Development of an optimal signal control method for the next-generation traffic at intersections

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***Abstract*— The next-generation traffic environment, which will contain automated vehicles and cloud-based infrastructures linked with individual vehicles using a high-speed communication network, is expected to provide real-time information to a traffic management system. This paper addresses such a next-generation traffic network and proposes an adaptive traffic signal control scheme at the intersection. The objective of the scheme is to reduce the waiting time of vehicles at the intersection by controlling the traffic signal timings. Particularly, the scheme in a model predictive control framework uses the information of all approaching vehicles and generates the optimal traffic signal for the intersection that minimizes the total traffic delay. For this purpose, a novel traffic flow model is developed that estimates the intersection crossing time of a vehicle for any given signal pattern. The model is found to be very accurate in predicting the vehicle's waiting time and facilitates in obtaining very fast optimization results. The optimal cycle and signal duration are used to control the traffic using a traffic simulator, and the performance of the proposed scheme is evaluated by observing 10 speed, density, idling time, and fuel consumption of all vehicles around the intersection. The results are compared with the existing traffic signal system.**

I. Introduction

We are having various problems in the road transportation network mostly due to traditionally driven vehicular traffic. For example, traffic congestion, environmental problems due to exhaust gases, and extra fuel consumption. The amount of fuel wasted in traffic in the United States costs $930 in 2014 [1]. Traffic congestion of a total of about 125 km is generated every weekday in Tokyo [2]. Traffic congestion increases fuel consumption, exhaust emissions, and travel time of vehicles significantly. Traffic congestion obviously occurs when the traffic volume exceeds the capacity of a road network. In particular, the signalized intersections and merging points are the common sources of traffic congestion, where traffic congestion may also occur at lower traffic volume than the intersection capacity due to injudicious regulation of the traffic lights [3]. However, most of the existing traffic signals at intersections are based on fixed rules and they are only tuned at an interval of a few hours according to the recent traffic flow data.

Research on traffic control at intersections is not new. The existing traffic signal control can be classified into three major categories (i) fixed timing, (ii) actuated, and (iii) adaptive. Due to involvement of costly vehicle detection method, most existing traffic signal control methods use historical traffic data and fix the time of signals. Using loop detectors, actuated coordinated traffic control methods tune the signal timing at every cycle depending on the detected arrival pattern of vehicles [4]. Both the actuated and fixed timing methods cannot determine the optimal signal timings that is suitable to the instantaneous traffic conditions. In these methods, some vehicles have to wait unnecessary long period at red signals although the green signals in the other side of the intersection remain unused.

In the recent works, various adaptive traffic signal control methods have been developed for real-time traffic signal control [5], [6], [7]. In some work, queue spill back traffic congestion is controlled by suitable control of the signal times considering both upstream and downstream traffic [6]. Using information from the connected vehicles, a traffic signal control algorithm was developed for a basic intersection consisting of two one-way streets with no turning focusing on minimizing vehicle delay and stops at the intersection [7]. An algorithm was proposed to optimize the phase sequence and duration of traffic signal by solving a two-level optimization framework with the objectives of minimization of both the total vehicle delay and queue length [8]. Machine learning and artificial intelligence techniques, e.g., [9], [10], are based on past data and they cannot optimize the signal by predicting the dynamic nature of traffic online, and hence, their uses are limited in theoretical or simulation studies. Despite promising results, these methods cannot be used to tune traffic signal timings optimally considering the arrival patterns of the individual connected vehicles.

In the next-generation traffic, using advanced communication known as connected vehicle technology, vehicles will be able to communicate with each other and with the infrastructures. It was suggested that connected vehicles may improve the mobility, safety and environmental performance as stated by. In such a traffic environment, information of vehicles such as the position, speed, acceleration can be obtained precisely in real-time. Such information can be utilized to predict the vehicles arrival at intersection and determine the optimal signal timings. It desired a new type of adaptive control of traffic signal that can address the state of each connected and automated vehicles in the next generation traffic and enable them to cross the intersection with minimum overall traffic delay.

