Evaluating Efforts on Delay Reduction: Methodology to Understand Potential-for-Improvement of Urban Arterial Networks

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Abstract: This research introduces a compact calculation module outputting Potential-for-Improvement (PfI), an index, for evaluating efforts in delay reduction of signal control strategies on urban networks. PfI is the gap between actual delay in network and delay under more optimized situations, calculated by a proposed macroscopic urban model and a GA optimizing process. We applied the module in an arterial network in Bunkyo-ku, Tokyo and found significantly different PfIs were calculated under several approaches in signal control improvement; PfIs of more than 30% were unveiled at the network in weekdays and more in weekends. While traffic control in peak-hours usually attracts more, these results can remind us of how traffic in off-peak hours has been neglected, particularly in the case of Japan. With a compact module requiring simple input data, yet, providing consistent results, this methodology shows possibilities to be applied in evaluating and comparing signal control strategies on urban networks.

Keywords: Potential-for-Improvement, Delay Reduction, Urban Arterial Networks, Signal Control, Optimization

1. INTRODUCTION

Enhancement of urban network’s performance is a challenging task. Many cities are trying to expand roads to reduce congestion. However those expansions probably will not help to solve the problem in a sustainable way. Beside the fact that expansion of road network's capacity is expensive and would be constrained by land limitation, it might stimulate a large amount of new demand, called "induced demand", and thus, density on the road networks, in long-term, would not decrease as expected. Some cities are utilizing ITS and other transport management tools to optimize the operation of traffic signal controls such as: London (SCOOT - Split, Cycle and Offset Optimization Technique), Sydney (SCATS - Sydney Coordinated Adaptive Traffic System) and Tokyo (MODERATO - Management by Origin-DEstination Related Adaptation for Traffic Optimization).

However, fewer studies have been focused on figuring out how well an urban arterial network is being operated, or how much we can improve performance of the current network. Recently, the concept of macroscopic fundamental diagram (MFD) in urban networks has been revealed and improved (Geroliminis and Daganzo, 2008; Geroliminis and Sun, 2011; Wu, Liu and Geroliminis, 2011). MFD describes the analytical relationship between traffic flow and density in an urban network, and depends on network's configuration and signal controls. Particularly, it indicates that with better infrastructure or signal controls, the network can achieve higher flow with the same density (Daganzo, Gayah and Gonzales, 2011). These studies help evaluating not only current status but also identifying potential for improvement of the network from the perspective of throughput.

This research attempts to develop a methodology to answer the questions from the perspective of delay reduction. We introduce a new index named Potential-for-Improvement (PfI) which is defined as the difference between actual delay in network and delay under better situations, in which traffic signal control would be optimized. In this study, PfI is used to assess effectiveness of multiple signal control strategies by showing how much current delay can be reduced with the proposed optimal situations.

To derive PfI, we develop a practical macroscopic model to calculate delay time in urban networks and combine it with Genetic Algorithm (GA) to form a simple module to identify the optimized situation. An optimized situation, in this study, is defined by a set of traffic signal control parameters, i.e. signal timing, offset and cycle length, which can minimize travel delay time in the network. Section 2 introduces the model and Section 3 shows how the model is integrated with GA to find out optimal solutions. Section 4 describes the formula of PfI and Section 5 explains necessary settings and algorithm for numerical calculation of delay model. Section 6 shows applications of PfI in evaluation. Table 1 shows Notations used in the model.

Table 1. Notations used in the model

Symbol	Description
$O_{i,d}(t)$	Departure flow rate from link i to downstream d
$O_i(t)$	Total departure flow rate from link i
$\beta_{i,d}$	Turning ratio from link i to downstream d
$A_i(t)$	Total arrival flow rate to link i
T_i	Travel time on link i
$Q_i(t)$	Number of queuing vehicles on link i
Δt	Duration of one time-step
$f_d(t)$	Free space on downstream d
s	Saturation flow rate
v	Link travel speed, determined exogenously
l_i	Link i's length.
w_i	Number of lanes in link i.
l_{veh}	Average vehicle's length
T	Duration of calculation

2. MACROSCOPIC MODEL FOR DELAY CALCULATION IN NETWORKS

Several macroscopic urban road models were proposed to predict the traffic flow in the urban network (Daganzo, Gayah and Gonzales, 2011; Lin, Schutter, Xi and Hellendoorn, 2009). Most of them describe relations among successive road sections in network under various conditions and real-time information. Those models require a large amount of site's data and are time-consuming. Lin et al. (2008) introduced a macroscopic urban road models based on link model in which queuing processes on a link are formulated in details. Thus the model requires input data that are not easy to observed, e.g. number of vehicle arriving at the tail of the waiting queue, especially on a long road section. And overall, these models did not explicitly describe the numerical calculation for delay time.

In this study, we constructed a model on the basis of macroscopic urban road models described by Lin *et al.* (2008) to formulate delay time in a network. Considering the possibility of data acquisition from site and the cost of data mining, we modified the model to replace parameters which need more time to obtain by ones which are easier to manipulate by conventional observation at intersections. This modification can reduce the cost of implementation without significant reduction in accuracy in delay calculation. This model will be explained below.

