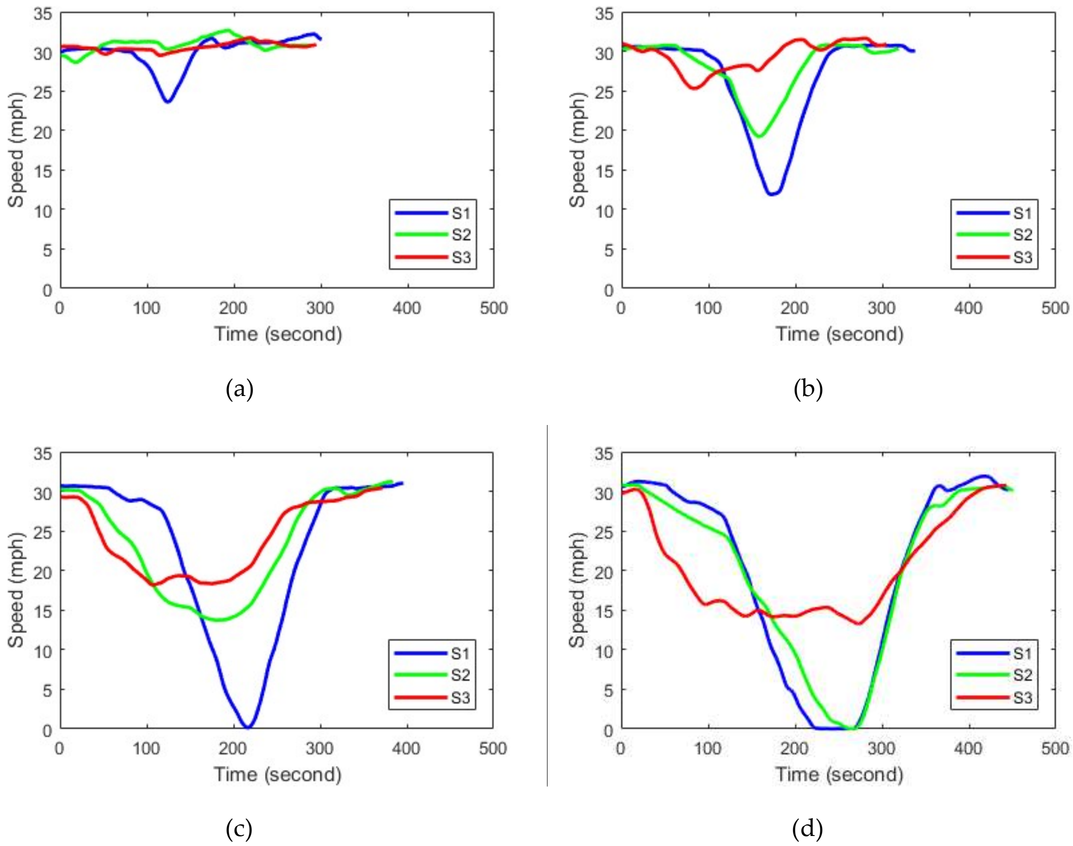

Figure 7. Vehicle speed profiles of a selected participant for downhill direction under various red offset timings: (a) 10 seconds; (b) 15 seconds; (c) 20 seconds; (d) 25 seconds.

4. Conclusions

This study proposed a bus eco-driving system, entitled B-GLOSA. The developed system is computes the fuel-efficient trajectory for buses using the traffic signal data received from downstream signalized intersections. In the proposed B-GLOSA system, a fuel consumption model for diesel buses was used to compute instantaneous fuel consumption rates, since this model is easy to calibrate using easy-to-access bus data. The vehicle dynamics model, fuel consumption model, the signal timings, and the vehicle speed and distance relationship are used to construct an optimization problem. Moreover, a moving-horizon dynamic programming and an A-start algorithm is used to solve the optimization problem and calculate the energy-optimized vehicle trajectory to assist buses to pass signalized intersections. The proposed system has been implemented into diesel buses, and we have conducted field test to validate the real-world benefits of using this system. The Virginia Smart Road test facility was used to conduct the field test using 30 participants. Each participant drove three scenarios including a base case uninformed drive, an informed drive with signal timing, and an informed drive with the recommended speed computed by the B-GLOSA system. The field test investigated the performance of using the developed B-GLOSA system for different impact factors of road grades and red indication offsets, using a split-split-plot experimental design. The test results demonstrated that the proposed B-GLOSA system can greatly smooth the bus trajectory while traversing a signalized intersection, and simultaneously save fuel consumption and travel times. Compared to the uninformed drive, the test results demonstrated that the B-GLOSA can efficiently reduce fuel consumption by 22.1% and simultaneously reduce vehicle travel times by 6.1%. In the future research, the B-GLOSA system will be tested within a microscopic simulation environment to validate the network level performances under various traffic conditions and heterogeneous traffic including LDVs and buses.

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