Bi-Level Optimization for Eco-Traffic Signal System

Hojin Jung†, Saerona Choi*, Byungkyu Brian Park*, Haengju Lee†, Sang Hyuk Son†
* Department of Civil and Environmental Engineering, University of Virginia
† Department of Information and Communication Engineering, Daegu Gyeongbuk Institute of Science and Technology (DGIST)
Email: hojinwkd@dgist.ac.kr, {sc2gs, bpark}@virginia.edu, {haengjulee, son}@dgist.ac.kr

***Abstract*—The main objective of this paper is to develop an Eco-Traffic Signal System (Eco-TSS) that can improve fuel consumption and delays at an isolated intersection under Connected Vehicle environment. The proposed system consists of an eco-driving algorithm and a traffic signal optimization process to find an optimal solution minimizing fuel consumption and delays. We designed a bi-level optimization method for the Eco-TSS and evaluated the impact of the Eco-TSS within traffic simulation to compare it with existing traffic signal controls. As results, the system showed 5-10% fuel savings and 12% travel-time reduction over existing control method.**

Keywords—connected vehicle, eco-driving, traffic signal optimization

I. Introduction

Transportation has been vital to economic growth and quality of life. Traffic congestion, which resulted in significant waste in fuel consumption, negatively affected both economic growth and quality of life. According to a report on recent energy statistics, the transportation sector is responsible for 28% (25,295 trillion Btu) of U.S. energy consumption in 2015 [1]. In addition, frequent stop and go conditions, especially at traffic-signal-controlled intersections, have caused inefficient fuel consumptions. Transportation emissions are the result of the interaction of the following factors: vehicle technologies (i.e., fuel efficiency), fuel technologies (e.g., gas, biofuels, and hydrogen), travel activities (e.g., driven miles) and vehicle/system operations (e.g., eco-driving and traffic signal optimization) [2].

Eco-driving seeks to achieve eco-friendly, fuel-efficient, safe, economical and comfortable driving, and has been practiced in many countries with various schemes to reduce fuel consumption, greenhouse gas emissions, and transportation costs [3]. Eco-driving systems aim at implementing vehicles' optimal trajectories by minimizing emissions or fuel consumption using both the current signal timing plan (i.e., cycle length, green start time and green end time) and vehicles' information (e.g., speed, location, etc.) [4]–[9]. Moreover, eco-driving algorithms have been proposed to take advantage of available information from vehicle-sensing and communication technologies. Using real-time signal phase and timing (SPaT) information collected from vehicles and infrastructure communications, these algorithms attempt to allow vehicles to go through an arterial corridor, saving fuel usage by around 12 % [10], [11].

Moreover, from a network-wide point of view, effective traffic signal control strategies could mitigate vehicles' idling behind the stop-bar and unnecessary accelerations/decelerations by maintaining moderate vehicle speeds. Meanwhile, most existing studies on traffic signal optimization have focused on minimizing personal delays [12]–[14], vehicle delays, and transit travel-times [15]–[17] using optimal signal settings based on weighted functions of delays or priority rules for pedestrians with various traffic signal controls such as fixed-time traffic signal control, responsive traffic signal control, adaptive traffic signal control, and real-time adaptive traffic signal control [18]. Recently, in terms of environmental sustainability, several researchers proposed traffic signal control systems, which are referred to as sustainable signal control [19], [20] or eco-signal operations [21], to reduce emissions at intersections. It has been reported that the eco-signal operations could potentially reduce fuel by 8% for a coordinated corridor and 21.8% when considering Cooperative Adaptive Cruise Control (CACC) capabilities [21].

At a signalized intersection, eco-driving and eco-signal operations have a similar goal to enhance environmental sustainability. Thus, it could be combined for more efficient operations. However, there are several challenges to combine them: i) an optimal trajectory estimated by eco-driving algorithm could be interrupted by a traffic signal timing plan, and ii) a traffic signal timing plan would not be an optimal solution when eco-driving is considered. This study developed an optimization system for a signalized intersection using bi-level optimization with a genetic algorithm proposed by Oduguwa and Roy [22]. Bi-level optimization is intended to solve a problem that is embedded within another problem, and it consists of the outer optimization task and the inner optimization task.