In order to eliminate the impact of lane-changing on the traffic stream, all vehicles are assumed to be able to arrive at their desired lane for moving to the next section so that no lane-changing is needed. Hence, vehicles arriving from up-streams will also queue at their desired lane and depart to their desired downstream without any obstacles as shown in Figure 1.

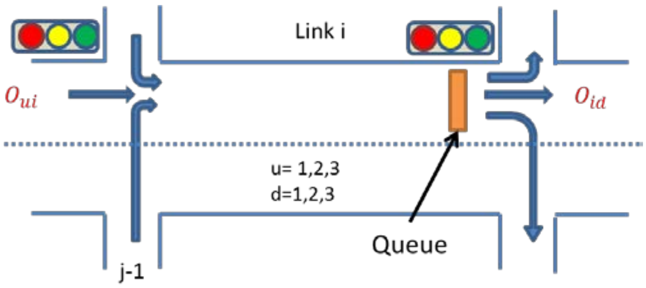


Figure 1. Assumed vehicles' movement on a link

With deterministic turning ratios, the departure flow rate from link i to downstream d ($d = 1,2,3\ldots$) is determined by the minimum value of number of existing vehicles on link i which are ready to move to downstream d, storage capacity of downstream d and saturation flow rate of the link. Shortly, it can be expressed by the following equation:

$$O_{i,d}(t) = \gamma_i(t) \min \{\frac{\beta_{i,d}}{\Delta t}[A_i(t - T_i)\Delta t + Q_i(t)], \frac{f_d}{\Delta t}, \beta_{i,d} s\} \quad (1)$$

where $\gamma_i(t)$, which is named transmission function, is expressed by:

$$\gamma(t) = \begin{cases} 0, & \text{if } t \in \text{ red time} \\ 1, & \text{if } t \in \text{ green time} \end{cases} \quad (2)$$

$\beta_{i,d}[A_i(t - T_i)\Delta t + Q_i(t)]$ is number of existing vehicles on link i which are ready to move to downstream d in a duration Δt; $A_i(t - T_i)$ is total arrival flow rate at stop line, whose values are total arrival flow rate at upstream of link i at T_i time before; T_i is link travel time $T_i = l_i/v$. $Q_i(t)$ is the number of queuing vehicles at time t.

As all vehicles entering a link must leave or wait to leave in next steps, i.e. queue on the link, relationship between numbers of arriving vehicles, departing vehicles and queueing vehicles in are expressed by the following equation:

$$A_i(t - T_i)\Delta t + Q_i(t) = \Delta t \sum_u O_{u,i}(t) + Q_i(t + \Delta t) \quad (3)$$

In arterial networks, usually link's length, l_i, is much larger than queue length. Thus, effects of queuing vehicles on link's capacity and travel time are negligible, which means that all vehicles entering link i would need the same travel time T_i to get to the stop line

From Equation (3), number of queuing vehicle $Q_i(t)$ is updated by:

$$Q_i(t+\Delta t) = Q_i(t) + \Delta t[(A_i(t-T_i) - O_i(t)] \tag{4}$$

where $O_i(t)$ is total departure flow rate from link i, which is the summation of departure flow rates over its downstreams

$$O_i(t) = \sum_d O_{i,d}\,(t) \tag{5}$$

Storage capacity of each link is the total number of vehicles that it can accommodate:

$$f_i = \frac{l_i \times w_i}{l_{veh}} \tag{6}$$

Total travel delay time on link i after T time from the beginning of the measurement, D_i, is the total number of queuing vehicles from beginning to time T, or

$$D_i = \int_0^T Q_i\,(t')\,\mathrm{d}t' \tag{7}$$

Total travel delay on network D is the summation of travel delay over all links:

$$D = \sum_i D_i \tag{8}$$

Average delay for each vehicle on network, AD, is defined as total travel delay divided by total number of arriving vehicles of all links. It is expressed by:

$$AD = \frac{D}{\sum_i \int_0^T A_i\,(t')\,dt'} \tag{9}$$

Approximately, AD can be discretized as:

$$AD = \frac{D}{\sum_i \sum_{k=0}^{n} A_i\,(t_0 + k\Delta t)\Delta t} \tag{10}$$

where: $n = T/\Delta t$ is total number of time-steps.

Using $\Delta t = 1$ unit, Equation (1), (4), and (10) were further simplified as:

$$O_{i,d}(t) = g_i(t)\min\{\beta_{i,d}[A_i(t-T_i) + Q_i(t)], f_d(t), \beta_{i,d}s\} \tag{11}$$

$$Q_i(t+1) = Q_i(t) + A_i(t-T_i) - O_i(t) \tag{12}$$

$$AD = \frac{D}{\sum_i \sum_{k=0}^{n} A_i\,(t_0 + k)} \tag{13}$$

In fact, transmission function $\gamma_i(t)$ is directly dependent on signal settings at each link, i.e., cycle lengths C_i, and offsets θ_i by following relations:

$$\gamma_i(t) = \begin{cases} 0, & \text{if } n.C_i, \leq t - \theta_i < \dfrac{(n+1)C_i,}{2} \\ 1, & \text{if } \dfrac{(n+1)C_i,}{2} \leq t - \theta_i < (n+1)C_i, \end{cases} , n = 0,1,2 \ldots \quad (14)$$

In general, $\boldsymbol{\gamma}(t) = \{\gamma_1(t), \gamma_2(t) \ldots\}$ can also be expressed by:

$$\boldsymbol{\gamma}(t) = \boldsymbol{\gamma}(t, \boldsymbol{C}, \boldsymbol{\theta})$$

where $\boldsymbol{C} = \{C_1, C_2 \ldots\}$, $\boldsymbol{\theta} = \{\theta_1, \theta_2 \ldots\}$ are sets of cycle lengths and offsets on a network, respectively.

