Article

Development and Testing of an Integrated Energy-Efficient Vehicle Speed and Traffic Signal Controller

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ABSTRACT

This paper develops a two-layer optimization approach that provides energy-optimal control for vehicles and traffic signal controllers. 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 in real-time signal controllers, 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 A-star dynamic programming is used to solve the formulated optimization problem in the second layer to expedite the computation speed so that the optimal vehicle trajectories can be computed in real-time and can be easily implemented in simulation software for testing. The proposed integrated controller is first tested on an isolated signalized intersection, and then an arterial network with multiple 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 with fuel savings up to 17.7%, at the same time enhancing traffic mobility by up to 47.18% reduction in traffic delay and up to 24.84% reduction in vehicle stops.

Keywords: Integrated controller; Signal time optimization; Vehicle speed control; Signalized intersections; Energy optimized solution; Connected and automated vehicles.

INTRODUCTION

The United States is one of the world's prime petroleum consumers, burning more than 20% of the planet's total refined petroleum, and 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 [1]. 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 [2].

Studies have shown that stop-and-go traffic near signalized intersections can greatly increase traffic delay, 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 [3, 4]. Starting from the 1980s, many studies have focused on optimizing traffic signal timings using measured traffic data to improve the operation of arterial roads [5-8]. In the past decade, the advanced communication power in CVs ensures a very high update rate of information, which enables researchers to develop eco-driving strategies to optimize vehicle trajectories in real-time according to signal phase and time (SPaT) to improve traffic mobility and save energy consumption and emissions [9-12]. Recently, a few studies have attempted to simultaneously optimize vehicle speeds 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 vehicle platoons and traffic signal timings using a mixed integer linear programming model [13]. 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. Therefore, 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 [14]. This method entails a two-level controller – the first level calculates the optimal signal timing and vehicle arrival time to minimize 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 [15]. A shooting heuristic algorithm was used to compute near-optimal vehicle trajectories to save computational cost. 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 abovementioned studies, optimizing both vehicle speed and signal timing is a promising method to improve the 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 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 test. 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 A-star dynamic programming is used to solve the formulated optimization problem in the second layer to expedite the computation speed so that the optimal vehicle trajectories can be computed in real-time and can be easily implemented into simulation software for testing. The proposed integrated controller is first tested in an isolated signalized intersection, and then an arterial network with multiple intersections is used to investigate the performance of the proposed controller under various traffic demands. The test results demonstrate the proposed integrated controller outperforms other methods and produces the most savings in fuel consumption, traffic delay and vehicle stop under various traffic demands.

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The remainder of this paper is presented as follows. The integrated control strategies are described in the next section, including the traffic signal optimization, and the vehicle speed controller. The proposed two-layer controller is then tested in an isolated signalized intersection. This is followed by implementing the proposed controller into a simulated arterial network in the city of Blacksburg, VA to test the network-level of performance under different traffic demands. The last section provides conclusions and recommendations for future research.

INTEGRATED CONTROL STRATEGIES

The proposed integrated controller includes two layers of optimizations for traffic signals and individual vehicles. 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 trajectory 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.

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 the optimum cycle length formulation that approximates the necessary signal timings to minimize vehicle delay [16], as seen in Equation (1). This formulation has been used in traffic analysis for years and is still one of the prevailing methodologies to determine the optimal cycle length for traffic signals.

$$C_{opt} = \frac{1.5L + 5}{1 - Y} \qquad (1)$$

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 aim at minimizing energy consumption and emissions. For instance, the study in [17] 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 emission at isolated intersections and found that the goal of decreasing delays at intersections and reducing emissions is not simply equivalent [18]. Delays at intersections will increase if the number of vehicle stops reduces, which will help to decrease the pollution at intersections. In addition, the study in [19] considers fuel-based signal optimization based on a model composed of a description of the fuel consumption and defines stochastic effects of vehicle movements that consume excess fuel. The proposed model was compared with the results using Webster's model as well as TRANSYT 7F and Synchro, the results showed the proposed model works best among all the methods by reducing fuel consumption up to 40%.

A recent study in [16] 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 been demonstrated to outperform Webster's equation to further reduce traffic delay, especially during higher traffic demand volumes. Given that optimizing traffic signal to meet traffic delay doesn't mean the fuel consumption is also minimized. Another new formulation in Equation (3) is obtained by optimizing the signal cycle length to minimize vehicle fuel consumption levels. Given the optimal cycle length, the signal timings can be computed by considering the green time yields the critical lane traffic ratio [20]. In this way, 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.