The objectives of this paper are 1) to develop a bi-level optimization method for an eco-traffic signal system that integrates an eco-driving algorithm and an eco-signal operation, and 2) to analyze the effectiveness of the proposed method comparing it with existing traffic signal timing plans (e.g., fixed traffic signal and actuated traffic signal) within a simulation environment. Furthermore, this study developed a traffic simulator using MATLAB that can evaluate the performance of each signal timing plan considering various Measures of Effectiveness (MOE).

The remainder of this paper is organized as follows. A concept of an Eco-Traffic Signal System (Eco-TSS) is introduced in section 2. An experimental environment to test the system using the traffic simulator is presented in section 3. The effectiveness of the system is compared with existing signal timing plans in terms of safety, mobility and environmental

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sustainability in section 4, followed by the findings and future studies in section 5.

II. ECO-TRAFFIC SIGNAL SYSTEM

An Eco-Traffic Signal System (Eco-TSS) is a proactive control strategy for both individual vehicle and a signal timing plan at an intersection under the Connected Vehicle (CV) environment. Eco-TSS attempts to provide an optimal signal timing plan and vehicles' trajectories (i.e., eco-driving trajectories) before vehicles enter the control area (e.g., 300 meters from the stop-bar) using the current signal status and the vehicle's trajectory to minimize not only the delay at an intersection but also the fuel consumption of each individual vehicle.

Fig. 1 illustrates the concept of Eco-TSS. Connected vehicles' trajectories and the current signal timing plan are collected via communication between vehicles and infrastructure. Using the information, an initial delay and fuel consumption are calculated. Based on these initial measures, the optimization process of Eco-TSS is operated to search trajectories and the signal timing plan that have the minimum delay and fuel consumption. When the optimal trajectories and signal timing plan are selected, Eco-TSS sends the updated information to vehicles and traffic signal controller.

The objective of a signal optimization process is to minimize the total delay at an intersection. Total delay can be described as the difference in arrival time between when the impact of signal timing plan is considered and ignored. In this study, a traffic signal optimization process by a genetic algorithm was implemented. Once the optimization process is activated, the current signal timing plan is considered as an initial signal status. And the total delay is calculated at the first iteration based on the initial signal status. Then, the genetic algorithm performs iterations to search for an optimal signal timing plan that minimizes the total delay at the intersection. When the genetic algorithm finds an optimal signal timing plan, the optimization process returns the optimal signal timing plan to the signal heads. The reason why we considered the objective function of delay minimization for the signal optimization is due to the efficiency of the system. It is noted that the signal timing optimization considering fuel consumption minimization takes over 15 minutes for each iteration time as it requires optimization of each individual vehicular trajectory before adjusting the timing plan.

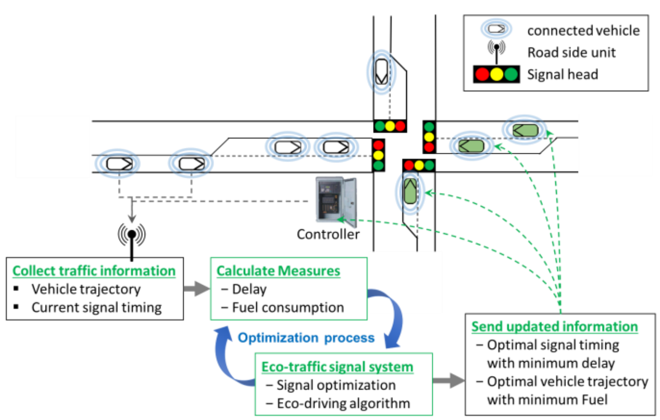


Fig. 1. A Concept of the Eco-Traffic Signal System

An existing eco-driving algorithm proposed by Barth et al. [10] was considered in this study. The reasons why this study used this eco-driving algorithm were i) consideration of vehicle dynamics model including acceleration maneuver, and ii) its fast computation time. The eco-driving algorithm's logic can be described by signal status. If the signal head has sufficient green time so that a vehicle can pass the stop-bar with current speed, then the algorithm maintains the current speed. If not, the algorithm calculates a required delay using vehicle information and optimum speed profile based on a fuel consumption model, and advises vehicle trajectories to maintain headway considering a car-following concept [10].