Thus, departure flow rate $O_{i,d}(t)$, number of queuing vehicles $Q_i(t)$ and average delay AD are also, implicitly, dependent on cycle length and offsets, or

$$O_{i,d}(t) = O_{i,d}(t, \boldsymbol{C}, \boldsymbol{\theta})$$
$$Q_i(t) = Q_i(t, \boldsymbol{C}, \boldsymbol{\theta})$$
$$AD = AD(\boldsymbol{C}, \boldsymbol{\theta})$$

These implicit relationships will be utilized to find optimal cycle length and offsets to minimize average delay in the following section.

3. INTEGRATION OF DELAY CALCULATION MODEL AND GENETIC ALGORITHM TO FIND OPTIMAL SIGNAL SETTINGS

D'Acierno *et al.* (2013) used a traffic simulation to evaluate delay time in an arterial. The research indicates that delay function, with respect to offsets, is a multi-peak function, i.e., having many local minimum points. With these characteristics, delay function is difficult to be optimized by conventional optimizers because solutions from those are easily trapped in local minimum points. In order to obtain as many as minimum points of delay function, a methodology that can search randomly in various directions is needed, and Genetic Algorithm (GA) has been proved to be an appropriate candidate by various researches (Lee, Abdulhai, Shalaby and Chung, 2005; Girianna and Benekohal, 2004).

Genetic Algorithm (GA) is a searching method imitating the process of natural selection and natural genetics. In this method, objective function is transformed to fitness value, and variables are modeled as individuals. Each individual evolves to produce the next generation. The next generations are combination of a part of genes from the previous ones and new genes produced by genetic operators: cross-over and mutation. Each generation is, then, selected based on the fitness value. Evolutions from one generation to next generation in GA produce individuals in various ranges enhancing the effectiveness of searching for global optimum points. Moreover, GA is simulation-based searching method, i.e., it is not necessary to have an explicit analytical relations among variables-to-be-optimized and objective function, or value of objective function can be calculated by routines using those variables as parameters.

In this minimization problem, average travel delay of network is the objective function, while cycle lengths and offsets are set as variables to be optimized. Offsets are constrained to be less than or equal to respective cycle lengths; cycle lengths and offsets are constrained to be integer to ensure that solutions are applicable in reality. The problem is formulated as:

$$\begin{aligned} \min_{\boldsymbol{C},\boldsymbol{\theta}} \quad & AD(\boldsymbol{C},\boldsymbol{\theta}) \\ \text{subject to} \quad & \boldsymbol{\theta} \le \boldsymbol{C}, \\ & \boldsymbol{\theta} \ge \boldsymbol{0}, \\ & C_i, \theta_i \in \mathbb{Z},\ i = 1, \dots, m. \end{aligned} \tag{15}$$

where: AD is average travel delay time of network resulted from calculation of model described in Section 2; $\boldsymbol{C} = \{C_1, C_2, \dots, C_m\}$ is set of cycle lenghts to be optimized; $\boldsymbol{\theta} = \{\theta_1, 0a_2, \dots, \theta_m\}$ is set of offsets to be optimized; m is total number of signals.

In other word, a set of optimal cycle lengths $C^*$and $\theta^*$for each network are identified as:

$$(C^*, \theta^*) = \quad \arg \min_{\boldsymbol{C},\boldsymbol{\theta}} AD(\boldsymbol{C},\boldsymbol{\theta}) \tag{16}$$

Delay calculation model is manipulated as a module for evaluating fitness values in GA process as shown in Figure 2. The calculation algorithm is listed as follows.

Step 0. Initial signal settings are input

Step 1. Delay is calculated by the model described in Section 2 and used to calculate fitness values

Step 2. The next generations of signal settings are produced by simple GA operators based on fitness values; return to Step 1 until minimum delay is found.

