Integrated Optimization of Vehicle Trajectories and Traffic Signal Timings

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Abstract: This research develops a bi-level optimizer that provides energy-optimal control for vehicles and traffic signals. The first level optimizes the traffic signal timings to minimize the total energy consumption of approaching vehicles. The traffic signal optimization can be easily implemented in real-time traffic signal controllers and overcomes the shortcomings of the traditional Webster method, which overestimates the cycle length when the traffic volume-to-capacity ratio exceeds 50 percent. The lower-level optimizer is the vehicle speed controller, which calculates the optimal vehicle brake and throttle levels to minimize the energy consumption of individual vehicles. The proposed integrated controller is first tested on an isolated signalized intersection, and then on an arterial network with multiple signalized intersections to investigate the performance of the proposed controller under various traffic demand levels. The test results demonstrate that the proposed integrated controller can greatly improve energy efficiency producing fuel savings of up to 17.7%. It can also enhance traffic mobility by reducing traffic delays by up to a 47.2% and reducing vehicle stops by up to 24.8%.

1 INTRODUCTION

The United States is one of the world's prime petroleum consumers, burning more than 20% of the planet's total refined petroleum. The surface transportation sector alone accounts for around 69% of the United States' total petroleum usage and 33% of the nation's CO_2 emissions (Administration, 2018). This presents the transportation sector with three important challenges: availability of fuel to drive vehicles, emissions of greenhouse gases, and vehicular crashes. It is, therefore, important to reduce petroleum consumption and greenhouse gas emissions to make surface transportation safer, more efficient, and more sustainable (Kamalanathsharma, 2014).

Studies have shown that stop-and-go traffic near signalized intersections can greatly increase traffic delays, energy consumption, and emission levels on arterial roads since vehicles are forced to stop ahead of traffic signals when encountering red indications, producing shock waves within the traffic stream (Barth & Boriboonsomsin, 2008). Starting from the 1980s, many studies have focused on optimizing traffic signal timings using measured traffic data to improve the operation of arterial roads (Gartner, Assman, Lasaga, & Hou, 1991; Park, Messer, & Urbanik, 1999). In the past decade, the advanced communication power in CVs ensures rapid information sharing, which enables researchers to develop eco-driving strategies to optimize vehicle trajectories in real-time using signal phase and timing (SPaT) data. This has the potential to greatly improve traffic mobility and reduce energy consumption and emissions (Almannaa, Chen, Rakha, Loulizi, & El-Shawarby, 2019; Chen & Rakha, 2020; Chen, Rakha, Loulizi, El-Shawarby, & Almannaa, 2016). Recently, a few studies have attempted to simultaneously optimize vehicle trajectories and traffic signal timings to further improve transportation efficiency and fuel economy on arterial roads. For instance, an integrated optimization method was developed to optimize

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vehicle platoons and traffic signal timings using a mixed integer linear programming model (C. Yu, Feng, Liu, Ma, & Yang, 2018). However, this method uses some unrealistic assumptions, such as assuming all vehicles are homogeneous and lane changes are instantaneous, which limit the method's applicability. A simplified simulation with one intersection was designed to validate the performance of the proposed method. In addition, another study developed a cooperative method of traffic signal and vehicle speed optimization at isolated intersections (Xu et al., 2018). This method entails a two-level controller – the first level calculates the optimal signal timings and vehicle arrival times to minimize the total travel time; the second level optimizes the engine power and brake force to minimize the fuel consumption of individual vehicles. However, the proposed method assumes a 100% market penetration of CAVs, so it cannot be used for CVs that are controlled by human drivers. In addition, the optimization problem is solved using an enumeration method, which results in a heavy computational cost. Thereafter, a dynamic programming and shooting heuristic approach is proposed to optimize CAV trajectories and the traffic signal controller at the same time (Guo et al., 2019). A shooting heuristic algorithm was used to compute near-optimal vehicle trajectories to save computational costs. Numerical tests were conducted that demonstrated that the proposed method outperforms adaptive signal control. Although the algorithm can be used with a mixture of CAVs and CVs, the developed controller only optimizes CAVs which can fully follow the speed control but does not provide optimized speed for CVs.