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

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

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 [9-12] to compute real-time fuel/energy-optimized speed profile to assist vehicles traversing signalized intersections. The control region was defined as 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 speed profiles of vehicles 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. [2]. 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 mode, collision avoidance constraint, 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 $v_2(t)$ is constrained by the steady-state vehicle spacing in the simulation software.
- The speed limit of $v_3(t)$ to avoid a rear-end vehicle collision.
- The maximum speed $v_4(t)$ allowed on the road.

Within the control region, the vehicle's behavior can be categorized into one of two cases: (1) the vehicle can pass through the signalized intersection without decelerating or (2) the vehicle must decelerate to pass 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 doesn't require the vehicle to decelerate to pass the signalized intersection. In this case, the cruise speed for the vehicle to approach the intersection during the red indication can be calculated by Equation (4) to maximize the average vehicle speed during the control region. When the vehicle enters the control region, it should adjust speed to u_c by following the vehicle dynamics model developed in [21]. After the traffic light turns from red to

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green, the vehicle accelerates from the speed u_c to the maximum allowed speed (speed limit u_f) by following the vehicle dynamics model until it leaves the control region.

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

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.

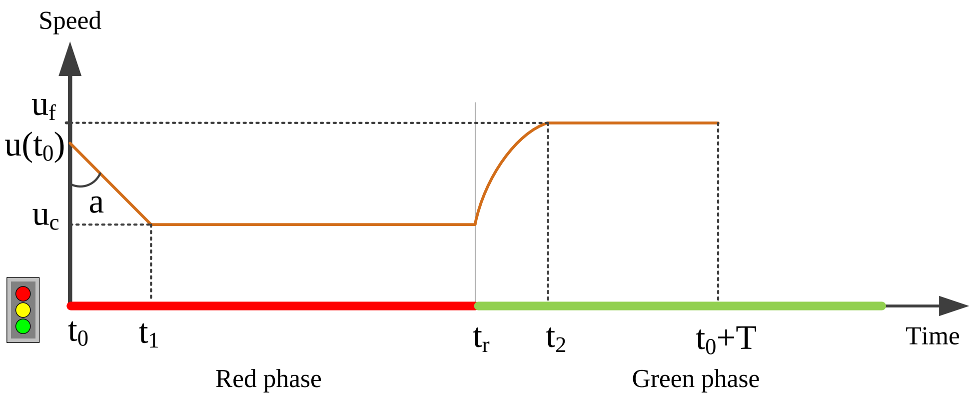

Figure 1: Vehicle optimum speed profile.

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

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

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:

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

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

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 [2]. 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 [2, 22].

The Virginia Tech Comprehensive Power-based Fuel Consumption Model (VT-CPFM) type 1 is selected in this study to estimate the instantaneous fuel consumption rate for ICEV [23]. The VT-CPFM utilizes instantaneous power as an input variable and can be easily calibrated using publicly available fuel economy data (e.g., Environmental Protection Agency [EPA]-published city and highway gas mileage). Thus, the calibration of model parameters does not require gathering any vehicle-specific field data. The VT-CPFM is formulated as below.

$$FC_{ICEV}(t)=\begin{cases}\alpha_0+\alpha_1P(t)+\alpha_2P(t)^2 & \forall\, P(t)\ge 0\\ \alpha_0 & \forall\, P(t)<0\end{cases} \quad (8)$$

$$P(t)=\left(ma(t)+\,mg\cdot\frac{C_r}{1000}(c_1u(t)+c_2)+\frac{1}{2}\rho_{Air}A_fC_Du^2(t)+mg\,\theta\right)u(t) \quad (9)$$

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 [24]; $P(t)$ 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 [25-27].

CASE STUDY

In order to test the performance of the proposed control strategies, we implement the controllers into 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

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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 [28, 29].

Test the Proposed Integrated Controller on an Isolated Intersection

This test considers the simplest case of a single-lane signalized intersection to validate the performance of using the proposed controller. Figure 2 shows the setup of the intersection, 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.