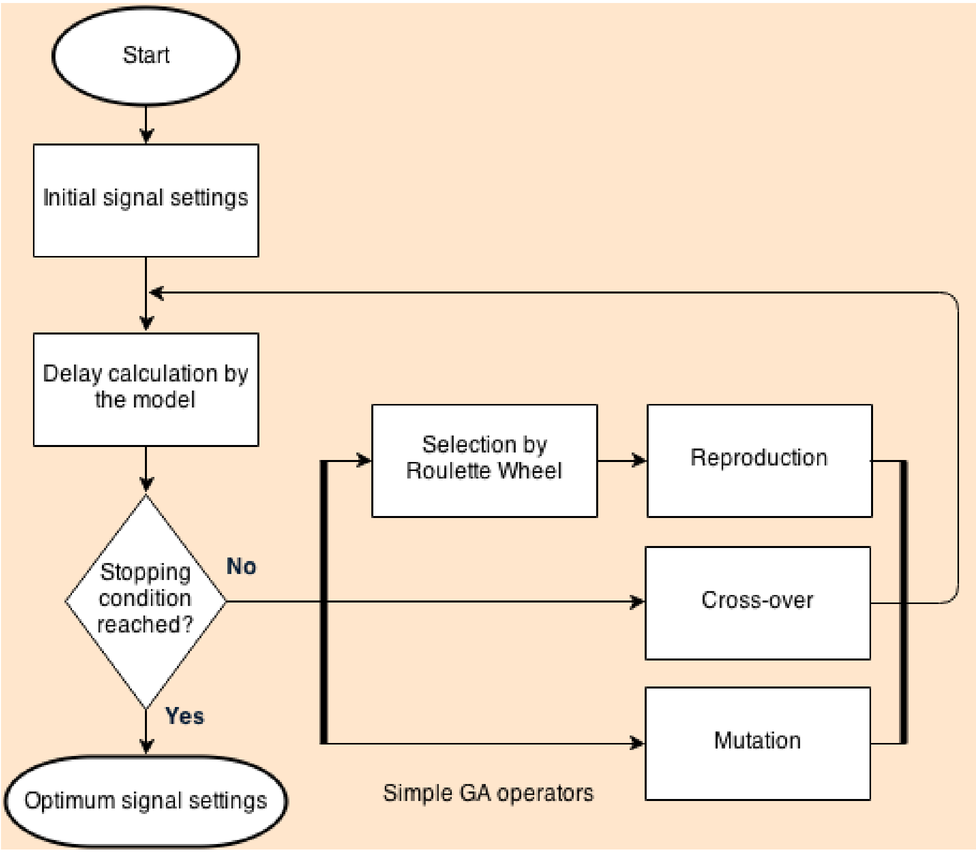


Figure 2. Integration of delay calculation model and GA

4. FORMULATION OF POTENTIAL-FOR-IMPROVEMENT

Potential-for-Improvement (PfI will be used as abbreviation for this phrase) is a new index introduced by this research, aiming for measuring the inefficiency of operations of current infrastructure and signal control of an urban network. It is formulated as the difference between network's performance, in terms of travel delay time, under current situation and that under optimized situation of signal settings.

$$\text{PfI} = \frac{Reduction\ of\ delay\ time\ under\ optimum\ signal\ settings}{Delay\ time\ under\ current\ signal\ settings}$$

Using optimal cycle lengths C^* and optimal offsets θ^* described in Equation (16), PfI can be formulated as:

$$\text{PfI} = \frac{AD(\boldsymbol{C_r}, \boldsymbol{\theta_r}) - AD(\boldsymbol{C}^*, \boldsymbol{\theta}^*)}{AD(\boldsymbol{C_r}, \boldsymbol{\theta_r})} \tag{17}$$

where $\boldsymbol{C_r}$ and $\boldsymbol{\theta_r}$ are actual cycle lengths and offsets obtained from survey.

5. NUMERICAL CALCULATION OF DELAY MODEL

5.1 Parameter Settings

Parameter settings of green-splits, offsets and turning ratios are defined as follows:

1) Green-splits: each node had two green-splits: one for North-South , South-North and the other for East-West, West-East links coming to it. These green-splits were either deduced from the real signals or calculated by real traffic flows. The green-splits deduced from the real signals were used for estimating real situations, while the latter were used for optimization problem.

   Optimized green-splits: from real traffic flows, green-splits were determined by critical flow of each direction. The two critical flows were defined as:

$$\rho_{N,S} = \max\left\{\frac{q_{NS}}{w_{NS}}, \frac{q_{SN}}{w_{SN}}\right\} \tag{18}$$

$$\rho_{W,E} = \max\left\{\frac{q_{WE}}{w_{WE}}, \frac{q_{EW}}{w_{EW}}\right\} \tag{19}$$

   where: q_x,w_x is, respectively, inflow from and number of lanes of direction x, with $x \in \{\text{NS, SN, WE, EW}\}$

   Then, green-splits $g_{N,S}$ and $g_{W,E}$ were calculated by:

$$g_{N,S} = \frac{\rho_{N,S}}{\rho_{N,S} + \rho_{W,E}} \tag{20}$$

$$g_{W,E} = \frac{\rho_{W,E}}{\rho_{N,S} + \rho_{W,E}} \tag{21}$$

2) Offsets: absolute offsets are used in the calculation; they are identified with respect to a selected reference signal.
3) Turning ratios: deterministic values obtained from surveyed data are used.

5.2 Calculation Algorithm

The calculation algorithm has following four steps:

Step 0. Parameters input – Information of network connectivity, i.e., downstream-upstream relations, road's lengths, road's widths, and signal settings for each link are read.

Step 1. Setting initial conditions

Assume that at the beginning of the calculation, the network is empty, i.e., no queuing vehicles in the network, or $Q_i(t=0)=0, \forall i$

Free-space of each link is estimated by: $f_i(t=0)=\frac{l_i w_i}{l_{veh}}$

Step 2. Variables update

Departure flows are calculated by Equation (11), and other variables are updated by Equations (12) – (14).

Step 3. Increase time-step by one unit, return to step 2

5.3 Calibration of GA's parameters

In other to calibrate GA, a simple case was constructed and tested. An arterial road with 4 signals and no turning vehicles as shown in Figure was input to the model to calculate average travel delay. In this arterial, signals were equally spaced by 300 m. Travel speed was set at 10 m/s.