For implementing any adaptive traffic signal regulation, it is necessary to estimate and predict the traffic arrival patterns at the intersections using some suitable traffic flow model. There are various microscopic and macroscopic traffic flow models. A microscopic car following models (e.g.,

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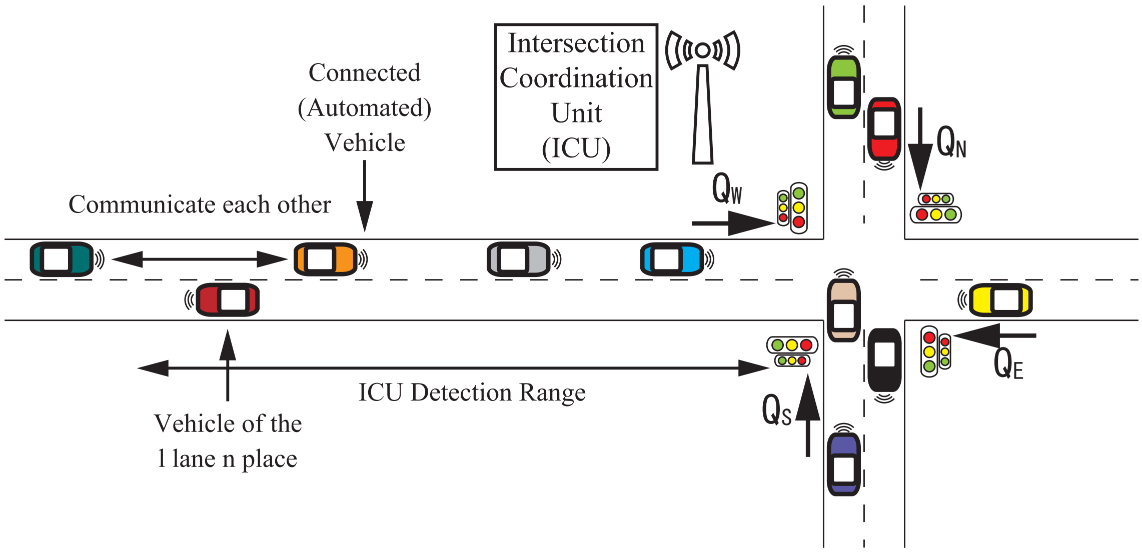


Fig. 1: A signalized intersection with intersection coordination unit (ICU) that receives information from the connected vehicles and decides the optimal traffic signals.

Intelligent Driver Model (IDM) [11], Gipps model [12], Optimal Vehicle Model (OVM) [13]) describes the behavior of each car how it changes speed, gap and acceleration or trajectories in the traffic. Using this kind of model, the position and speed of a car can be predicted easily. However, it is difficult to calculate the behavior of thousands of cars in a network using such a model for adjusting the traffic signals. Macroscopic traffic flow models (e.g., Cellular Automata, Cell transmission model (CTM) [14]) describes the overall traffic volumes, speed and density instead of considering each car, similar to the flow of fluids such as water. Although this type of model is simple in estimating traffic in a large network, they cannot be used to tune traffic signal timings considering the individual cars. Hence, both kinds of models are not suitable for developing a optimization method of traffic signals, and the necessity of a new model is emerged that can consider each vehicle without the need of calculating their trajectories and estimate the approximate arrival time at the intersection.

In this paper, we develop a new type of traffic flow model for connected vehicles that can predict the intersection crossing behavior of each car for optimizing the traffic signal more efficiently. The proposed model uses the position and speed of each vehicle, and considering the given future traffic signal timings, it estimates the approximate crossing time of a car. This model is used to calculate total traffic delay for any traffic signal patterns, and the optimal signal patterns are decided that provide the least waiting time of all the cars at the intersections. More specifically, an optimization problem is formulated with the objective of reducing the total delay of all vehicles by choosing optimal traffic signal timings. Using the proposed model, a convex cost function is developed and the problem is solved in real-time using the state of all vehicles approaching the intersection. Finally, signal optimization is implemented to control the traffic at an intersection, and the performance of the proposed system is compared. Using a traffic simulator, it is found that the model provides highly accurate prediction, and with the proposed signal control method, the performance of vehicles greatly improved.

