A STUDY OF THE SIGNAL CONTROL FOR THE MINIMIZATION OF CO_2 EMISSION

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ABSTRACT

This research analyses the difference between the signal control parameters from the different control policies for minimizing CO_2 emission and minimizing total delay time. First, a method to estimate the volume of CO_2 emission using probe vehicle data and traffic simulation is proposed. In this method, the volumes of CO_2 emission of each vehicle can be estimated using their travel time, travel distance and the acceleration energy equivalent, and using the CO_2 estimating method the isolated signal control parameters can be calculated, which minimize the volume of CO_2 emission. Next, these two signal control policies are compared in order to confirm in which condition these two signal control parameters become different. As a result, this study indicated that these two signal control parameters must be different but difference does not appear in some traffic situations.

KEYWORDS
Emission of CO_2, Signal Optimaization, Probe car

INTRODUCTION

The signal control parameters at signalized intersection has been set so as to minimize total delay time with due consideration of traffic safety and fairness for the vehicles coming from each approaches. For the isolated signal intersection, Webster[1] constructed the experimental formulation estimating for optimal cycle length under the assumption of the random arrival in traffic demand. Using the formulation or modified ones, signal parameters are calculated to minimize total delay time. Gordon[2] reported that if the traffic condition is near or over saturation, management of the inevitable queues should be required for the effective traffic control. On the other hand, spillback problem has to be considered for the linked several signal intersections, and Pignataro et al.[3], Rathi[4] proposed the strategies of ‘reverse offset’. These strategies try to minimize the impact of spillback queue. The signal timings at an upstream intersection are determined by the start of green downstream instead of providing for forward progression of vehicle platoons, and the green starting time is set when the front of the queue reach the intersection. These strategies are designed for non-dynamic operation such as fixed-time signal control. Recently, a lot of dynamic traffic signal control systems have been developed and introduced. These systems require the observation data of traffic flow using various sensors so as to be able to respond to changes of traffic situation, and each system has its special algorithm. In England, Hunt et al. [5] developed SCOOT, Split Cycle and Offset Optimizing Technique system. In the SCOOT system, using vehicle detectors located on the upstream of each approach queue length are estimated, and signal parameter is judged to change responding to the estimated queue length. OPAC[6], Optimization Policies for Adaptive Control system, is developed in U.S.A., which is one of the demand-responsive signal control system. Introducing rolling horizon approach, signal parameters are changed according to the estimated queue length. SCATS[7], Sydney Co-ordinated Adaptive Traffic System, is developed in Australia, and signal control parameters are calculated based on the 'degree of saturation' in the SCAT system. MODERATO[8] is developed and introduced and CARREN[9], Control Algorithm Returning paRameters with self performance EvaluatioN, is proposed in Japan. MODERATO consists of macro control and micro control which share functions to control intersection signals. The macro control operates on the central computer, and determines signal control parameters (cycle length, split, and offset) and the micro control operates on the local signal controller, and determines the timing for ending green based on the traffic flow data around the signal intersection, using the green time determined by the macro control as reference with a pre-determined range for extending/shortening it at 0.1-second step. CARREN is a new traffic signal control system based on a queuing model with ITS sensing technologies, which can measure the travel time of individual vehicle. Moreover, UTOPIA[10], Urban Traffic Optimization by Integrated Automation, CLAIRE[11], A Context-Free AI Based Supervisor for Traffic Control, and other many systems have been developed. All of these strategies and dynamic control systems do not have a policy to minimize the volume of vehicle exhaust but minimize total delay time or the number of vehicle stops.