According to theory of Koshi (1975), optimum cycle length for successive signals is defined as:

$$C^* = \frac{T}{n} = \frac{2D}{nV} \tag{22}$$

where:

C^* : optimum cycle length
T : round-trip travel time
n : integer, n odd defines 50% offset situation
n even defines 0% offset situation
D : link's length (m)
V : speed on the whole route (m/s)

Average delay calculated by the model with 0% offset and 50% offset are visualized by graphs shown in Figure. From the graphs, it was quite obvious to infer the optimum cycle length that minimizes the travel delay time for each case of offset. For example, with 0% offset, delay was minimized at $C^*=30$ (s); or with 50% offset delay was minimized at $C^*=20$ (s). These results were agreeable with Equation (22).

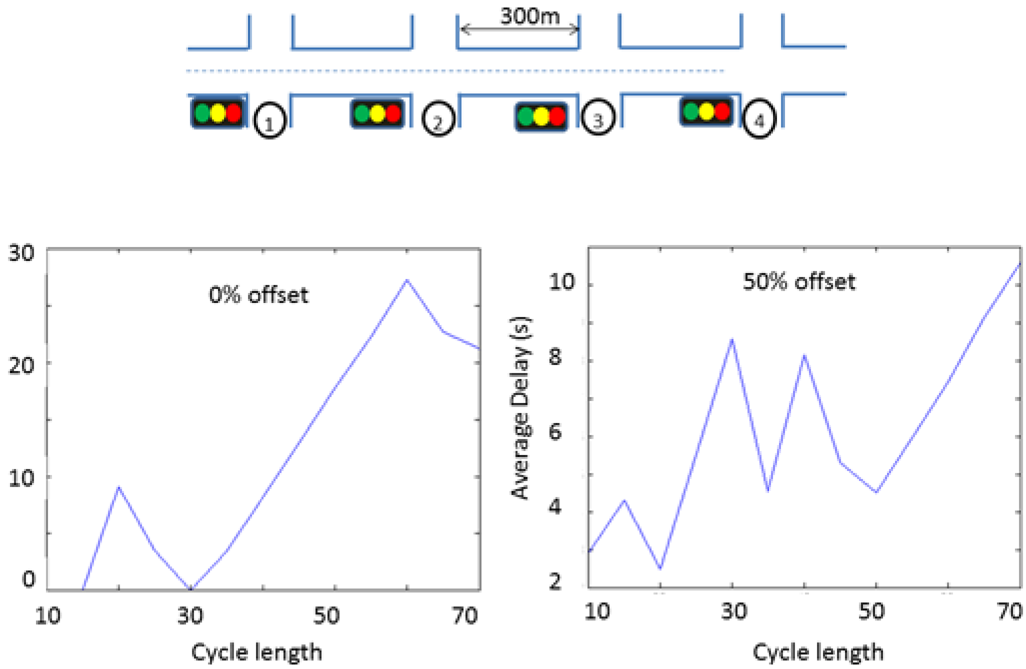


Figure 3. Details of tested arterial and results of average travel delay

Table 2 Calibrated GA parameters

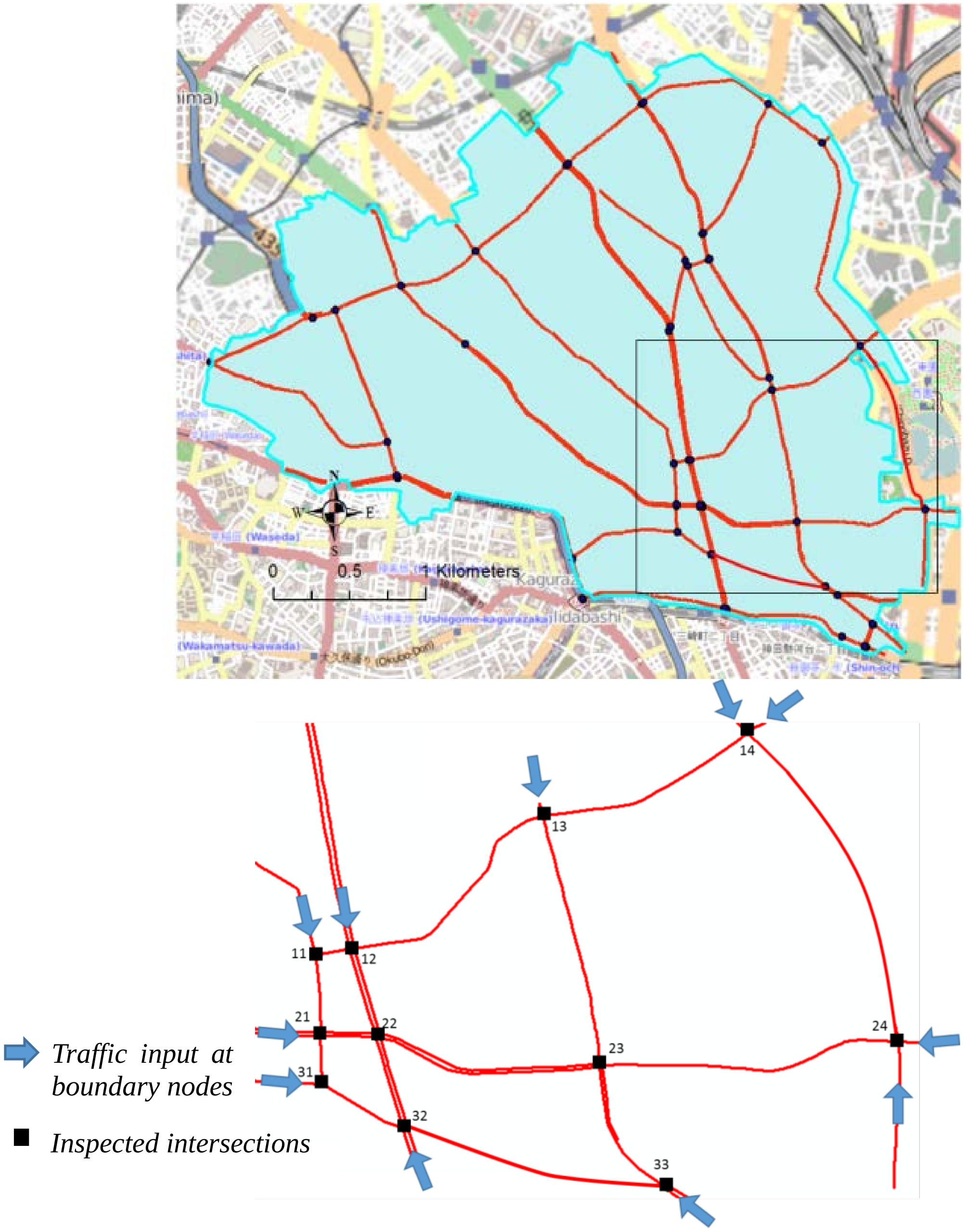
Parameter	Value
Population size	50
Cross-over fraction	0.7
Selection method	Roulette wheel
Max. number of generation	100