According to the aforementioned studies, optimizing both vehicle trajectories and signal timings is a promising method to improve transportation system efficiency and fuel economy on arterial roads. However, there are several issues in these studies. First, the developed methods are generally very complicated with high computational costs, and thus there is a need to develop a simpler approach with low computational cost so that it can be easily implemented in real-time applications. Second, existing studies only validated the developed methods either in numerical tests or simplified simulation tests with only one intersection. This is also because these methods are very complicated to implement into simulation software or field tests. So, there is a need to test the approach using microscopic traffic simulation software and validate the performances under various conditions, such as different traffic demand levels on the arterial network with multiple signalized intersections.

This study considers these issues in the previous literature to develop an integrated vehicle speed and traffic signal controller. In the proposed system, we develop a two-layer optimization approach that is computationally fast to provide energy-optimal control for vehicles and traffic signal controllers. These two optimizers will work in tandem by sharing information. The optimizer in the first layer computes the traffic signal timings to minimize the total energy consumption levels of approaching vehicles from upstream traffic. The traffic signal optimization can be easily implemented into the real-time signal controller, and it overcomes the issues in the traditional Webster's method of overestimating the cycle length when the traffic volume-to-capacity ratio exceeds 50 percent. The second layer optimizer is the vehicle speed controller which calculates the optimal vehicle brake and throttle levels to minimize the energy consumption of individual vehicles. The proposed integrated controller is first tested in an isolated signalized intersection. An arterial network with multiple intersections is then used to investigate the performance of the proposed controller under various traffic demands. The test results demonstrate that the proposed integrated controller outperforms other methods and produces the most savings in fuel consumption, traffic delay, and vehicle stop under various traffic demands.

The remainder of this paper is presented as follows. The integrated controller is described in the next section, including the traffic signal optimization, and the vehicle speed controller. The proposed bi-level controller is then tested in an isolated signalized intersection. This is followed by implementing the proposed controller on a simulated arterial network in the town of Blacksburg, VA to test the network-level performance under different traffic demands. The last section provides the study conclusions.

2 PROPOSED INTEGRATED CONTROLLER

The proposed integrated controller includes two levels of optimization: one for traffic signals and the other for vehicle trajectories. The traffic signal controller optimizes the signal cycle length and timing according to the incoming traffic flow rate from the upstream links of the signalized intersection. The individual vehicle speed controller optimizes the vehicle trajectories using the data from traffic signals and surrounding vehicles through V2I and V2V communications. The integrated controller computes the optimized signal timing and vehicle trajectory to minimize the energy consumption of the entire traffic network. The details of the two-layer control strategies are provided below.

2.1 Traffic Signal Optimization

The traditional goal of optimizing traffic signal cycle length usually focuses on minimizing vehicle delay and increasing throughput at the intersection. The classic method is designed by British researcher F.V Webster, who developed an optimal cycle length formulation that approximates the signal timings necessary to minimize vehicle delay (Webster, 1958), as seen in Equation (1). This formulation has been used in traffic analysis for years and is still one of the prevailing methodologies used to determine the optimal cycle length for traffic signals.

$$C_{opt} = \frac{1.5L + 5}{1 - Y} \tag{1}$$

where,
C_{opt} = cycle length to minimize delay in seconds.
L = total lost time for cycle in seconds.
Y = sum of flow ratios for critical lane groups.

However, several studies have found that the optimal signal timing for minimizing delays is not necessarily identical to the timing plans that minimize energy consumption and emissions. For instance, a generalized formulation was developed in (Akcelik, 1981) to compute optimal cycle time for signalized intersections by different performance measures including fuel consumption, cost and delay. An additional parameter was introduced into the equation, and different values were calibrated to optimize cycle length for fuel consumption and delay.

The study in (Ma, Jin, & Lei, 2014) proposed and compared various traffic signal optimization methods using VISSIM and SUMO. The test results indicated that there are apparent trade-offs between the goal of mobility and sustainability. Moreover, researchers studied the emissions at isolated intersections and found that the goal of decreasing delays at intersections and reducing emissions is not simply equivalent (Li, Wu, & Zou, 2011). Delays at intersections will increase if the number of vehicle stops decrease, which will help reduce the pollution at intersections. In addition, the study in (Liao, 2013) considers a fuel-based signal optimization model, which describes the stochastic effects of vehicle movements that consume excess fuel. The proposed model was compared with the results from Webster's model, TRANSYT 7F, and Synchro, demonstrating the greatest efficiency among all the methods with fuel consumption reductions of up to 40%.

