Traffic Signal Control Policy from the Viewpoint of Emission at Isolated Intersections*

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1. Introduction

Signalized intersections are areas with high concentration of emission due to vehicles' frequent deceleration, acceleration and long idle time. Traffic signal control policy can alleviate emission burden in an accurate and quick way by giving signal control optimization strategies from the viewpoint of emission based on the explicit and quantitative interpretation on their relationship.

The impact of signal control strategies on emission level lies in how strategies influence on 1) the number of deceleration, acceleration, and 2) the total idle time.

For conventional traffic signal control policy at isolated intersections, control delay is the critical performance measure. Optimization strategies to minimize delay are generally considered approximately able to reduce emission as well, while emission is closely related to stop besides impact from delay.

Therefore, there exists difference between delay based policy and emission based policy. And for these two policies, compatibility needs be analyzed under various traffic conditions. Those conditions where prominent incompatibility occur and emission based policy distinguish to reduce emission should be identified. Furthermore based on such identification process, the premises for typical emission based policy need be confirmed and recommended which can serve as a basis for planning emission responsive control strategies.

This paper aims to address the above mentioned issues at isolated intersections. First emission is modeled as a universal function of driving modes. Then using such a universal function, cycle length and green time split are optimized from the viewpoint of emission and compared with the optimized values of the delay based policy. Finally conditions where the emission based policy distinguishes with delay based one are indentified and premises to realize the typical emission based policy are recommended.

2. Literature Review

Planning of the emission based policy needs basis 1) Generalized and explicit interpretation are given between traffic signal control parameters and emission level without any dependency on specific emission estimation models. 2) Analysis of compatibility with the delay based policy and identification of incompatibility can be realized in a generalized way.

However very few studies addressed the issue of traffic signal control policy from the viewpoint of emission and its compatibility with the conventional delay based one. Most of the existing works in this aspect concern on developing estimation models of vehicle emission or optimizing control parameters based on some specific emission estimation models.

Oneyama, et al. (2001)[1)] developed a methodology for emission estimation based on driving modes. Utilizing an original emission estimation model, optimum cycle length for minimizing emission at isolated intersections was calculated, and difference between emission based policy and delay based one was shown. However using that optimum value which depends on a specific emission estimation model, identification results of the compatibility between the two policies cannot serve as a general basis for developing the emission based.

Kawashima, et al. (2001)[2)] studied impact of adaptive signal control on emission reduction. Utilizing emission calculation function in the simulation software VISSIM, optimized green time split was shown which can reduce emission more effectively compared with the delay based policy. This study did not interpret the generalized relationship between traffic signal control parameters and emission level.

Li, et al.(2004)[3)] proposed an emission based signal control policy optimizing signal cycle length and green time split by establishing a comprehensive objective function of traffic quality, fuel consumption and emission. A simulation was used to get optimized values however still did not offer any explicit interpretation between control parameters and emission level. Also premise for under what conditions the emission based policy will distinguish was not given.

The existing research results cannot offer sufficient basis for planning emission based policies. This paper aims to establish that basis and investigate the characteristics of the emission based policy.

3. Methodology

The trajectory of one vehicle which experiences a time stop at the stop line of an intersection approach is illustrated in **Figure 1**. Emission derives from four driving modes, namely deceleration, acceleration, idle and cruise.

*Keywords: *Emission, isolated intersection, cycle length, green time split*

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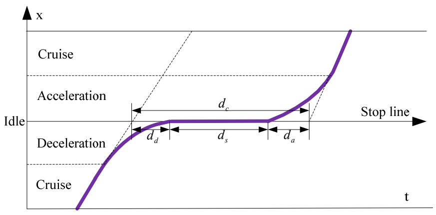

Figure 1: Vehicle trajectory and driving modes

The emission from this single vehicle can be expressed by Equation (1).

$$e = \frac{de_i}{dt} \times t_{idle} + (e_d + e_a) + \frac{de_c}{dx} \times x_{cruise} \tag{1}$$

Where e is total emission from a singal vehicle (g), de_i/dt is emission rate for idle mode (g/s), t_{idle} is idle time (s), e_d is emission volume for one deceleration (g), e_a is emission volume for one acceleration (g), de_c/dx is emission rate for cruise mode (g/m) and x_{cruise} is cruise distance (m).