Using GA with parameters shown in Table2, the same solutions were obtained, i.e., $C^* = 30$ (s) with 0% offset, and $C^* = 20$ (s); or with 50%. Hence, these parameters would be used as standard parameters in all calculations.

6. APPLICATIONS

6.1 Test Area

Arterial network of Bunkyo-ku, Tokyo (Figure 4) was selected as test area for the module. Its traffic state is almost unsaturated, which is the key situation which PfI should be applied. In addition, simplicity of its intersections’ structure, i.e., no more than 4-leg-intersection and no grade-separations, is suitable for the proposed delay model. Data were collected by video recorders at selected intersections on Tuesday afternoon, from 15:00 - 16:30. A 5-minute-clip was recorded at each intersection. From the clips, average traffic flow (veh/h), actual green-splits and off-sets were measured.



(a)

(b)

Figure 4. Targeted network: (a) location; (b) inspected intersections and network topology

6.2 Validation of Delay Calculation

Model is validated by comparing with real delay measured at field. From the video clips, numbers of queuing vehicles are counted. Diagrams in Figure 5 and Figure 6 show the fluctuation of queuing vehicles over survey period.

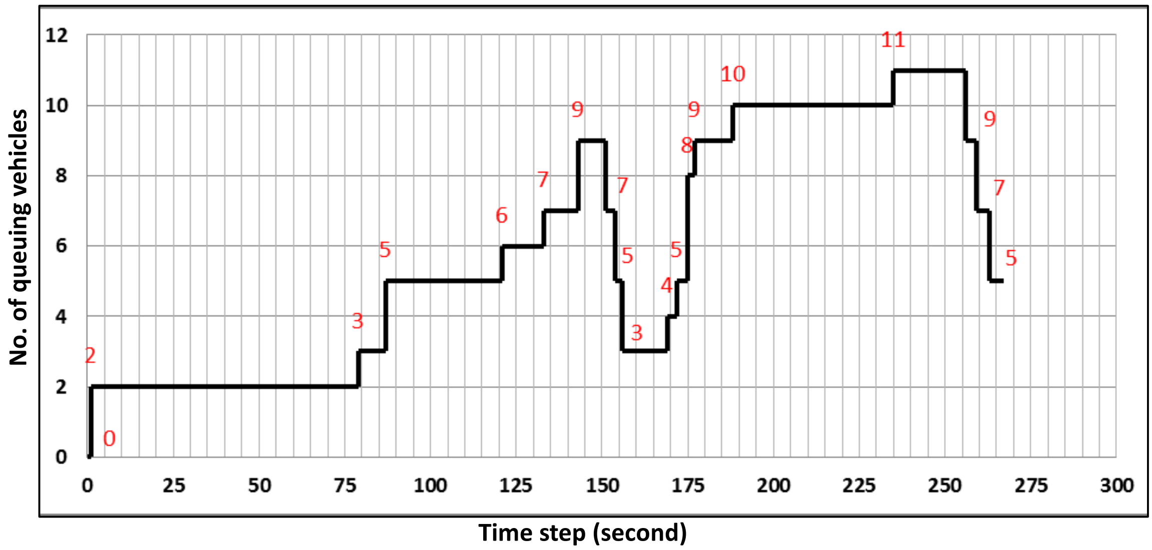


Figure 5. Fluctuation of queuing vehicles on link 21-22 at intersection 22

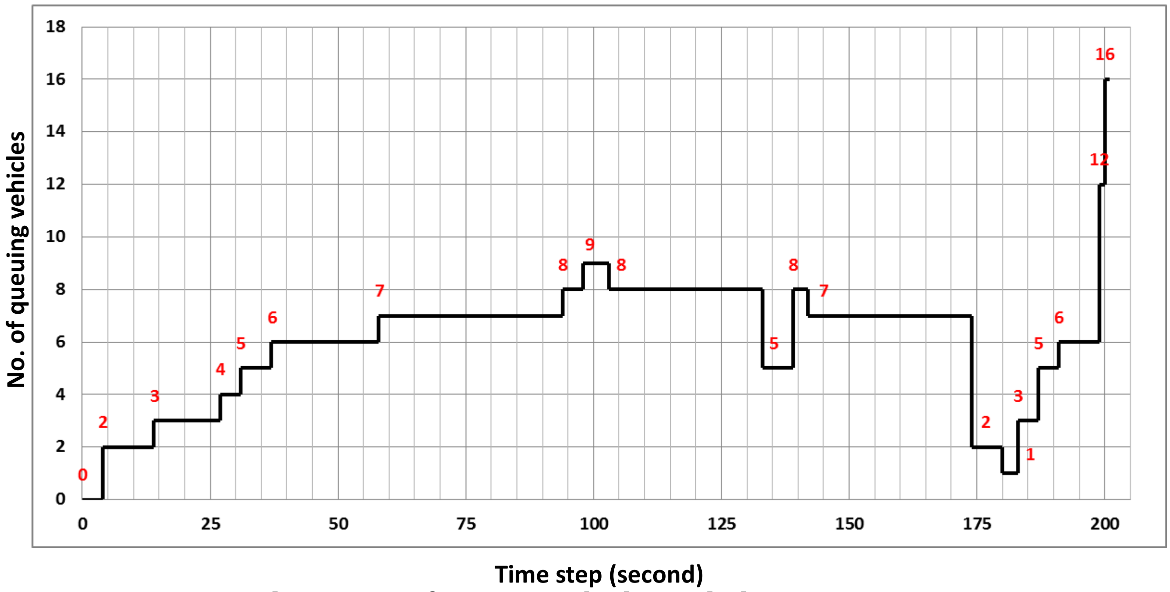


Figure 6. Fluctuation of queuing vehicles on link 12-22 at intersection 22

Total observed delay time is the total time spending by all the queuing vehicles, expressed by following equation:

$$Obs.Total\ Delay = \sum_i (queuing\ at\ period\ i) \times (duration\ of\ period\ i) \tag{23}$$

Observed average delay is calculated by:

$$\text{Obs. AD} = \frac{Obs.Total\ Delay}{Total\ Arriving\ Vehicles} \tag{24}$$

The proposed simple macroscopic urban model is also compared with below Webster's delay formulation:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0.65(\frac{c}{q^2})^{1/3} x^{(2+5\lambda)} \quad (25)$$

where: d is average delay per vehicle (s/veh), c is cycle length (s), q is flow rate (veh/s), λ is proportion of effective green with respect to cycle length, i.e., $\lambda = g/c$ with g is the effective green time, and x is degree of saturation, i.e., $x = q/s$ with s is saturation flow rate.