The estimating methods of the volume of vehicle emission usually assume that each vehicle type has a given coefficient of exhaust per unit running distance, and this coefficient is multiplied by vehicle-kilometer by each vehicle type to estimate total emissions[12]. Post et al. [13] and many other researches developed estimating CO2 emission models. However, most of them estimate the volume of CO2 emission by regression models using traveling velocity as an explanatory variable. On the other hand, Oguchi et al.[14] proposed the formulation estimating the volume of CO2 emission through the practical analysis. They followed the three levels of emission models proposed by Lay et al.[15], and developed a model in which the relationship between vehicle state i.e. steady speed, accelerating or decelerating and the volume of CO2 emissions are determined under heavy traffic condition. Then they proposed an experimental formulation that consists of three factors, travel time, travel distance and travel state.
Vehicle exhaust has not been considered at calculating signal parameters, because minimization of total delay is considered to achieve the minimization of the volume of vehicle exhaust. However, Yoshii et al.[16] indicated that different signal control parameters must be calculated by the two types of the signal controls, one is for minimizing total delay and the other one is for minimizing the volume of CO2 emission. Therefore, this paper first construct the estimating method of CO2 emission using the trajectory data of probe vehicles, and second analyses in which condition the signal control parameters for minimizing CO2 emission is different from one for minimizing total delay.

METHOD OF ESTIMATING CO_2 EMISSION

Formulation of the CO2 Estimation

Equation (1) indicates the regression model, which estimates the volume of CO_2 emission proposed by Oguchi *et al.* [14].

$$E = K_C(0.3T + 0.028D + 0.056AEE) \quad (1)$$

$$AEE = \sum_{k=1}^{K} s_k (v_k^2 - v_{k-1}^2) \quad (2)$$

where,

E : volume of CO_2 emission[cc]

T : travel time[s]

D : travel distance[m]

AEE: acceleration Energy Equivalent [m^2/s^2]

Kc : coefficient to convert the gasoline fuel consumption to the volume of CO_2 emission

s_k : $s_k = 1$ if $n_k > n_{k-1}$, otherwise $s_k = 0$

v_k : velocity at time k [m/s]

There are three explanatory variables in the model, vehicle's travel time, travel distance and AEE (Acceleration Energy Equivalent) value. These are corresponding to the first, second and third terms of the right side of the equation (1) respectively. Travel times of each vehicle are evaluated to sum up free-flow travel time and delay time. Travel distance must be constant if the study section is fixed. AEE value can be calculated by vehicle travel mode in acceleration and deceleration using data of vehicle trajectory from probe vehicles. The three coefficients, which are evaluated by experimental approach, take different values in accordance with individual vehicle type. However, fixed values are used in this research, because it is sufficient to carry out the comparison study of the signal control parameters from the two different control policies.

AEE Evaluation

AEE is evaluated by pre-determined values correspondent to the number of stops as followings. From the probe vehicles, vehicle position and velocity can be obtained every time interval (e.g. 1sec). Using the data, the speed profiles of each vehicle can be described shown in Figure 1 as an example. The figure shows the speed profile of a vehicle with two stops in queue. AEE values of the following four sections of each profile can be calculated from equation (2) separately;

1) Until the first stop (see A in Figure1)
2) From the final stopping point to the entrance of the intersection (see B in Figure 1)
3) After entrance to the intersection (see C in Figure 1)
4) From a stopping point to next stopping point in case of more than two stops (see the D in Figure 1)

After many profiles are obtained, AAEE (Averaged AEE) values of each four sections can be calculated. Then AEE value of each vehicle can be evaluated depending on the number of stops. Equation (3) indicates the AEE value of non-stop vehicle, which is calculated as the summation of AAEE values of section A and C. Equation (4) indicates that of one-stop vehicle, which is calculated by taking a summation of AAEE values of A, B and C. Section D is required for the evaluation of vehicles with more than 2 stops, but they are not considered in this study framework.