Since idle time is equal to stopped delay time that can be obtained through control delay minus the delay caused by deceleration and acceleration, Equation (1) can be transformed into:

$$e = \frac{de_i}{dt} \times d_s + (e_d + e_a) + \frac{de_c}{dx} \times x_{cruise} \tag{2}$$

$$d_s = d_c - d_d - d_a \tag{3}$$

Where d_s, d_c, d_d, d_a are stopped delay, control delay, deceleration delay and acceleration delay(s) respectively for a single vehicle.

For a certain traffic flow, assuming vehicle type and cruise speed are uniform, the total emission can then be aggregated by summing up emission from individual vehicles.

$$E = \frac{de_i}{dt} \times \sum d_s + n \times (e_d + e_a) + \frac{de_c}{dx} \times \sum x_{cruise} \tag{4}$$

Where E is total emission (g) for a traffic flow and n is the number of stopped vehicles.

Total stopped delay $\sum d_s$ can be obtained through total control delay $\sum d_c$ minus total deceleration and acceleration delay $\sum(d_d+d_a)$. Since for any of stopped vehicles based on the above assumptions, deceleration and acceleration delay are the same, the Equation (5) is satisfied:

$$\sum(d_d + d_a) = n \times (d_d + d_a) \tag{5}$$

Combing with Equation (3), (4), Equation (4) can be transformed into:

$$E = \frac{de_i}{dt} \times \sum d_c - \frac{de_i}{dt} \times n \times (d_d + d_a) + n \times (e_d + e_a) + \frac{de_c}{dx} \times \sum x_{cruise} \tag{6}$$

Then for traffic flow relationship between contribution of total control delay and the total number of stopped vehicles to emission is shown in Equation (7). $F(e)$ shows how many seconds of control delay can produce the same emission volume with that from one stopped vehicle.

$$F(e) = \frac{(e_d + e_a)}{\frac{de_i}{dt}} - (d_d + d_a) \tag{7}$$

4. Control Parameter Optimization

Cycle length and green time split are control parameters for isolated intersection signal control. Regarding emission minimization, Equation (6) is used as the objective function which takes the impacts of both delay and stop into account.

4.1 Cycle Length

Cycle length serves as one of the most important parameters.

The traditional methods use Webster's model[4)] to determine optimum cycle length assuming random arrival as shown in Equation (8)

$$C_o = \frac{1.5L + 5}{1 - Y} \tag{8}$$

Where C_o is optimum cycle length(s), Y is the sum of critical lane volume divided by saturation flow rate and L is loss time per cycle (s).

Akcelik[5)] expanded Webster's optimization equation by also taking impact from stops into account besides delay. This expansion made it possible to optimize performance measures which are influenced by not only delay but also stop.

As shown in Equation (9), K can supplement the impact of stopped vehicles on fuel consumption, emission and driving comfort level besides impact from delay.

$$PI = D + K \times n \tag{9}$$

Then using performance index PI as optimization objective, the optimized cycle length can be calculated as:

$$C_0 = \frac{(1.4 + K)L + 6}{1 - Y} \tag{10}$$

For emission, compare the Equation (6) and (9), K can be got and substituted in Equation (10), then optimized cycle length for minimal emission can be achieved by using Equation (11).

$$C_o = \frac{\left(1.4 + \frac{F(e)}{3600}\right)L + 6}{1 - Y} \tag{11}$$

4.2 Green Time Split

The generally applied policy for green time split aims to equalize V/C ratio for critical phases and the following Equation (12) is used.

$$\frac{g_u}{\sum_{u=1}^{U} g_u} = \frac{y_u}{\sum_{u=1}^{U} y_u} \tag{12}$$

Where g_u is effective green time (s), u is the u th critical signal phase; y_u is flow ratio and U is the number of critical phases.

Using this equation, the equalized V/C is considered able to reduce total intersection delay. Then two questions are raised 1) Does the equalized V/C guarantee the minimal total intersection delay? 2) What is the optimized green time split for emission based policy and how it differs from that for delay based policy?

Assumed intersection conditions and signal timing are illustrated in **Figure 2** and **Figure 3**.

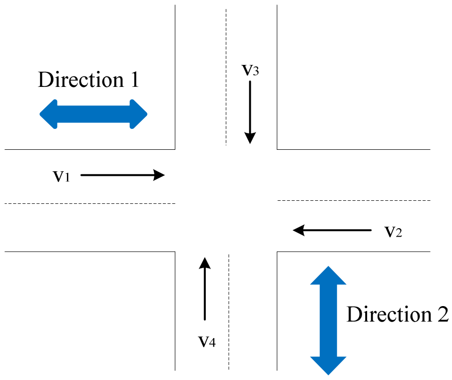

Figure 2: Assumed intersection conditions

Figure 3: Assumed signal control timing

The other assumptions are as follows: the same saturation flow rate S for all approaches, arrival type is uniform, no lost time and amber time, under saturation, demand v_1, v_2, v_3, v_4 for direction 1, 2, only through traffic for all approaches.