The field measured results are compared with calculated values in Table 3.

Table 3. Comparison of field measured delay, model based delay and Webster's delay

	Observed average delay	Model simulation	Webster's random delay estimation	Model error
Link 21-22 at intersection 22	31	28	25	-9.7%
Link 12-22 at intersection 22	25.6	24	22	-6.25%

The results indicated that the model has under-estimated the average delay at the intersection by less than 10% and Webster's estimation has larger errors.

6.3 Application 1 – Comparing Effects on Delay Reduction of Optimizing Different Signal Control Parameters

While optimizing and adjusting multiple signal control parameters are complicated task, it is necessary to choose the most appropriate scheme for a network. This application shows that PfI can be used as an index to estimate benefits of different choices.

The network was tested under 3 different scenarios. In Scenario 1, only offsets would be optimized, cycle lengths and green-splits are actual values; in Scenario 2, green-splits and offsets would be optimized, cycle lengths are actual values; in Scenario 3, a common cycle length, offsets and green-splits would be optimized.

Figure 7 shows results of PfI in three scenarios. The results indicated that optimization of different signal control's parameters would give significantly different impact on Potential-for-Improvement. In the first scenario when only offsets were optimized, the Potential-for-Improvement is 7%, in the second one when green-splits and offsets are optimized, PfI increases to 13%, and in the last scenario when all 3 parameters: cycle length, green-splits and offsets are optimized, PfI increases to 40%. Obviously, optimizing all parameters as in Scenario 3 will help reduce the largest amount of delay time. However, to balance between cost and benefit, Scenario 1 and Scenario 2 can also be considered in certain cases. These quantitative results would help logically select the most appropriate scheme of optimization for signal control.