II. Problem Formulation

It is thought that the car will run in the future while communicating with each other (V2V). By this communication, we can decide the appropriate speed and realize the flow of the smooth cars. This leads to a traffic jam decreasing. And, it makes improving the capacity of the general road and highway [15]. Also, it is thought that the infrastructure communicates with a vehicle (V2I) in the future. Then we can decide the timing that the signal is switching more efficiently. It makes to reduces time stopping at intersections. This leads to reducing the waiting time at the intersection. When V2V and V2I were realized, it is expected that a car ceases to stop with a signal and that a car runs at a faster speed [16]. Furthermore, decreasing the speed change of vehicles may hold a smaller amount of fuel consumption and exhaust gas of vehicles. Besides, I can expect that emergency vehicles such as an ambulance or the fire engine can arrive at the destination faster by regulating the timing of the signal.

Consider traffic in a general crossroads intersection with a single lane on each road shown in 1. We consider Japanese context where vehicles flow in the left side of the roads. The vehicles all are connected and the frequently broadcast their position (GPS), speed and other information and the other vehicles within the communication range receive such information. An intersection coordination unit (ICU) also receives such information and broadcast the traffic signal timings for the next cycles to the vehicles. The main task of the ICU is to collect information of all approaching vehicles and calculate the best traffic signal timing to regulate the traffic lights.

The vehicle movements in the intersection can be divided under four signal phases [17], as shown in 1. It allows straight and left turning traffic in the same phase, and turning right in another phase. Traffic coming from the East and West are taken in one group, and the traffic coming from the North and South are taken in another group. Let Q_{N}, Q_{S}, Q_{E} and Q_{W} be the traffic volumes going to the intersection from the north, south, east and west sections, respectively, and the total flow is given by $Q = [Q_{\mathrm{N}}, Q_{\mathrm{S}}, Q_{\mathrm{E}}, Q_{\mathrm{W}}]$.

1) Car Flow Model: The longitudinal motion of car n on any lane is given by the state equation in discrete time k of step size Δt

$$s_n(k+1) = As_n(k) + Bu_n(k), \tag{1}$$

where

$$A = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}, B = \begin{bmatrix} 0.5\Delta t^2 \\ \Delta t \end{bmatrix}, \tag{2}$$

and the state in terms of position and speed, and the input acceleration of the car n are given by $s_n(k) = [x_n(k), v_n(k)]^{\mathrm{T}} \in \mathbb{R}^2$ and $u_n(k) \in \mathbb{R}$, respectively. Acceleration $a_n(k)$ depends on the parameters of the host and the preceding cars and signal state of the nearby intersection. Acceleration can be calculated by cars using a car following model given by

$$a_n(k) = f_{\mathrm{cfm}}\left(v_n(k), \Delta v_n(k), \Delta x_n(k), v_n\right), \tag{3}$$

where f_{cfm} is a function represents intelligent driver model (IDM) in this study. The states v_n is the desired speed of the host car, $\Delta v_n(k)$ is the relative distance to the preceding car or the next intersection at x_J with red signal in the direction of running. The parameter $\Delta x_n(k)$ can be described as

$$\Delta x_n(k) = \begin{cases} x_J - x_n(k), & \text{if } x_J > x_{n-1} \text{ and} \\ & \text{signal is red,} \\ x_{n-1}(k) - x_n(k), & \text{otherwise,} \end{cases} \tag{4}$$

and the corresponding relative speed is defined as

$$\Delta v_n(k) = \begin{cases} v_n(k), & \text{if } x_J > x_{n-1} \text{ and} \\ & \text{signal is red,} \\ v_n(k) - v_{n-1}(k), & \text{otherwise.} \end{cases} \tag{5}$$

In this way, the IDM is used to decided the acceleration of the car with or without presence of a preceding car or intersections [18]. Particularly, the IDM used to represent f_{cfm} is defined as

$$f_{\mathrm{cfm}}(v_n, \Delta v_n, \Delta x_n, v_n) = \alpha\left(1 - \left(\frac{v_n}{v_0}\right)^4 - \left(\frac{S^*(v_n, \Delta v_n)}{S_n}\right)^2\right), \tag{6}$$

where the desired spacing $S^*(v_\alpha, \Delta v_\alpha)$ between the cars or from the intersection is given by

$$S^*(v_\alpha, \Delta v_\alpha) = S_0 + v_\alpha T + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}}, \tag{7}$$

and T,a,b,s_0 are the constant model parameters denote time gap, desired acceleration, and minimum spacing, respectively.