The total delay and number of stopped vehicles correspond to the triangle area and farthest distance for back of queue divided by flow rate respectively in **Figure 4**. They are expressed in Equation (13) and (14).

$$D = \frac{VS}{2(S-V)} r^2 \qquad (13)$$

$$n = \frac{VS}{(S-V)} r \qquad (14)$$

Where V is flow rate (veh/h), S is saturation flow rate (veh/h) and r is red time (s).

4.2.1 Green Time Split for Delay based Policy

For simplicity, a balanced flow is assumed ($v_1=v_2=V_1$, $v_3=v_4=V_2$). Being influenced solely by directional traffic demand difference of direction1 and 2, how optimized values differ between the two policies is analyzed.

Then denoting green time split for direction 1 is θ, applying the current green time split policy expressed in Equation (12), θ can be got by Equation (15).

$$\theta = \frac{V_1}{V_1 + V_2} \qquad (15)$$

After summing up delay of direction 1and 2, total intersection delay D_{total} can be calculated by using θ as variable. To get the minimal value of total delay, the optimized θ can be got by making the value of $\partial D_{total}/\partial\theta$ equal to 0.

$$\theta = \frac{\frac{V_1}{S-V_1}}{\frac{V_1}{S-V_1} + \frac{V_2}{S-V_2}} \qquad (16)$$

Comparing Equation (15) and (16), difference can be found which means current policy cannot guarantee the minimal total intersection delay by realizing equalized saturation ratio.

One new concept is declared as **efficiency to dissipate queue** which is expressed by ***V/(S-V)***. Such a concept reflects the ability to reduce delay and stop through dissipating queue at given unit interval. According to Equation (16), green time split for the minimal total intersection delay should be based on *V/(S-V)*.

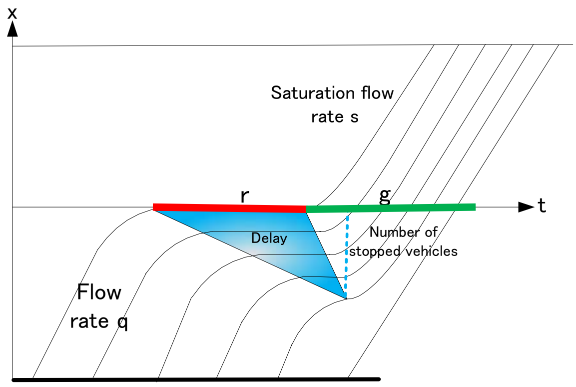

Figure 4: Time-space diagram

4.2.2 Green Time Split for Emission based Policy

For emission minimization, by integrating Equation (6), (13) and (14), emission can be modeled as a function of signal control parameters as follows:

$$E_{sum} = \frac{de_i}{dt} \times \frac{VS}{2(S-V)} r^2 + \frac{de_i}{dt} \times F(e) \times \frac{VS}{(S-V)} r + \frac{de_c}{dx} \sum x_{cruise} \qquad (17)$$

After summing up emission of direction 1and 2, total intersection emission E_{total} can be calculated using θ as variable. To get the minimal value of total emission, the optimized θ can be got by making the value of $\partial E_{total}/\partial\theta$ equal to 0.

$$\theta = \frac{\frac{V_1}{S-V_1}}{\frac{V_1}{S-V_1} + \frac{V_2}{S-V_2}} + F(e)\frac{1}{C}\frac{\frac{V_1}{S-V_1} - \frac{V_2}{S-V_2}}{\frac{V_1}{S-V_1} + \frac{V_2}{S-V_2}} \qquad (18)$$

Comparing Equation (16) and Equation (18), a shift $\Delta\theta$ exists as illustrated in **Figure 5** showing difference of these two policies. Emission based policy emphasizes *V/(S-V)* more and further compares its difference among directions. Correspondingly additional term expressed in Equation (19) responds to the impact from stop on emission.

$$\Delta\theta = F(e)\frac{1}{C}\frac{\frac{V_1}{S-V_1} - \frac{V_2}{S-V_2}}{\frac{V_1}{S-V_1} + \frac{V_2}{S-V_2}} \qquad (19)$$

5. Identification of Difference

1) Only for very extreme condition where besides the premise of a balanced flow, additional requirement of the same demands for direction 1, 2 should also be satisfied meaning that all approaches must have the same efficiency to dissipate queue (*V/(S-V)*), $\Delta\theta$ does not exist.