Recent studies in (Calle-Laguna, Du, & Rakha, 2019; Calle Laguna, 2017) improved the traditional equation recommended by Webster by using the data obtained from microscopic traffic simulation software. The improved model, represented in Equation (2), has also outperformed Webster's equation to further reduce traffic delay, especially during higher traffic demand volumes. Since optimizing traffic signal to minimize traffic delay doesn't mean the fuel consumption is also minimized, another new formulation in Equation (3) is computed by optimizing the signal cycle length to minimize vehicle fuel consumption levels. A case study has shown that the improved equations overcome the issues in the traditional Webster's method of overestimating the cycle length when the traffic volume-to-capacity ratio exceeds 50 percent, the detailed test results can be found in (Calle-Laguna et al., 2019; Calle Laguna, 2017). First, the optimal cycle length is obtained, thereafter the signal timings are computed by considering the green times using the critical lane traffic ratio (Urbanik et al., 2015). Eventually, the optimal signal timings can be computed according to the traffic flow rates from upstream links of the signalized intersections at each interval, e.g., five minutes.

$$C_{opt,delay} = \frac{0.33L + 8.56}{1 - Y} + 3.8 \tag{2}$$

$$C_{opt,fuel} = \frac{0.82L}{1 - Y} + 40 \tag{3}$$

2.2 Vehicle Trajectory Optimization

In this study, the vehicle trajectory is optimized by the connected eco-driving controller, named eco-cooperative adaptive cruise control at intersections (Eco-CACC-I), previously developed in (Almannaa et al., 2019; Chen & Rakha, 2020; Chen et al., 2016) to compute real-time fuel/energy-optimized vehicle trajectories in the vicinity of signalized intersections. The control region was defined from a distance upstream of the signalized intersection (d_{up}) to a distance downstream of the intersection (d_{down}) in which the Eco-CACC-I controller optimizes the vehicle trajectories approaching and leaving signalized intersections. Upon approaching a signalized intersection, the vehicle may accelerate, decelerate, or cruise (maintain a constant speed) based on several factors, such as vehicle speed, signal timing, phase, distance to the intersection, road grade, headway distance, etc. We assumed no leading vehicle ahead of the subject vehicle so that we could compute the energy-optimized vehicle trajectory for the subject without considering the impacts of other surrounding vehicles. The computed optimal speed was used as a variable speed limit, denoted by $v_e(t)$, which is one of the constraints on the subject vehicle's longitudinal motion. When a vehicle travels on the roadway, there are other constraints to be considered, including the allowed speed constrained by the vehicle dynamics model, steady-state car following model, collision avoidance constraints, and roadway speed limit. All these constraints work together to control the vehicle speed. In this way, the proposed controller can also be used in the situation that the subject vehicle follows a leading vehicle, and the vehicle speed can be computed by $v(t) = \min(v_1(t), v_2(t), v_3(t), v_4(t), v_e(t))$ using the following constraints:

- The maximum speed $v_1(t)$ allowed by the vehicle acceleration model for a given vehicle throttle position.
- The maximum speed $v_2(t)$ constrained by the steady-state vehicle spacing in the simulation software.
- The speed $v_3(t)$ to avoid a rear-end vehicle collision.
- The road speed limit $v_4(t)$.

Within the control region, the vehicle's behavior can be categorized into one of two cases: (1) the vehicle can proceed through the signalized intersection without decelerating or (2) the vehicle must decelerate to proceed through the intersection. Given that vehicles drive in different manners for cases 1 and 2, the Eco-CACC-I control strategies were developed separately for the two cases.

Case 1 does not require the vehicle to decelerate to traverse the signalized intersection. In this case, the cruise speed for the vehicle to approach the intersection during the red indication can be calculated using Equation (4) to maximize the average vehicle speed within the control region. When the vehicle enters the control region, it should adjust its speed to u_c by following the vehicle dynamics model developed in (K. Yu, Yang, & Yamaguchi, 2015). After the traffic signal indication turns from red to green, the vehicle accelerates from the speed u_c to the maximum allowed speed (speed limit u_f) by following the vehicle dynamics model until it leaves the control region.

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

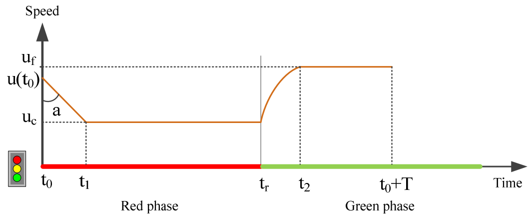

Figure 1: Vehicle optimum speed profile.