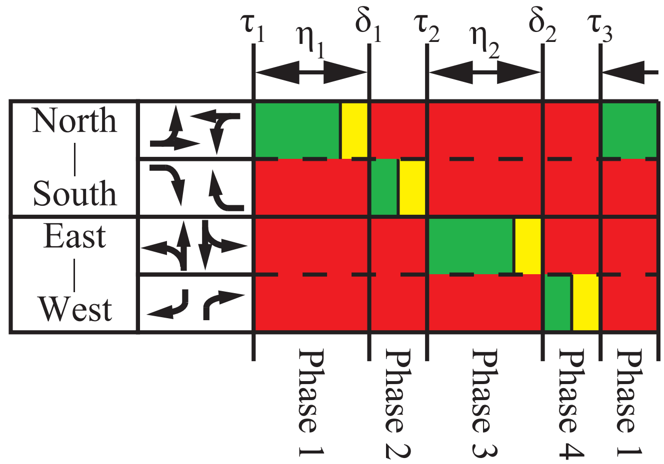


Fig. 2: Grouping of traffic movements under four signal phases and mathematical representation of signal duration η and their changing timings τ and δ.

2) Modeling Traffic Signals: We have developed a model that can estimate the expected crossing time of a car when the future traffic signal timing is given. The proposed model is the modified version of an earlier proposed model designed in [18]. Consider 4 signal phases with the sequence determined by $n = 1, 2, 3, 4$. Let a be the signal pattern and k be the phase changing counter or the step number in a few cycles of upcoming signals. The signal phases of K steps can be given by the vector $\delta = [\delta_1, \delta_2, \ldots, \delta_K]$, where each element can be given

$$\delta_j \in \{a_1, a_2, a_3, a_4\}, j = 1, 2, \ldots, K.$$

Phase δ_j is also interpreted as the green signals at the jth step in the horizon. Here $K \geq 4$ is a necessary condition to show more than one cycle. The length of signal phase of K steps can be given by the vector

$$\eta = [\eta_1, \eta_2, \ldots, \eta_K],$$

which is the decision variable in the signal control system in the ICU. Timings of switching traffic signals are determined based on both the vectors δ and η. As illustrated in Fig. 2, the timings of green light starting and ending are given by vectors $\tau = [\tau_1, \tau_2, \ldots, \tau_k]$ and $\theta = [\theta_1, \theta_2, \ldots, \theta_k]$, respectively. The green signal period of $\theta_1(k)$ at the current time starts at $\tau_1(k) = 0$ and ends at $\theta_1(k) = \eta_1(k)$. The starting and the ending times of the green signals in each phase, i.e., $\delta_2(k), \delta_3(k), \ldots, \delta_K(k)$, are obtained successively as

$$\tau_{j+1}(k) = \theta_j k + h_c, \qquad j = 1, \ldots, K-1, \tag{8}$$

where h_c is the clearance time, and

$$\theta_{j+1}(k) = \tau_{j+1}(k) + \eta_{j+1}(k). \tag{9}$$

A cyclic sequence of signal phase can simply be described as

$$\delta_{j+1}(k) = a_n \text{ s.t. } n = \begin{cases} m+1, & \text{if } \delta_j(k) = a_m \text{ and} \\ & m < 4, \\ 1, & \text{otherwise.} \end{cases} \tag{10}$$

This equation better represents the sequence of signal phases than the model in [18] as the proposed model does not require chronological phase number.

A. Optimization of Traffic Signal

Considering all cars approaching the intersection from the east, west, north and south lanes, it is necessary to determine the optimal signal duration η. Let $x_{l,n}(k)$ and $v_{l,n}(k)$ are the parameters representing the position and velocity, respectively, of the nth car on road section l at step k. Assume, $x_{l,n}$ is the distance to the center of the intersection. Once the information of all cars on all road sections are given at step k, the phase sequence $\delta(k)$ is determined as explained in the previous section. The goal considered in this study is to minimize the total waiting times of all cars. Specifically, the performance index of the signal control scheme is intended to obtain the optimal input vector $\eta^*(k)$ for the given phase sequence $\delta(k)$ by minimizing cost function

$$J(k) = \sum_{l=1}^{L} \sum_{n=1}^{N_l(k)} t_{w,l,n} \left(x_{l,n}(k), v_{l,n}(k), \eta(k) \right) \tag{11}$$