$$m_0 = m_A + m_C \quad (3)$$

$$m_1 = m_A + m_B + m_C \quad (4)$$

where,

m_i : AEE value of i-stop vehicle $i=0,1$

m_K : AAEE value of section K $K=A,B,C,D$

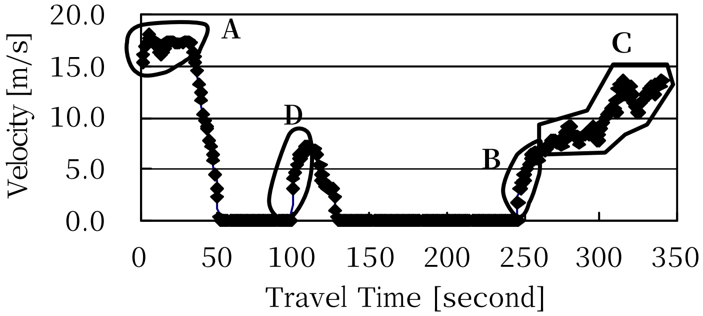

Figure 1 - Speed Profile of a probe vehicle (two stops)

Signal Control Setting for Minimizing CO_2 Emission

Under the assumption of uniform arrival, the optimum cycle length in order to minimize CO_2 emission is discussed. If the cycle length is longer than the minimum cycle length, which can achieve minimum delay time, total delay time must become larger, but number of vehicles which are forced to stop in the waiting queue at the intersection decrease. On the other hand, if the ratio of the stopping vehicles is decrease, CO_2 emission is possible to be decreased because AEE value becomes smaller. CO_2 emissions are calculated by three factors, travel time, distance and AEE value. Among these three factors, delay time and AEE value must be changed depending on the signal control but distance is never changed. Therefore, volume of CO_2 emissions is evaluated depending on these two factors, delay time and AEE value. Figure 2 describes the relationships between cycle length and volume of CO_2 emissions, delay time, AEE values. If the slope of the curve denoting AEE value is gentle as dotted line (a), the value of CO_2 emission is evaluated as dotted line (b), which is a monotonously increasing. Therefore, the optimum cycle length is equal to the 'minimum cycle length (C_{min} in Figure 2)'. On the other hand, if the slope of the curve is steep as line (c), the value of CO_2 emission is evaluated as line (d), which has a minimal value. So, the optimum cycle length should be different to the 'minimum cycle length(C_{opt} in Figure 2)'.

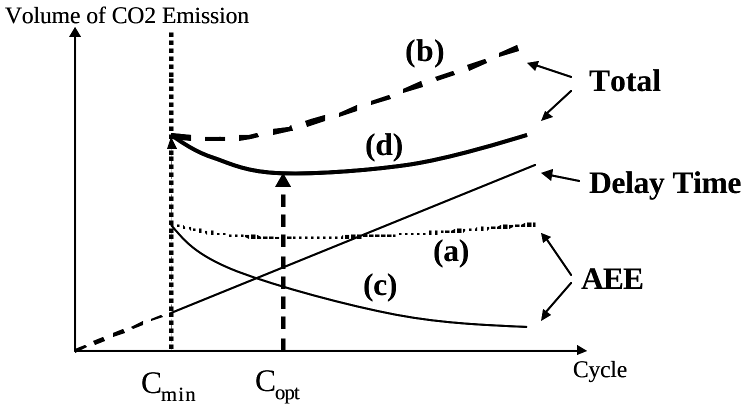

Figure 2 - Volume of CO_2 emission generated by delay time and AEE value

COMPARISON ANALYSIS UNDER A SIMPLE TRAFFIC SITUATION

Study Intersection and Traffic Demand

This study considers an isolated signalized intersection as shown in figure 3, and following condition is assumed as a primitive stage.

1) Across one-way traffic

2) $S_1=S_2=S$
3) $Q_1=Q_2=Q<S$, Uniform arrival rate in both directions
4) Point queue is assumed at the intersection

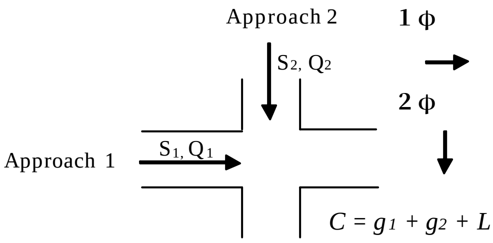

Figure 3 - Outline of intersection

where,

g_i : effective green time for approach i [sec]
L : lost time per cycle length ($L = l_1 + l_2$) [sec]
C : cycle length [sec]
Q_i : traffic demand for approach i [$veh/hour$]
S_i : saturation flow rate of approach i [$veh/hour$]