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

Assuming a vehicle enters the Eco-CACC-I control region at time t_0 and leaves the control region at time t_0+T, the objective function entails minimizing the total energy consumption as

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

where EC denotes the energy consumption at instant t. The energy models for internal combustion engine vehicles (ICEVs) are presented in Equations (8) ~ (9). The constraints to solve the optimization problem can be built according to the relationships between vehicle speed, location, and acceleration/deceleration as presented below:

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

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

where $u(t)$ is the velocity at instant t; m is the vehicle mass; $a(t) = dv(t)/dt$ is the acceleration of the vehicle in [m/s^2] ($a(t)$ takes negative values when the vehicle decelerates); function F denotes vehicle tractive force, and function R represents all the resistance forces (aerodynamic, rolling, and grade resistance forces). Note that the maximum deceleration is limited by the comfortable threshold felt by average drivers (Kamalanathsharma, 2014). The throttle value f_p ranges between f_{min} and f_{max}. An A-star dynamic programming approach is used to solve the problem by constructing a graph of the solution space by discretizing the combinations of deceleration and throttle values and calculating the corresponding energy consumption levels; the minimum path through the graph computes the energy-efficient trajectory and optimum parameters (Guan & Frey, 2013; Kamalanathsharma, 2014).

$$FC_{ICEV}(t) = \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2 & \forall P(t) \geq 0 \\ a_0 & \forall P(t) < 0 \end{cases} \tag{8}$$

$$P(t) = (ma(t) + mg \cdot \frac{C_r}{1000}(c_1 u(t) + c_2) + \rho_{Air} A_f C_D u^2(t)/2 + mg\,\theta) u(t) \tag{9}$$

where $FC_{ICEV}(t)$ is the fuel consumption rate for ICEV; α_0, α_1 and α_2 are the model parameters that can be calibrated for a particular vehicle using public available vehicle specification information from the manufacturer, and the details of calibration steps can be found in (Rakha, Ahn, Moran, Saerens, & Van den Bulck, 2011); $P(t)$ is the instantaneous total power (kW); g [m/s^2] is the gravitational acceleration; θ is the road grade; C_r, c_1 and c_2 are the rolling resistance parameters that vary as a function of the road surface type, road condition, and vehicle tire type; ρ_{Air} [kg/m^3] is the air mass density; A_f[m^2] is the frontal area of the vehicle, and C_D is the aerodynamic drag coefficient of the vehicle.

3 CASE STUDY

In order to test the performance of the proposed control strategies, we implement the controllers in the microscopic traffic simulation software and conduct two tests using an isolated signalized intersection and an arterial traffic network with multiple signalized intersections, respectively.

INTEGRATION is used as the simulation tool to simulate the traffic network in the case study. INTEGRATION is an integrated simulation and traffic assignment model that creates individual vehicle trip departures based on an aggregated time-varying O-D matrix. In consideration of traffic control devices and gap acceptance, INTEGRATION moves vehicles along the network in accordance with embedded preset traffic assignment models and the Rakha-Pasumarthy-Adjerid (RPA) car-following model. A more detailed description of INTEGRATION is provided in the literature (M. V. Aerde & Rakha, 2007a, 2007b).

3.1 Isolated Intersection Test Case

This test considers the simplest case of a single-lane signalized intersection to validate the performance of using the proposed controller. The traffic stream parameters on the major road are free flow speed of 40 mph, a speed at capacity of 30 mph, a saturation flow rate of 1600 veh/h/lane, and a jam density of 160 veh/km/lane. The total simulation time is 60 minutes, and the traffic signal timing is optimized every 5 minutes. The vehicle speed is optimized within the control region: 200 meters upstream and 200 meters downstream of the intersection. Three levels of traffic demand volumes are considered in the test using the volume over capacity values of 0.1, 0.5, and 1, respectively. Five test scenarios described below are compared in the test.

- Scenario 1 (S1): Base

  This is the base scenario without signal optimization and vehicle speed control. The fixed-time signals (cycle length and green times) were obtained by using the final optimized signal timings in scenario 2 after running for 60 minutes.

- Scenario 2 (S2): Signal Optimization – Webster

  The traffic signal is optimized using Webster's method as shown in Equation (1).

- Scenario 3 (S3): Signal Optimization – Delay

  The traffic signal is optimized using the modified method to minimize traffic delay as shown in Equation (2).