where $t_{w,l,n}$ is the estimated waiting time of the nth car on section l at step k at the intersection. A key part in this optimization is to estimate the waiting time $t_{w,l,n}$ of each car, which is obtained using the following proposed model as follow

$$\begin{aligned} & t_{w,l,n}\left(x_{l,n}, v_{l,n}, \eta\right) = \\ & \qquad t_{O,l,n}\left(x_{l,n}, v_{l,n}, \eta\right) - t_{R,l,n}\left(x_{l,n}, v_{l,n}, \eta\right), \end{aligned} \tag{12}$$

where $t_{R,l,n}$ and $t_{O,l,n}$ are the estimated times required to reach and pass the intersection by the car, which needs to be estimated based on their current position $x_{l,n}$, velocity $v_{l,n}$ and give future signal patterns δ and η as

$$t_{R,l,n}(k) = \max\left(\frac{x_n(k)}{v_c} + \varepsilon\left(v_c - v_n(k)\right), t_{R,l,n-1}(k) + h_f \right) \tag{13}$$

where $\varepsilon(v_c - v_n)$ is the start up delay time for the car when it is at nearly idling condition and v_c is the reference crossing speed. Let $\psi_{l,n}(k) \in \{a_1, a_2, a_3, a_4\}$ be the phase matching with the movement of the nth car on section l in the intersection. Depending on the phase of each traffic signal, the actual time that the car needs to pass the intersection can be obtained as

$$t_{O,l,n} = \begin{cases} t_{R,l,n} + h_f, & \text{if } \psi_{l,n} = \delta_i, \\ & \text{s.t. } \tau_i \le t_{R,l,n} \le \theta_i, \\ & i \le K, \\ \tau_j + h_f, & \text{if } \psi_{l,n} \ne \delta_i, \psi_{l,n} = \delta_j, \\ & \text{s.t. } \tau_i \le t_{R,l,n} \le \theta_i, \\ & i < j \le K, \\ \tau_K + \Delta(\delta_K, \psi_{l,n}), & \text{otherwise}, \end{cases} \tag{14}$$

where function $\Delta(\delta_K, \psi l, n)$ represent the interval of the next green signal considering an average cycle length.

Under the proposed traffic control, before the change of a signal phase, information of all vehicles are collected and the above problem is solved to obtain η^*, and the ICU switches the traffic light for a duration of η_1, and the whole process is repeated by extending the horizon again for the next K steps.

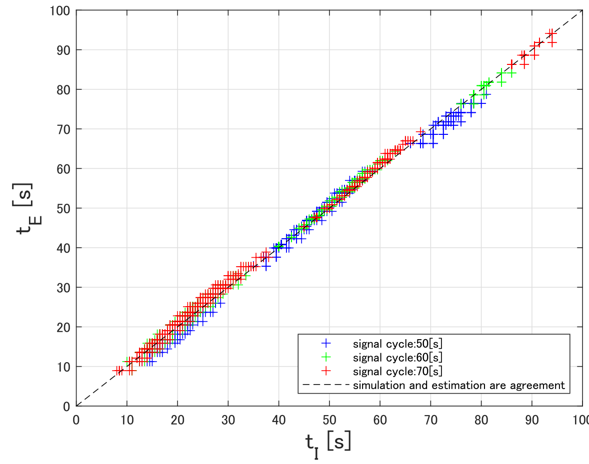


Fig. 3: Accuracy of the predicted crossing times of individual vehicles estimated by the developed model.

III. Simulation Results

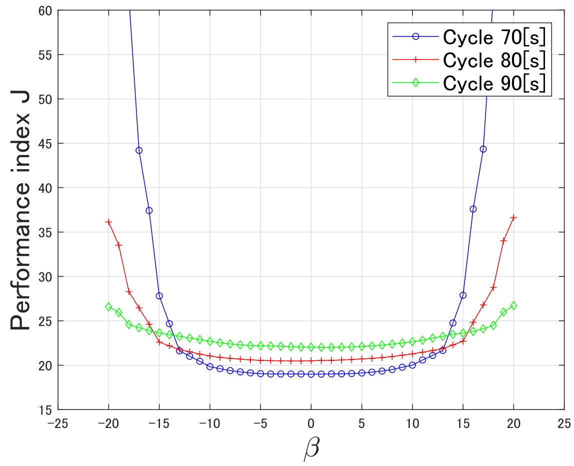
An intersection shown in 1 is considered for implementing and evaluating the proposed signal control system. For this purpose, an extended microscopic traffic simulator built in MATLAB is used as developed in [18]. The individual cars are driven by the IDM with the parameters: the desired speed v_0 is randomly chosen between 50 to 55 km/h, desired time gap T 1.0 to 1.8 sec, $s_0 = 1.0$ m, $a = 2.0$ m/s^2, and $b = 2.5$ m/s^2,