Signal Control for Minimizing Delay Time

In this study intersection, minimum cycle length for minimizing delay time is showed like equation (5).

$$C_{\min} = \frac{L}{1-l} \qquad (5)$$
$$l = l_1 + l_2$$

where,

l_i : degree of saturation at phase i (= Q_i/S_i)

Then, effective green times, which can achieve minimum delay time, can be written as equation (6).

$$g_{d1} = g_{d2} = g_{delay} = \frac{L \cdot l}{2 \cdot (1-l)} \qquad (6)$$

where,

g_{delay} : effective green time for both phases which can achieve minimum delay time [sec]
g_{di} : effective green time for phase i which can achieve minimum delay time [sec]

Signal Control for Minimizing CO_2 Emission

Because travel distances of the vehicles are not changed, the second term of equation (1) can be left out of the estimation. Therefore, Equation (5) can be changed for estimating cycle length which minimizes CO_2 emission as

$$\min E = \frac{Kc}{C}\sum_{i=1}^{2}\left[\sum_{k=1}^{N_i} 0.3 \cdot \left(T_{delay}^{i}(k)\right) + 0.056 \cdot \left\{m_0^i N_i (1-q_i) + m_1^i N_i q_i\right\}\right] \qquad (7)$$

$$q_i = \frac{1}{1-l_i} \cdot \frac{C-g_i}{C} \qquad (8)$$

$$C = \sum_{i=1}^{2} g_i + L \qquad (9)$$

$$C \geq C_{\min} \qquad (10)$$

where,

N_i : number of arrival vehicle per 1 cycle into approach i

q_i : rate of stopping vehicle on approach i

$T_{delay}^{i}(k)$: delay time of the k th vehicle of approach i

m_k^i : AEE value in case of the vehicle stopping k times at approach i.

Delay time per 1 cycle can be calculated using equation (11). It is corresponding to the area of triangle of the figure 4.

$$T = \frac{1}{2}(C-g) \cdot N \cdot q \qquad (11)$$

So, equation (7) can be changed to the new form as equation (12).

$$E = \frac{Kc}{C}\sum_{i=1}^{2}\left[0.3 \cdot \left\{\frac{1}{2}(C-g_i)N_i q_i\right\} + 0.056 \cdot \left\{m_0^i N_i (1-q_i) + m_1^i N_i q_i\right\}\right] \qquad (12)$$

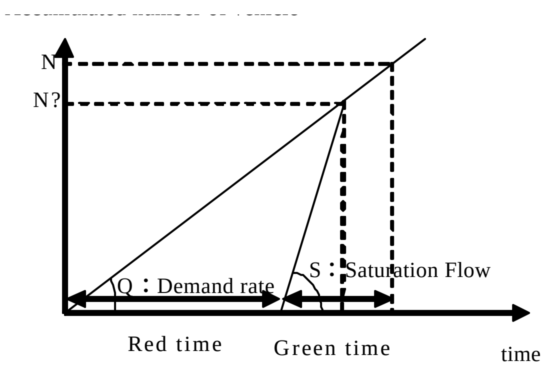

Figure 4 - Delay time

Moreover, N_i can be written as equation (13).

$$N_i = Q_i C \qquad (13)$$

Then, equation (12) is changed as equation (14).

$$E = Kc\sum_{i=1}^{2} 0.3 \cdot \left\{\frac{1}{2} \cdot (C-g_i)Q_i q_i\right\} + 0.056\left\{m_0^i Q_i (1-q_i) + m_1^i Q_i q_i\right\}$$

$$= \sum_{i=1}^{2} a_i + b_i \cdot (C-g_i) \cdot q_i + c_i q_i \qquad (14)$$

where,

$$a_i = 0.056Kcm_0^iQ_i$$
$$b_i = 0.15KcQ_i$$
$$c_i = 0.056KcQ_i \cdot (m_1^i - m_0^i)$$