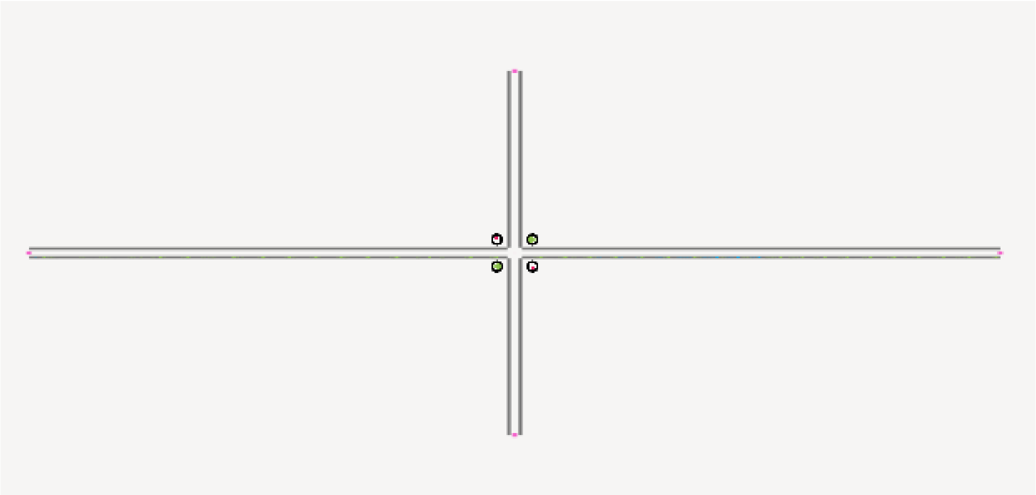

Figure 2: Test on an isolated signalized intersection.

- Scenario 1 (S1): Base
  This is the base scenario without signal optimization and vehicle speed control.

- 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.

The test results of five scenarios under various traffic demands are summarized in Table 1. For uncongested traffic conditions, both modified signal optimization methods in S3 and S4 outperform Webster's method in S2 by producing more fuel savings. But the total delay in S4 is higher than S1~S3, which matches with the findings in previous studies 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 7.91% compared to the base scenario without any controller. However, it also produces an increased total delay of 3.55% compared to S1. Similar trends can be found in the medium and congested traffic conditions. For the medium traffic demand, the fuel consumption keeps reducing from S1 to S5. The integrated controller produces the most fuel savings of 7.12%, but the corresponding total delay is increased by 1.03% compared to S1. For congested traffic conditions, the integrated controller in S5 saves 6.52% fuel consumption, but it also greatly increases the traffic delay by 10.02% compared to S1. Overall, the test results demonstrate the proposed integrated controller can effectively reduce fuel consumption when vehicles transverse isolated signalized intersections.

Table 1: Test results on isolated signalized intersection.

Uncongested (v/c=0.1)

Scenarios	FC (liter)	FC reduction	Delay (sec)	Delay reduction
S1	0.1012		11.4026	
S2	0.0979	-3.26%	10.8538	-4.81%
S3	0.0972	-3.95%	10.7853	-5.41%
S4	0.0955	-5.63%	11.524	1.06%
S5	0.0932	-7.91%	11.8076	3.55%

Medium (v/c=0.5)

Scenarios	FC (liter)	FC reduction	Delay (sec)	Delay reduction
S1	0.1054		12.8154	
S2	0.1021	-3.13%	12.3806	-3.39%
S3	0.1019	-3.32%	12.21379	-4.69%
S4	0.0998	-5.31%	12.319	-3.87%
S5	0.0979	-7.12%	12.9469	1.03%

Congested (v/c=1)

Scenarios	FC (liter)	FC reduction	Delay (sec)	Delay reduction
S1	0.1089		32.7019	
S2	0.1056	-3.03%	32.4825	-0.67%