III. A BI-LEVEL OPTIMIZATION FOR ECO-TRAFFIC SIGNAL SYSTEM

A. A Bi-level Optimization

As noted, bi-level optimization is intended to solve a problem that is embedded within another problem and, it consists of the outer optimization task (i.e., upper-level optimization) and the inner optimization task (i.e., lower-level optimization). In the transportation field, a bi-level programming approach has been used for traffic management [23], [24] or network design [25], [26].

A bi-level optimization problem (BLOP) has two levels that have their own objective functions and constraints. And the optimal solution of the lower-level problem determines the feasible space of the upper-level optimization problem. This means that the objective function at the lower-level is optimized under given factors by the objective function at the upper-level to select the factors [27]. A general function of the BLOP can be formulated as follows [28]:

$$\min_{x\epsilon X, y\epsilon Y} F(x,y) \tag{1}$$

$$\text{subject to: } G(x,y) \leq 0;$$

$$y \in \arg\min_{z\epsilon y}\{f(x,z) : g(x,z) \leq 0\}$$

where F and f represent the upper-level and the lower-level objective functions, respectively. x and y represent, respectively, the upper-level decision vectors and the lower-level decision vectors. G and g represent inequality constraint functions at the upper and lower levels, respectively. Equality constraints may also be present in a bi-level program, but they have been omitted for brevity [28].

B. Problem Description

Eco-TSS controls traffic signals in real-time using vehicles' trajectories generated from the eco-driving algorithm. The objective function of the traffic signal control optimization (i.e., delay minimization) is highly correlated with the objective function of the eco-driving algorithm (i.e., fuel consumption minimization). This is because lower fuel efficiency is mainly caused by traffic congestion at an intersection.

Objective functions for the upper-level and lower-level optimizations can be defined as a reasonable signal timing plan to minimize the total delay and vehicles' trajectories to minimize total fuel consumption, respectively. As described in Eq. (2) and Eq. (2.1), the objective function of the upper-level is to find an optimal signal timing plan (ψ_i) among feasible signal timing plans with the number of n vehicles by minimizing delay when vehicles' arrival times at the stop-bar are p_i^v [28], [29]. p_i^v is calculated by vehicle v's current desired speed and acceleration, and it should be larger than vehicle $v-1$'s arrival time (p_i^{v-1}) as shown in Eq. (2.2). A range of green time is between g_{min} and g_{max} [30] as shown in Eq. (2.3). The maximum length of ψ_i is 20 seconds with 1 second of red clearance and 3 seconds of yellow time.

$$\min_{p_i^v \in X, \psi_i \in Y,} \sum_i \sum_v D(p_i^v, \psi_i) \quad (2)$$

Subject to:

$$\psi_i = \{(g, r, y)_1, \dots, (g, r, y)_n\}, 1 \le n \quad (2.1)$$

$$p_i^{v-1} \le p_i^v \le p_i^{v+1} \quad (2.2)$$

$$g_{min} \le g \le g_{max}, r = 1, y = 3 \quad (2.3)$$

Where

ψ_i is a traffic signal timing plan at iteration i;

p_i^v is the arrival time at the stop-bar of an individual vehicle v;

D is the total delay(second) for iteration i;

$g, r,$ and y are the status of the signal head: green, red and yellow time.

At the lower-level, the objective function is to select an optimal set of desired speeds (u_i^v) and accelerations (a_i^v) for vehicle v by minimizing fuel consumption (F) under the given traffic signal timing plan (ψ_i) as described in Eq. (3) [29], [31]. The desired speed (u_i^v) is selected between 0 to the speed limit (u_{max}, 15 m/s) as shown in Eq. (3.1), and the desired acceleration (a_i^v) is selected between a_{min} (-7.5 $\mathrm{m/s^2}$) and a_{max} (3.5 $\mathrm{m/s^2}$) [34] as shown in Eq. (3.2). Fuel consumption for the vehicle v with the set of u_i^v and a_i^v is calculated by VT-Micro model [33].

$$\min_{v_i^t \in V, a_i^t \in A, \psi_i \in \xi} \sum_i \sum_v F(u_i^v, a_i^v, \psi_i) \quad (3)$$

Subject to:

$$0 \le u_i^v \le v_{max} \quad (3.1)$$

$$a_{min} \le a_i^v \le a_{max} \quad (3.2)$$

where

u_i^v is the desired speed of vehicle v at iteration i;

a_i^v is the desired acceleration of vehicle v at iteration i;

F is fuel consumption;

ψ_i is the traffic signal timing plan that is selected in the upper-level.