A. Evaluation of the model

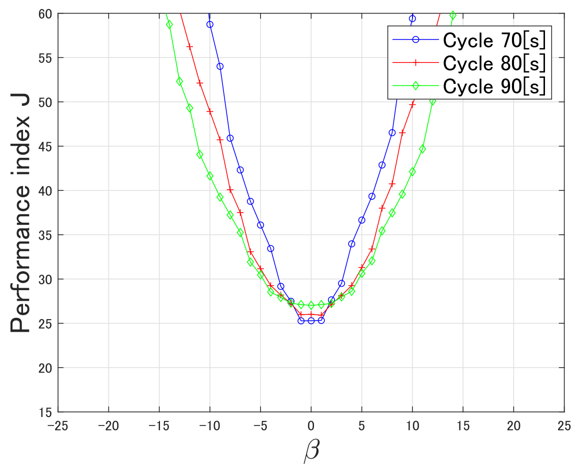
At first, the developed model is evaluated to verify its ability to estimate the crossing times of cars for any given traffic signal patterns. For this purpose, in a single section the information of all incoming vehicles are collected. The using the model and provided signal, their crossing times are estimated. Later, the actual crossing time of these vehicles are recorded and compared. We performed this simulation by changing signal cycle for 50 sec, 60 sec, 70 sec. The estimated crossing times of the intersection and the actual crossing times for all vehicles are compared in Fig. 3. The dotted line shows the mean value that the estimated result from the model. It is found that the model was able to estimate the correct crossing phase of a car with an accuracy of 94 %. For these cars, the mean square error in estimated crossing time is less than 2.5%.

B. Optimization of traffic signal

Next using the model, we have observe the influence of signal duration η on the average waiting time of vehicles as given in the performance index. This process is also used to choose the optimal signal. Assume the incoming traffic volumes are constant in all traffic lanes. Let η_1, η_2, η_3, η_4 express the duration of each signal phases. Here η_1 for the east and west side traffic and η_3 for the north and south traffic

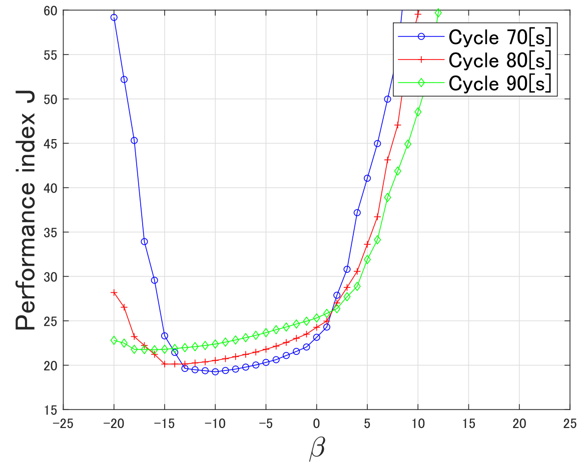


(a) Low traffic volume

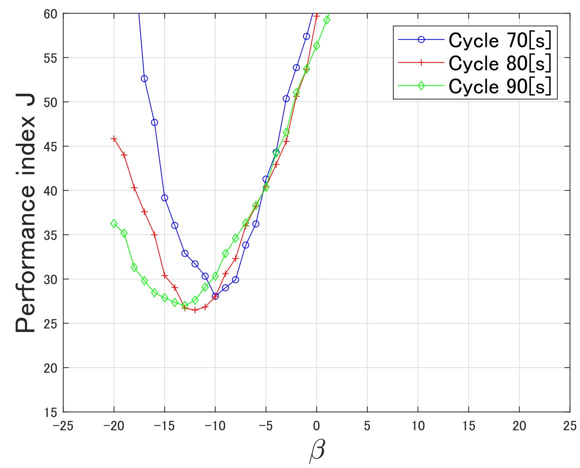


(b) Medium traffic volume.