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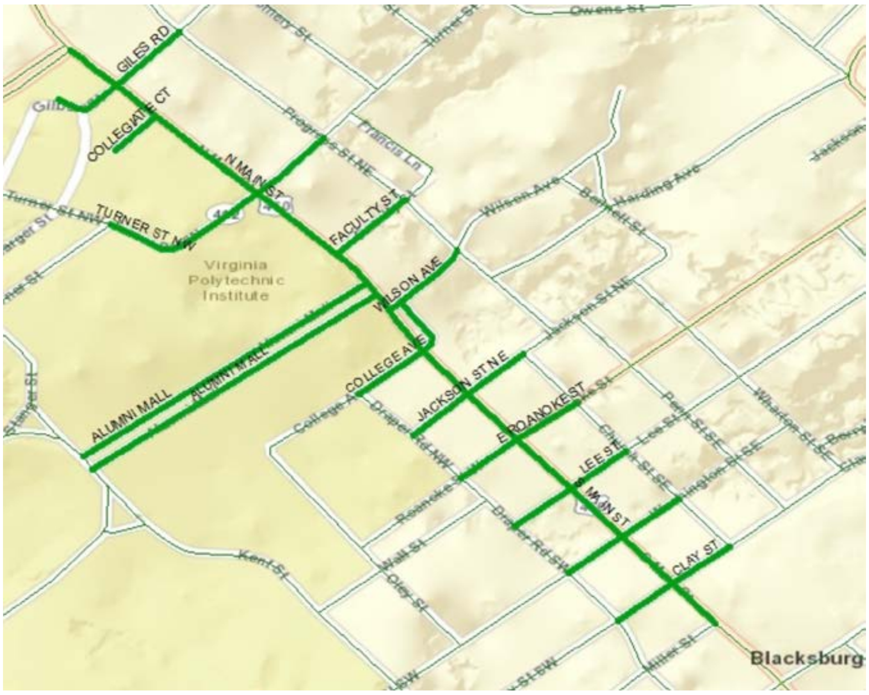
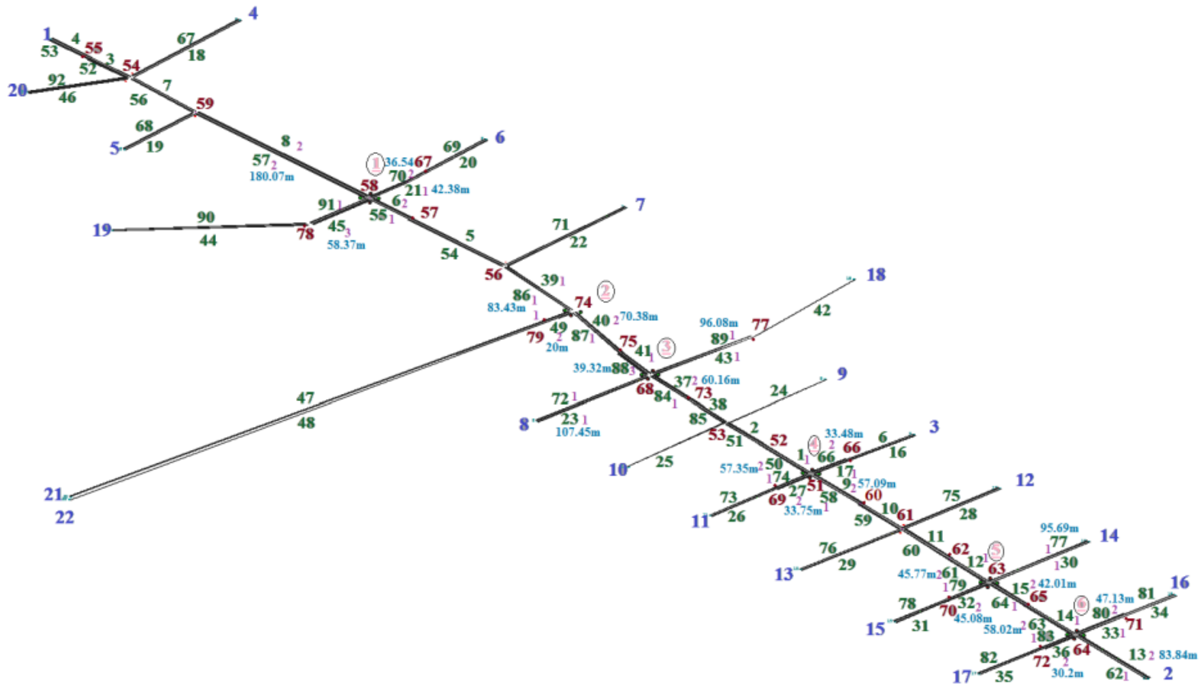
S3	0.1052	-3.40%	31.9564	-2.28%
S4	0.1032	-5.23%	32.2797	-1.29%
S5	0.1018	-6.52%	35.9777	10.02%

Test the Proposed Integrated Controller on an Arterial Traffic Network

The proposed integrated controller is further tested on an arterial network located in the heart of downtown Blacksburg, as shown in Figure 3. The O-D demand matrices were generated using QueesOD software [30] and were based on traffic counts collected during the afternoon peak period (4 ~ 6 pm), at 15 minutes intervals, for the year 2012 [31]. 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. The 100% demand represents the O-D demand matrices calibrated by the field data during afternoon peak hours. Then we also consider the 25% and 50% demand to investigate the performances of different controllers.