C. The Optimization Process

The solution approach for the bi-level optimization problem in this study used two techniques: a genetic algorithm and an exhaustive search method at the lower-level and the upper-level, respectively. A genetic algorithm is a probabilistic algorithm that is used to generate useful solutions for optimization and search problems [28]. An exhaustive search method is a general problem-solving technique that compares the given problem's statement to each candidate in order to find the optimal solution among all possible candidates. A procedure to search the optimal solution consists of five steps as presented in Fig. 2.

(1) When the remaining green time (g_t) is zero, the Eco-TSS mode is activated.

(2) Considering current traffic signal timing plan, arrival times (p_i^v) of vehicles are collected at iteration i.

(3) The objective function of the upper-level finds a reasonable signal timing plan to minimize delay using p_i^v. Current signal timing plan (ψ_i) is updated to minimize delay by a genetic algorithm (GA) until the GA's stopping condition is satisfied. Considering length of current green split (start of green (sg^k) and end of green (eg^k)), total delay at iteration i (D_i) is calculated for all vehicles. Then, an optimal signal timing plan (ψ^*), which has the minimum delay (D_{min}), is selected

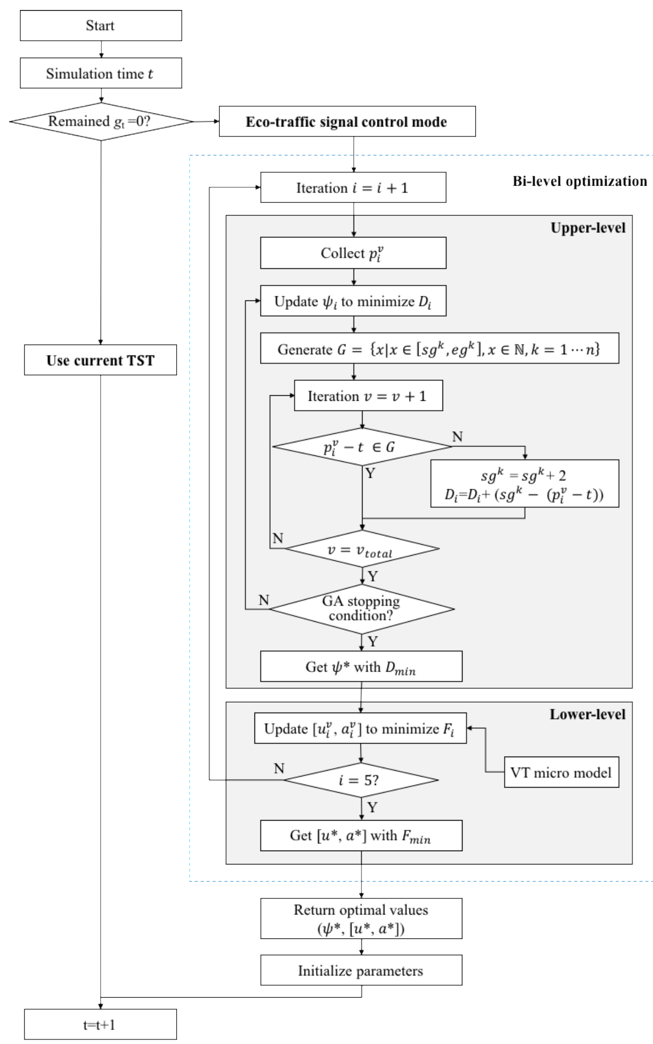


Fig. 2. The Bi-level optimization process

as next signal timing plan. A look-ahead period of the optimal traffic signal timing plan is 100 seconds, and this period has 5 phases because the length of single phase is 20 seconds.

(4) The objective function of the lower-level selects an optimal trajectories to achieve the minimum fuel consumption by an exhaustive search. Fuel consumption is calculated by the VT-micro model using the signal timing plan (ψ^*) and the arrival times (p_i^v) with the trajectories including desired speeds and accelerations ($[u_i^v, a_i^v]$).