The necessary requirement for minimizing equation (14) is shown in equation (15).

$$\frac{\partial E}{\partial g_1} = \frac{\partial E}{\partial g_2} = 0 \tag{15}$$

Moreover, if travel distance and free flow travel time at target section of approach i are also same for both approaches, effective green time can be written as

$$\frac{\partial E}{\partial g_1} - \frac{\partial E}{\partial g_2} = \frac{1}{(g_1 + g_2 + L)} \cdot [b \cdot \{2 \cdot (g_1 - g_2) \cdot (g_1 + g_2 + L)\}] = 0 \tag{16}$$

where,

$$b = b_1 = b_2 \tag{17}$$

And then, the necessary requirement for minimizing CO_2 emission can be shown as equal green time for both directions, equation (18).

$$g_1 = g_2 = g \tag{18}$$

By the equation (18), equation (16) can be changed to the following form

$$\frac{\partial E}{\partial g_1} = \frac{\partial E}{\partial g_2} = \frac{1}{(2g + L)^2}\{2b(g^2 + gL) - cL\} = 0 \tag{19}$$

The effective green time g has to satisfy,

$$g \geq g_{delay} > 0. \tag{20}$$

So, the effective green time, which should satisfy the condition (19), is shown as equation (21).

$$g = -\frac{L}{2} + \frac{\sqrt{(bL)^2 + 2bcL}}{2b} \tag{21}$$

Therefore, the green time minimizing CO_2 emission can be expressed as equation(22), because, if the green time is shorter than g_{delay}, the green time takes the same value as g_{delay} due to condition (20).

$$\begin{cases} g_{emission} = g_{delay} & if \quad g < g_{delay} \\ g_{emission} = -\frac{L}{2} + \frac{\sqrt{(bL)^2 + 2bcL}}{2b} & if \quad g \geq g_{delay} \end{cases} \tag{22}$$

The necessary conditions in case that different signal control parameters should be set for minimizing delay time and CO_2 emission($g_{emission} \neq g_{delay}$) can be written as shown inequality (23).

$$-\frac{L}{2}+\frac{\sqrt{(bL)^2+2bcL}}{2b} > \frac{L \cdot l}{2\cdot(1-l)} \tag{23}$$

Under the condition that the value of l should take the value between 0 and 1, the condition (23) can be solved as,

$$0 \leq l < 1-\sqrt{1+\frac{4\cdot c}{b\cdot L-4\cdot c}} \tag{24}$$

This inequality shows the necessary condition for different signal control between minimizing delay time and CO_2 emission.

Practical Study

In order to understand the necessary condition (24) intuitively, practical study has been carried out. Yoshii et al.[16] had observed the AEE values of an actual field as equation (25).

$$m_0 = 596 \quad [m^2/\sec^2], \quad m_1 = 694 \quad [m^2/\sec^2] \tag{25}$$

Using these actual data, the necessary condition (24) can be transformed the condition including the two variables, the saturation flow rate and the lost time. Figure 5 indicates the condition under when different signal control parameters can be obtained for minimizing delay time and minimizing CO_2 emission. The shaded area of the figure satisfies the condition of the equation (24). It can be understood from the figure that the signal control parameters should be changed depending on their control policies regardless of the value of the degree of saturation λ when the length of the lost time is small. On the contrary, when the length of the lost time becomes larger, only the case where the degree of saturation λ takes small value, the two signal control parameters for minimizing delay time and CO_2 emissions take different values. For example, if the lost time is 2 seconds and the degree of saturation is 80%, the condition is satisfied and if the lost time is 8 seconds and the degree of saturation is 80%, the condition is not satisfied.