Fig. 4: A relationship of performance index with respect to the change of the signal duration when traffic in the both groups are the same.



(a) Traffic volume is low.



(b) Traffic volume is medium.

Fig. 5: A relationship of performance index with respect to the change of the signal duration when traffic in the both groups are not symmetric.

side represent the times for the straight or left turning period, and η_2 and η_4 are the time of signal phase when cars can turn right only. In this study we kept the right turning period fixed at a minimum value. Let β is a variable that expresses the tuning of signal duration in a given cycle in the range of -20 to 20 sec. We consider about one cycle consisted of duration $[\eta_1+\beta,\eta_2,\eta_3-\beta,\eta_4]$. For a particular traffic condition, using all vehicles data, the performance index J is evaluated over the range of β. We recorded performance index J by changing β for signal cycle 70 sec, 80 sec, 90 sec for regulating signals at the intersection.

At first, the symmetrical pattern of traffic is considered when the traffics from all the phases are equal. We consider two such cases with low and medium traffic at the intersection. Fig. 4(a) shows how the performance index changes with β at three different cycles when traffic is about 300 vehicle/h. It is found that a short signal cycle with $\beta=0$ provides the lowest value of J, which can be clearly picked up as the optimal solution. Fig. 4(b) shows for the case when traffic is about 600 vehicle/h. It is found that a short signal cycle with $\beta=0$ provides the lowest value of J. In both cases, it is clear that the proposed performance index is a convex function of the cycle and phase duration, and therefore, it guarantees the global optimal solution to minimize the collective waiting times of all vehicles.

Next, in the same way, it is evaluated when traffic at each phase are not equal. Fig. 5 shows how the performance index varies with phase duration change by the control parameter β, for three different cycles. Fig. 5 (a) and (b) show the results corresponding to the traffic settings $Q=[300,300,600,600]$, and $Q=[400,400,900,900]$, respectively. From these results, it is shown that the optimal phase periods are not equal when the traffic at each phase are not equal. The optimal cycle and phase timings can be

TABLE I: The overall traffic performance at the intersection using the proposed method and existing method.

	Existing method	Optimized method
Average speed (km/h)	36.8	39.4 (6.62[%])
Idling time (s)	21.6	16.2 (-33.33[%])
Density (Vehicle)	41	38 (-7.89[%])
Fuel (mL)	41.0	38.9 (-5.40[%])

selected from the lowest point of the performance index. From both graphs, it is found that at higher traffic little deviation from the optimal point may cause a large increase in the performance index or the waiting time of the cars. In these studies, it is found that the scheme require fraction of second to solve the optimization problem, and hence it can be implemented real time..

C. Simulating Traffic Performance

Finally, the proposed traffic signal control method is directly implemented to control the traffic flows in the traffic simulator and actual performances of vehicles are observed. The traffic is set at volumes low and medium ($Q = [300, 300, 600, 600]$) and simulated by controlling the traffic lights at the intersection. We monitored all cars within 200m from the intersection and recording their speed, time, fuel consumption. For these cars, the fuel consumption is estimated by using the method developed in [19]. For that purpose, we have also evaluated the traffic performance using the existing fixed timing signal control method. The summary of the results are shown in TABLE I. The proposed adaptive signal control method improves the speed, and traffic density, reduces the idling time and fuel consumption of cars significantly.

IV. Conclusion

We have developed an adaptive traffic signal control scheme for controlling traffic the intersection. We have formulated a model that can estimate the intersection crossing timing of a car for the given future traffic signals. The model is found to be accurate and provides estimated traffic delay due to any change in future traffic signal. Finally, traffic signal is optimized and implemented in a simulator to evaluate traffic performance at an intersection. It is found that the proposed method improves the average speed, traffic density, idling time and fuel consumption of the cars significantly. Since the density decreases, the proposed method may delay any jam occurrence. Reduction in fuel consumption indicates that the proposed method is more environment friendly.

In the future, we would like to extend the scheme for a partially connected environment with mixed traffic and considering influences of the pedestrian.

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