(5) The bi-level optimization process is repeated until the number of iteration reaches 5. Among the results of 5 iterations, an optimal trajectory ($[u^*, a^*]$) with the lowest fuel consumption is selected. Then the algorithm returns a set of ψ^* and $[u^*, a^*]$ to traffic simulation. Once the optimal signal timing plan and the optimal trajectories are determined by this process, these factors are returned and initialized.

IV. EVAUATION ANALYSIS OF ECO-TRAFFIC SIGNAL SYSTEM

A. Analysis Scenarios

Several traffic signal controls including the pre-timed and actuated signal controls and traffic volume inputs were selected to compare performances according to traffic conditions and traffic signal control strategies. We considered the following four scenarios: i) pre-timed signal control, ii) actuated signal control, iii) pre-timed signal control and eco-driving mode, and iv) eco-driving mode and signal optimization (i.e., Eco-TSS). For each scenario, various traffic conditions with different volume inputs were considered as shown in Table I. A total of 120 scenarios was established. To obtain unbiased results, ten simulation repetitions with different random seeds were made for each scenario.

To evaluate the scenarios, several Measures of Effectiveness (MOE) were considered in terms of mobility (total travel-time (second) and total stop-time (second)) and environmental sustainability (fuel consumption (liter/second)). Total stop-time means sum of vehicles' idling time at the stop-bar.

TABLE I. VOLUME INPUTS FOR VARIOUS TRAFFIC CONDITIONS

Scenario	Volume (vph)		Volume difference	Total
	East-west	North-south		
1	200	200	0	400
2	100	300	200	
3	300	100		
4	300	400	100	700
5	400	300		
6	200	500	300	
7	500	200		
8	100	600	500	
9	600	100		
10	500	500	0	1000
11	400	600	200	
12	600	400		
13	300	700	400	
14	700	300		
15	200	800	600	
16	800	200		
17	100	900	800	
18	900	100		
19	600	700	100	1300
20	700	600		
21	500	800	300	
22	800	500		
23	400	900	500	
24	900	400		
25	300	1000	700	
26	1000	300		
27	200	1100	900	
28	1100	200		
29	100	1200	1100	
30	1200	100		

B. Experimental Environment

An experimental environment was developed to evaluate Eco-TSS. This study considered a hypothetical signalized intersection that has single through lane for all approaches. The speed limit was 54 km/h, and vehicle entrance points were located at 300 meters ahead of the stop-bar. Traffic signal timings and traffic volume inputs were applied according to analysis scenarios. And the following assumptions were included in the experimental environment to evaluate Eco-TSS:

- There are no impacts by adjacent intersections;
- Vehicles comply with the speed limit;
- All vehicles have an on-board unit (OBU);
- The road side unit (RSU) and OBUs communicate with one another without any latencies and packet drops;
- Basically, vehicles follow a car-following model to avoid rear-end conflict;
- 100% vehicles follow proposed trajectories (speeds and accelerations) by Eco-TSS.

We designed a traffic simulator using MATLAB for the experimental environment for efficient calculation to solve the optimization problem. The traffic simulator includes a traffic model and a fuel consumption model. The traffic model is based on a car-following concept. Generally, car-following models characterize the relationship between following vehicles and leading vehicles using speed or acceleration formulations (e.g., speed differences or vehicle spacing). The car-following model adopted in this study is known as a psycho-physical car-following model proposed by WIEDEMANN in 1974 [31].

For the fuel consumption model, we considered the Virginia Tech Microscopic energy and emissions model (VT-Micro model) that is a microscopic dynamic emissions model to estimate vehicle fuel consumption of an individual vehicle using second by second speeds and accelerations. The VT-Micro model is an emerging model that was developed using instantaneous speed and acceleration levels as independent variables [33]. In this study, fuel consumption was calculated by the VT-micro model using vehicle trajectories collected within the intersection. The model can be formulated as following equation [33].

$$E_x(t) = \exp(\tilde{v}^{\mathrm{T}}(t) \mathrm{P}_x \tilde{a}(t)), \qquad (4)$$

where

E_x represents the estimation of variable $x \in$ {CO, fuel};

$\tilde{v}^T(t) = [1\ v(t)\ v(t)^2\ v(t)^3]^T$ where $v(t)$ represents the vehicle speed at time t;

$\tilde{a}(t) = [1\ a(t)\ a(t)^2\ a(t)^3]^T$ where $a(t)$ represents the acceleration at time t;

P_x is the model parameter matrix for the variable x [33].