- Scenario 4 (S4): Signal Optimization – Fuel

  The traffic signal is optimized using the modified method to minimize fuel consumption as shown in Equation (3).

- Scenario 5 (S5): Integrated Controller (Signal Optimization – Fuel + Eco-CACC-I)

  The traffic signal is optimized using the modified method to minimize fuel consumption as shown in Equation (3), and vehicle speed is optimized using the Eco-CACC-I controller within the control region.

Table 1: Test results on isolated signalized intersection.

Uncongested (v/c=0.1)

Scenarios	FC (liter)	FC saving	Delay (sec)	Delay saving
S1	0.1012		11.4	
S2	0.0979	-3.3%	10.9	-4.8%
S3	0.0972	-3.9%	10.8	-5.4%
S4	0.0955	-5.6%	11.5	1.1%
S5	0.0932	-7.9%	11.8	3.6%

Medium (v/c=0.5)

Scenarios	FC (liter)	FC saving	Delay (sec)	Delay saving
S1	0.1054		12.8	
S2	0.1021	-3.1%	12.4	-3.4%
S3	0.1019	-3.3%	12.2	-4.7%
S4	0.0998	-5.3%	12.3	-3.9%
S5	0.0979	-7.1%	13.0	1.0%

Congested (v/c=1)

Scenarios	FC (liter)	FC saving	Delay (sec)	Delay saving
S1	0.1089		32.7	
S2	0.1056	-3.0%	32.5	-0.7%
S3	0.1052	-3.4%	31.9	-2.3%
S4	0.1032	-5.2%	32.3	-1.3%
S5	0.1018	-6.5%	36.0	10.0%

The test results of the five scenarios for various traffic demand levels are summarized in Table 1. For uncongested traffic conditions, both the modified signal optimization methods in S3 and S4 outperform Webster's method (S2) by producing more fuel savings. But the total delay in S4 is higher than S1~S3, which matches with findings in previous studies stating that the optimal signal timing for minimizing delays is not necessarily identical to the timing plans that aim at minimizing energy consumption and emissions. The proposed integrated controller in S5 produces the most fuel savings of 7.9% compared to the base scenario without any controller. However, it also produces an increased total delay of 3.6% compared to S1. Similar trends can be found in the medium and congested traffic conditions. For the medium traffic demand, the fuel consumption continues to decrease from S1 to S5. The integrated controller produces the most fuel savings of 7.1%, but the corresponding total delay is increased by 1.0% compared to S1. For congested traffic conditions, the integrated controller in S5 reduces fuel consumption by 6.5%, but it also greatly increases the traffic delay by 10.0% compared to S1. Overall, the test results demonstrate the proposed integrated controller can effectively reduce fuel consumption at isolated signalized intersections.

3.2 Arterial Traffic Network Test Case

The proposed integrated controller is further tested on an arterial network located in the heart of downtown Blacksburg, as shown in Figure 2. The O-D demand matrices were generated using QueesOD software (M. Aerde & Rakha, 2010) and were based on traffic counts collected during the afternoon peak period (4 ~ 6 pm) at 15 minutes intervals for the year 2012 (Abdelghaffar, Yang, & Rakha, 2017). The simulations were conducted using the following parameter values: free-flow speed of 40 km/h based on the roadway speed limit, speed-at-capacity of 29 km/h, jam density of 160 veh/km/lane, and saturation flow rate of 1800 veh/h/lane. In the simulation, vehicles were allowed to enter the links in the first 2 hours, and the simulation ran for an extra 15 minutes to guarantee that all vehicles exited the network. Three different traffic demand volumes are investigated during this test. 100% demand represents the O-D demand matrices calibrated by the field data during afternoon peak hours. Then we also consider 25% and 50% demand to investigate the performances of the different controllers.

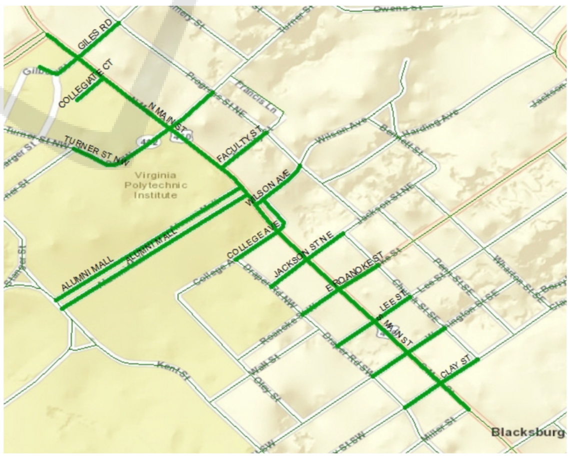

Figure 2: The arterial roadways in the city of Blacksburg, VA.