(a)



(b)

Figure 3: The Arterial Roadways in the city of Blacksburg, VA; (a) Google Images; (b) the simulated traffic network in the INTEGRATION software.

Table 2: Test results on arterial network.

25% Demond

Scenarios	FC (liter)	FC reduction	Delay (sec)	Delay reduction	Stops	Stops reduction
S1	0.0751		33.4		1.49	
S2	0.0688	-8.39%	22.7	-32.04%	2.08	39.60%
S3	0.0692	-7.86%	21.3	-36.23%	2.01	34.90%
S4	0.0675	-10.12%	23.2	-30.54%	2	34.23%
S5	0.0646	-13.98%	22.9	-31.44%	1.13	-24.16%

50% Demond

Scenarios	FC (liter)	FC reduction	Delay (sec)	Delay reduction	Stops	Stops reduction
S1	0.0757		34.6		1.53	
S2	0.0675	-10.83%	20.9	-39.60%	1.97	28.76%
S3	0.0681	-10.04%	20.1	-41.91%	1.94	26.80%
S4	0.0664	-12.29%	21.6	-37.57%	1.92	25.49%
S5	0.0643	-15.06%	20.9	-39.60%	1.15	-24.84%

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100% Demond

Scenarios	FC (liter)	FC reduction	Delay (sec)	Delay reduction	Stops	Stops reduction
S1	0.0791		39		1.61	
S2	0.0671	-15.17%	19.4	-50.26%	1.86	15.53%
S3	0.0679	-14.16%	18.5	-52.56%	1.84	14.29%
S4	0.0668	-15.55%	20.9	-46.41%	1.82	13.04%
S5	0.0651	-17.70%	20.6	-47.18%	1.24	-22.98%

In this test, the same five different scenarios as described in the isolated intersection test are also considered. The test results of five scenarios under three traffic demand levels are summarized in Table 2. For 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 most delay reduction of 36.23%. The fuel-optimized method in S4 outperforms Webster's method in S2 and the delay optimized method in S3 by producing the most fuel saving of 10.12%. These findings are consistent with the test results in [16] and prove that Webster's method represented in Equation (1) indeed is improved by the modified methods in Equations (2) and (3). However, the scenarios of S2, S3 and S4 result in more than 34% increase in vehicle stops on the arterial network. Among all the five scenarios, the integrated controller in S5 can greatly reduce vehicle stops by 24.16% compared to S1. And the S5 also produces the most fuel saving of 13.98% among all five scenarios. The test results under 25% demand indicate the integrated controller can greatly enhance traffic mobility by 31.44% reduction of totally delay and 24.16% reduction of vehicle stops, at the same time improving the energy efficiency with 13.98% of fuel saving. Similar trends can be observed under 50% and 100% demand. In both cases, the integrated controller produces the most savings in fuel and vehicle stops, at the same time it also produces a large amount of savings of traffic delay. Overall, the test results on the arterial network indicate that the proposed controller can greatly improve energy efficiency with 17.7% of fuel saving, at the same time enhancing the traffic mobility by up to 47.18% reduction in totally delay and 24.84% reduction in vehicle stops.

CONCLUSIONS AND FUTURE WORK

Recent studies show that optimizing both vehicle speed and signal timing is a promising method to improve the transportation system efficiency and fuel economy on arterial roads. However, the developed methods are generally very complicated with high computational costs. On the other hand, existing studies validated the developed methods either in numerical tests or simplified simulation tests with only one intersection. 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. To solve those issues, this paper develops a two-layer optimization approach that provides energy-optimal control for vehicles and traffic signal controllers. 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

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controller which calculates the optimal vehicle brake and throttle levels to minimize the energy consumption of individual vehicles. The A-star dynamic programming is used to solve the formulated optimization problem in the second layer to expedite the computation speed so that the optimal vehicle trajectories can be computed in real-time and can be easily implemented into simulation software for testing. The proposed integrated controller is first tested in an isolated signalized intersection, and then an arterial network with multiple intersections is used to investigate the performance of the proposed controller under various traffic demands. The test results demonstrate that the proposed integrated controller can greatly improve energy efficiency with up to 17.7% of fuel saving, at the same time enhancing the traffic mobility by up to 47.18% reduction in totally delay and 24.84% reduction of vehicle stops. 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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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Hao Chen, Hesham Rakha; data collection: Hao Chen; analysis and interpretation of results: Hao Chen, Hesham Rakha; draft manuscript preparation: Hao Chen, Hesham Rakha. All authors reviewed the results and approved the final version of the manuscript.

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