V. RESULTS

A. Comparison by Traffic Signal Controls

Results of the evaluation for Eco-TSS over the existing traffic signal controls and the eco-driving algorithm by total volume scenarios are shown in Table II. We investigated four types of MOEs (travel-time, stop-time, fuel consumption and time-to-collision) for each traffic signal control.

Generally, the MOEs were deteriorated as the number of total volume increased. In case of the actuated control with a low total volume case (400 vph), travel-time (TT), stop-time (ST) and fuel consumption (FC) increased when compared with the pre-timed case by 1.55%, 6.78%, and 0.26%, respectively. When the eco-driving was considered, TT, ST and FC were reduced by 0.87%, 47.85% and 2.01%, respectively. Moreover, with Eco-TSS, MOEs were dropped by 14.19%, 79.19% and 10.03% for travel-time, ST and FC, respectively. In case of other total volumes, all traffic signal controls were improved when compared with the base case in terms of TT, ST and FC.

Focused on the performance of Eco-TSS, it worked better at the lower volume cases than at the higher volume cases. In addition, it outperformed other traffic controls and the eco-driving algorithm in general. When Eco-TSS and eco-driving are compared, the results of Eco-TSS showed better performances than the results of eco-driving only. Therefore, we found that the optimization process of traffic timing plans should be considered to improve eco-driving algorithm's performance.

TABLE II. EVALUATION RESULTS

MOEs	Traffic signal control	Total volume (vph)			
		Pre-timed	Actuated	Eco-driving	Eco-TSS
Travel-time (second)	400 (low)	4,122	4,186	4,087	3,537
	700 (medium)	7,520	7,407	7,278	6,533
	1000 (high)	11,315	11,268	10,972	9,901
	1300 (very high)	17,027	16,248	16,385	15,566
Stop-time (second)	400 (low)	510	544	266	106
	700 (medium)	1,262	1,066	652	388
	1000 (high)	2,431	2,055	1,541	878
	1300 (very high)	5,397	3,938	4,037	3,608
Fuel consumption (liter/second)	400 (low)	5.833	5.848	5.715	5.248
	700 (medium)	10.307	10.331	10.036	9.425
	1000 (high)	14.984	15.309	14.638	13.96
	1300 (very high)	20.671	21.037	20.157	19.654

B. Impacts of Volume Difference between Approaches

To analysis impacts of volume differences between east-west and north-south, the MOEs were investigated by traffic signal controls in terms of fuel and delay savings as shown in Table III and Table IV, respectively.

Table III presents the results of fuel savings by volume differences and traffic signal controls. At lower volume cases, the pre-timed and actuated controls showed similar fuel consumptions. But at high volume cases, the actuated control showed higher fuel consumption than the pre-timed control. In addition, the percentage difference of fuel consumption (%) between the pre-timed and the actuated increased as the volume difference increased. In the traffic condition with big volume difference, the major approach is likely to have stop-and-go condition and vehicles could accelerate or decelerate frequently. On the other hand, vehicles on the minor approach might have to wait longer than the major approach due to shorter green split. This is because effective green time for each approach is determined considering volume inputs. Those two cases can cause higher fuel consumption at the same total volume. However, it can be adjusted by using eco-driving because eco-driving outperformed for all volume differences.

In addition, Eco-TSS outperformed all other traffic signal control cases in saving fuel for all volume cases even there were big volume differences. The results of the actuated signal control showed slightly lower performance than the pre-timed signal control at some of higher volume cases, however, it was not statistically significant different ($\alpha > 0.05$).

Table IV describes the results of delay savings by volume differences and traffic signal controls. Both eco-driving and Eco-TSS reduce delays significantly for all total volume cases and volume differences. However, Eco-TSS should be considered to maximize delay savings at an intersection. Hence, this result demonstrates that Eco-TSS could be effectively used as an optimization strategy by controlling both signal timings and vehicle movements to reduce delay and fuel consumption at an intersection. In case of the actuated signal control, it shows higher performance than the pre-timed in order to reduce delays because it is able to detect approaching vehicles and assign the appropriate green time to deal with the congestion.