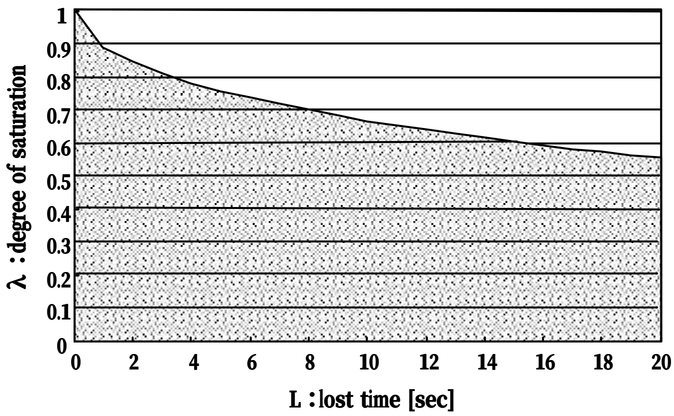

Figure 5 - Condition for the different signal control parameters

The volume of CO_2 emission can be reduced by introducing the signal control for minimizing the CO_2 emission instead of one for minimizing the total delay time. The effect of the improvement in CO_2 emission is evaluated quantitatively through a case study. In this section, the effect of the improvement is calculated using these values as;

$$S_1 = S_2 = 1800 \quad [veh/hour] \quad , \quad D_1 = D_2 = 2150 \quad [m]$$
$$m_0 = 596 \quad [m^2/\sec^2] \quad , \quad m_1 = 694 \quad [m^2/\sec^2]$$
$$L = 10 \quad [\sec]$$

Figure 6 shows the calculation result. From this figure, it can be understood that lower degree of saturation, more improvement in CO_2 emission can be obtained by shifting signal control policy. For example, when the degree of saturation is 0.2, 2% of the volume of CO_2 emission is expected to be reduced. And, if traffic volume become larger and degree of saturation exceeds the threshold level, which is 0.66 in this case, both of signal control parameters take same values and no improvement can be obtained.

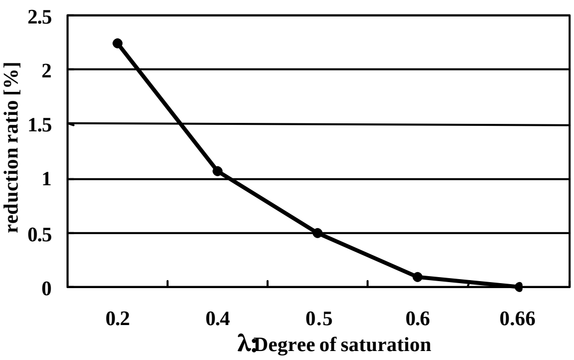

Figure 6 - Reduction Effect of the improvement in CO_2 emission

CONCLUSION

This paper discussed the difference of the signal control parameters from the different control policies between for minimizing delay time and minimizing CO_2 emission. The method evaluating the volume of CO_2 emission is developed using vehicle trajectory data, which can be obtained by probe vehicle for example. Next, the difference between signal control parameters for minimizing the total delay time and for minimizing the volume of CO_2 emission is studied, and the reason is clearly shown why the difference is appears. Then, through the comparison analysis using a simple intersection and simple traffic demand, the necessary condition has been presented that leads the difference between two of signal control parameters to achieve minimum delay time and minimum volume of CO_2 emission. Moreover, using actual data and usual situation, it is shown what combination of the values of the degree of saturation and the lost time can satisfy the presented necessary condition, and also be shown what a extent the volume of CO_2 emission can be reduced by introducing the signal control parameters for minimizing CO_2 emission. As a result, it is shown that in case of the lower degree of saturation, more improvement in CO_2 emission can be obtained by shifting signal control policy.
In future, this study will be extended to the more general analysis. For example, more general intersection or random arrival will be assumed, and the influences of special vehicles such as idling-stop vehicles or lower emission vehicles. Finally, we want to establish the signal control system for minimizing CO_2 emission by using ITS technologies, probe vehicle or the other traffic monitoring technology.

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