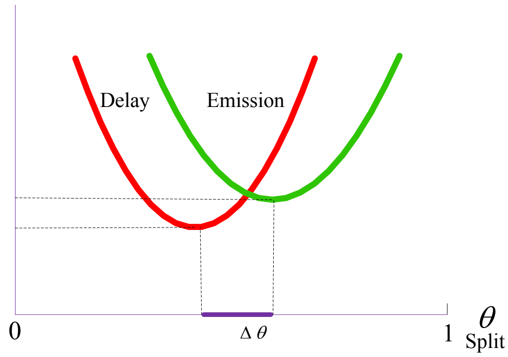

Figure 5: Illustration for the difference of emission based split and delay based one

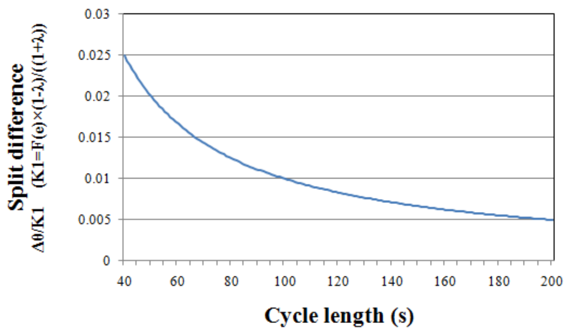

Figure 6: Split difference to cycle length

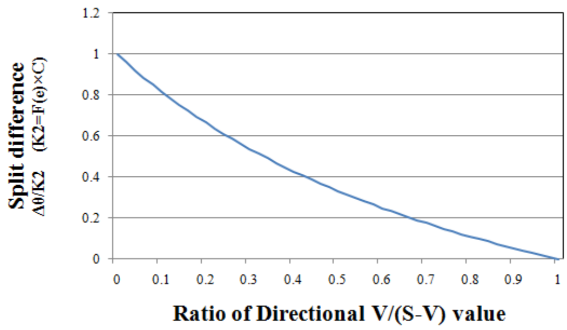

Figure 7: Split difference to V/(S-V)

2) Since there are directional demand differences on common conditions causing difference of *V/(S-V)*, $\Delta\theta$ exists. That means the emission based policy generally differs with delay based one.

3) Though the existence of $\Delta\theta$ is general, it varies due to different traffic conditions. For conditions where the value of $\Delta\theta$ is small these two policies can be considered as compatible. Those conditions where $\Delta\theta$ indicates significant difference and incompatibility exceeds the acceptable extent need be identified. Such conditions are typical premise for emission based policy to distinguish with the delay based policy.

6. Recommended Premises

According to Equation (18), there are two other factors influencing the value of $\Delta\theta$ besides *Fe*. One is cycle length and the other is directional *V/(S-V)* difference between direction 1 and direction 2.

Premise of cycle length: Assuming ratio λ of directional *V/(S-V)* values is fixed, as shown in **Figure 6**, $\Delta\theta$ decreases with increase of cycle length, implying that for long cycle length, i.e. those applied in Japan (120S-180S) $\Delta\theta$ is comparably small. Short cycle length is one premise to distinguish emission based policy.

Premise of directional V/(S-V) difference: Assuming cycle length C is fixed, ratio λ of directional *V/(S-V)* varies. As shown in **Figure 7**, $\Delta\theta$ decreases with increase of λ, indicating that directional difference of *V/(S-V)* which is influenced by saturation conditions determines another typical premise for emission based policy.

Recommendations: 1) when directional saturation conditions differ greatly causing distinct *V/(S-V)* values, regarding emission reduction, emission based policy will distinguish with delay based one. 2) For the short cycle length cases, the distinguishing characteristic of emission based policy will be further strengthened.

7. Conclusions and Future Works

This paper discusses traffic signal control policy from the viewpoint of emission and investigated difference between emission based policy and delay based policy at isolated intersections. Optimized control parameters were calculated based on a universal emission function which did not depend on any specific emission estimation model or simulation model, then generalized and explicit interpretation between emission level and traffic signal control parameters were demonstrated. Also those conditions where emission based policy can minimize emission were indentified and premises to realize typical emission based policy were recommended.

For future work, regarding certain emission type, i.e. NOx, CO, based on their emission rates, traffic control parameters can be optimized to minimize one of them or their combination.

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