To implement the proposed system in field, the system efficiency is important for traffic signal and vehicle control in real-time. We analyzed computation times of upper level in Eco-TSS to find an optimal traffic signal plan for next loop ahead time (i.e., 100 seconds) by an objective function of the genetic algorithm. When a high volume case (e.g., 1300 vph) was considered as shown in Fig. 3, the average computation times were calculated using the results of 10 iterations. When we considered the objective function of delay minimization for the upper level, the average computation time was only 2.72 seconds. Therefore, Eco-TSS could be effectively implemented as a real-time traffic control in the near future. In addition, we expect that Eco-TSS can be enhanced with an objective function of fuel minimization if it could be more efficient in terms of computation time because the average computation time was 1041 seconds.

TABLE III. FUEL SAVINGS BY VOLUME DIFFERENCES

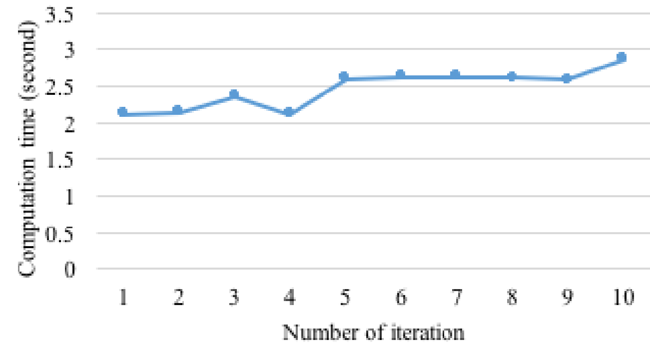
Total volume	Volume difference	Pre-timed	Actuated	Eco-driving	Eco-TSS
400	0	5.9	5.9 (-0.6%)	5.8 (-2.2%)	5.3 (-11.1%)
400	200	5.8	5.8 (0.7%)	5.7 (-1.9%)	5.2 (-9.5%)
700	100	10.5	10.6 (0.7%)	10.3 (-2.5%)	9.6 (-8.9%)
700	300	10.4	10.4 (0.6%)	10.1 (-2.4%)	9.5 (-8.7%)
700	500	10.0	10 (-0.6%)	9.7 (-3.0%)	9.2 (-8.1%)
1000	0	15.6	15.6 (0.4%)	15.2 (-2.2%)	14.3 (-8%)
1000	200	15.5	15.6 (1.0%)	15.1 (-2.3%)	14.2 (-8.1%)
1000	400	15.1	15.5 (2.5%)	14.8 (-2.3%)	14 (-7.2%)
1000	600	14.7	14.9 (1.7%)	14.2 (-3.0%)	13.6 (-7.6%)
1000	800	14.4	15 (4.5%)	14.1 (-1.7%)	13.9 (-3.7%)
1300	100	21.4	21.1 (-1.3%)	20.9 (-2.3%)	19.9 (-7.1%)
1300	300	21.1	20.9 (-0.8%)	20.6 (-2.3%)	19.9 (-5.8%)
1300	500	21.4	21.4 (0.2%)	20.9 (-2.3%)	20.4 (-4.8%)
1300	700	20.8	21.3 (2.4%)	20.3 (-2.5%)	20.1 (-3.4%)
1300	900	20.0	20.9 (4.4%)	19.5 (-2.9%)	19.1 (-4.5%)
1300	1100	19.3	20.5 (6.4%)	18.8 (-2.7%)	18.5 (-3.8%)