In this test, the same five different scenarios as described in the isolated intersection test are also considered. The test results of five scenarios for three traffic demand levels are summarized in Table 2. For

Table 2: Test results on arterial network.

25% Demond

Sc.	FC (liter)	FC saving	Delay (sec)	Delay saving	Stops	Stops saving
S1	0.0751		33.4		1.49	
S2	0.0688	-8.4%	22.7	-32.0%	2.08	39.6%
S3	0.0692	-7.9%	21.3	-36.2%	2.01	34.9%
S4	0.0675	-10.1%	23.2	-30.5%	2	34.2%
S5	0.0646	-14.0%	22.9	-31.4%	1.13	-24.2%

50% Demond

Sc.	FC (liter)	FC saving	Delay (sec)	Delay saving	Stops	Stops saving
S1	0.0757		34.6		1.53	
S2	0.0675	-10.8%	20.9	-39.6%	1.97	28.8%
S3	0.0681	-10.0%	20.1	-41.9%	1.94	26.8%
S4	0.0664	-12.3%	21.6	-37.6%	1.92	25.5%
S5	0.0643	-15.0%	20.9	-39.6%	1.15	-24.8%

100% Demond

Sc.	FC (liter)	FC saving	Delay (sec)	Delay saving	Stops	Stops saving
S1	0.0791		39		1.61	
S2	0.0671	-15.2%	19.4	-50.3%	1.86	15.5%
S3	0.0679	-14.2%	18.5	-52.6%	1.84	14.3%
S4	0.0668	-15.6%	20.9	-46.4%	1.82	13.0%
S5	0.0651	-17.7%	20.6	-47.2%	1.24	-23.0%

25% traffic demand, the delay-optimized method in S3 outperforms Webster's method in S2 and the fuel-optimized method in S4 by producing the greatest reduction in delay at 36.2%. The fuel-optimized method in S4 outperforms Webster's method in S2 and the delay optimized method in S3 by producing the most fuel savings at 10.1%. These findings are consistent with the test results in (Calle-Laguna et al., 2019; Calle Laguna, 2017) and prove that Webster's method represented in Equation (1) is indeed improved by the modified methods in Equations (2) and (3). However, the scenarios of S2, S3 and S4 result in more than a 34% increase in vehicle stops on the arterial network. Among all five scenarios, the integrated controller in S5 produces the greatest reduction in vehicle stops compared to S1, at 24.2%. S5 also produces the most fuel savings (14.0%) of all five scenarios. The test results under 25% demand indicate that the integrated controller can greatly enhance traffic mobility with a 31.4% reduction in total delay and a 24.2% reduction in vehicle stops, at the same time improving the energy efficiency with a 14.0% reduction in fuel consumption. Similar trends can be observed for the 50% and 100% demand levels. In both cases, the integrated controller produces the most savings in fuel consumption and vehicle stops while significantly reducing traffic delay. Overall, the test results on the arterial network indicate that the proposed controller can greatly improve energy efficiency with 17.7% fuel savings and enhance traffic mobility with up to a 47.2% reduction in total delay and 24.8% reduction in vehicle stops.

4 CONCLUSIONS

This paper develops a bi-level controller that provides energy-optimal traffic signal and vehicle trajectory control. At the upper level, the controller computes the traffic signal timings to minimize the total energy consumption levels of approaching vehicles. The traffic signal optimization can be easily implemented in real-time signal controllers and overcomes the problems with the traditional Webster's method of overestimating the cycle length when the traffic volume-to-capacity ratio exceeds 50 percent. At the lower level, the controller optimizes the vehicle brake and throttle levels to minimize the energy consumption of individual vehicles. The proposed integrated controller is first tested in an isolated signalized intersection, and then on an arterial network with multiple signalized intersections to test the controller under various traffic demand levels. The test results demonstrate that the proposed integrated controller can greatly improve energy efficiency with up to 17.7% fuel savings, at the same time enhancing the traffic mobility by reducing total delay by 47.2% and vehicle stops by 24.8%. More tests on city-level traffic networks will be considered in future work. We will also consider expanding the integrated control strategies to different vehicle types such as battery electric and hybrid electric vehicles.

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