TABLE IV. DELAY SAVINGS BY VOLUME DIFFERENCES

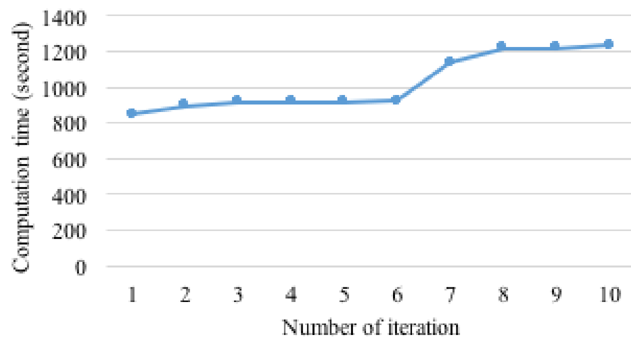
Total volume	Volume difference	Pre-timed	Actuated	Eco-driving	Eco-TSS
400	0	576.7	574.6 (-0.4%)	271.2 (-53%)	125.5 (-78.2%)
400	200	476.1	528.9 (11.1%)	263.1 (-44.7%)	96.4 (-79.8%)
700	100	1345.7	1236.2 (-8.1%)	685.8 (-49%)	452.8 (-66.4%)
700	300	1241.2	1122.6 (-9.6%)	674.7 (-45.6%)	414.5 (-66.6%)
700	500	1198.2	838.5 (-30%)	595.6 (-50.3%)	298.1 (-75.1%)
1000	0	2978.4	2497 (-16.2%)	1919.3 (-35.6%)	1176.3 (-60.5%)
1000	200	2904.2	2461.5 (-15.2%)	1861.2 (-35.9%)	1078.9 (-62.9%)
1000	400	2629.2	2240.8 (-14.8%)	1642.5 (-37.5%)	979.9 (-62.7%)
1000	600	2417.8	1788.8 (-26%)	1386.5 (-42.7%)	729.3 (-69.8%)
1000	800	1500.1	1505.7 (0.4%)	1085.7 (-27.6%)	574.7 (-61.7%)
1300	100	6663.0	4762.2 (-28.5%)	5224.6 (-21.6%)	3556.9 (-46.6%)
1300	300	6366.6	4608.7 (-27.6%)	4941 (-22.4%)	3996.6 (-37.2%)
1300	500	6010.6	4422.3 (-26.4%)	4526.9 (-24.7%)	4502.4 (-25.1%)
1300	700	5198.6	3970 (-23.6%)	3765.1 (-27.6%)	4701.5 (-9.6%)
1300	900	4423.8	3200.4 (-27.7%)	3034.2 (-31.4%)	2991.5 (-32.4%)
1300	1100	3722.2	2664.1 (-28.4%)	2727.9 (-26.7%)	1898.6 (-49%)

VI. CONCLUSIONS AND FURTHER RESEARCH

To enhance environmental sustainability, this research developed a bi-level optimization method for an eco-traffic signal system. A hypothetical intersection was simulated considering existing traffic signal timing plans and various traffic conditions within a microscopic traffic simulation using MATLAB. The proposed Eco-Traffic Signal System (Eco-TSS) consists of an eco-driving algorithm and a traffic signal optimization process to determine an optimal solution by reducing fuel consumption and delays. To evaluate Eco-TSS, this study compared the performance of the Eco-TSS to other traffic signal controls using various Measures of Effectiveness.



(a) Objective function: delay minimization



(b) Objective function: fuel minimization

Fig. 3. Computation times by an objective function of the genetic algotirhm with high volume (1300vph)

As results, Eco-TSS improved the mobility and environmental sustainability in comparison with existing traffic signal controls including pre-timed and actuated controls. Also we found that the performance of an eco-driving algorithm can be further enhanced when it adjusts vehicles' trajectories considering optimal traffic signal timings. In addition, this study evaluated Eco-TSS in terms of fuel and delay savings considering volume differences between directions of an intersection. The fuel savings of the actuated traffic control were deteriorated when high volume differences were considered, however, Eco-TSS showed environmental benefits for all volume scenarios. Hence, we strongly believe that Eco-TSS could be effectively used as an optimization strategy by controlling both traffic signal timings and vehicle movements to reduce delay and fuel consumption at an intersection.

In the future, this research can be improved and extended from the following aspects. Given this study used a simple network within a traffic simulation using MATLAB for efficiency, more general networks with multi-lanes and various traffic conditions need to be considered. In addition, this study used a delay optimization concept for the upper level and a simple eco-driving algorithm for the lower level to ensure computational efficiency. An advanced eco-driving algorithm or signal optimization method directly minimizing fuel consumption can be used to enhance the performance of Eco-TSS. Also, real-time traffic signal control algorithms under the Connected Vehicle environment can be used as a traffic signal operation strategy for Eco-TSS to enhance the performance. The findings of this study are expected to be of great use in trying to implement the eco-driving concept considering effective traffic signal operations to improve network performances and environmental sustainability.

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