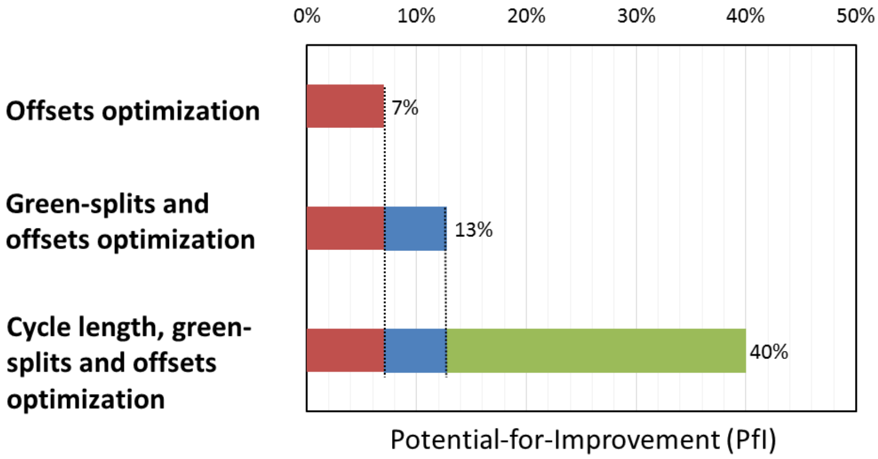


Figure 7. Impact of optimizations of different parameters on PfI

6.4 Application 2 – Using PfI for Evaluating Efforts in Delay Reduction

6.4.1 Sensitivity analysis of network's sizes

In order to utilize PfI as a new index for comparing signal control's strategy among different networks or different situations, it is necessary to identify sufficient size of network for analysis. Apparently, larger networks will give more reliable results but also will increase the cost of calculation. In other to balance the accuracy and computational cost, a sensitivity analysis of network's size was conducted to verify stability of the result with respect to the change of network's size.

Analysis was conducted with three sizes of network 1 km^2, 1.5 km^2 and 2 km^2. Their locations are shown in Figure 8 and the result of PfIs in 5 times of calculation is shown in Figure 9.

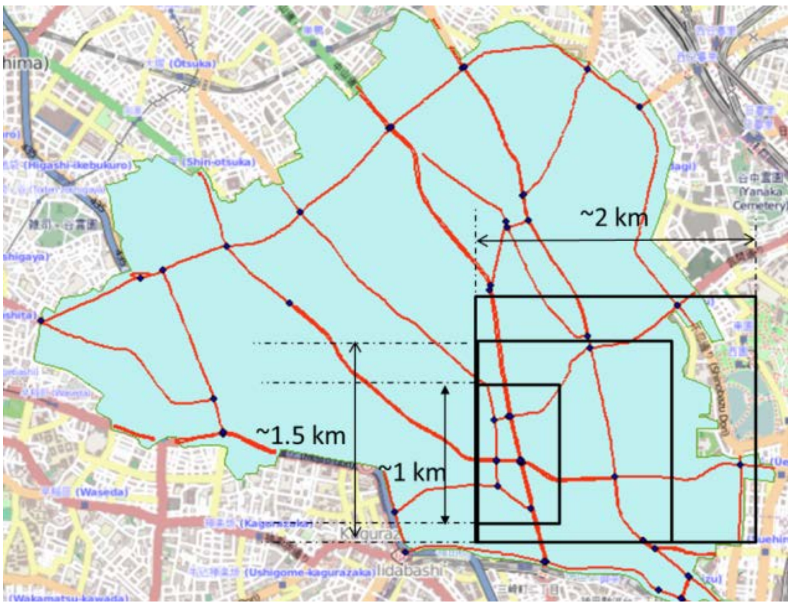


Figure 8. Three sizes of network for sensitivity analysis.

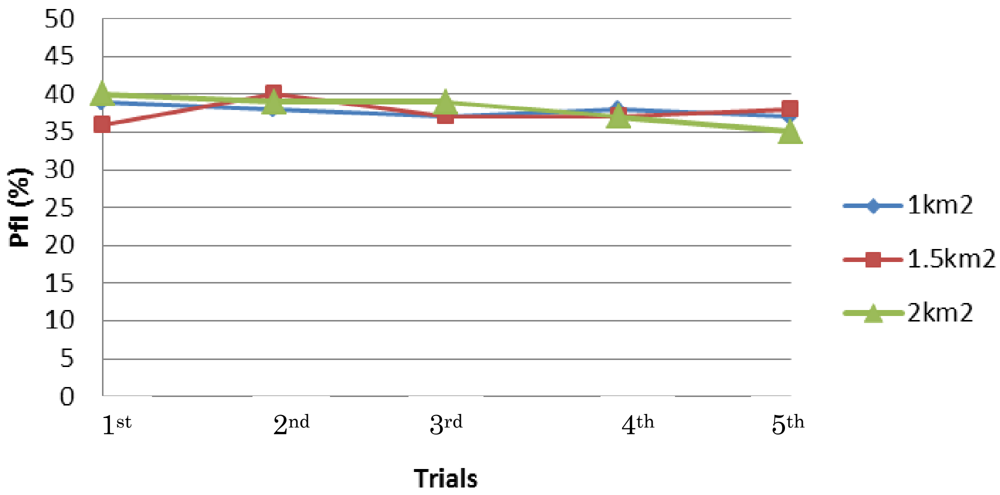


Figure 9. Sensitivity of PfI to network's sizes

The result indicates a fluctuation of no more than 5% occurring in the result of PfI when changing the network's size. Hence, it is possible to conclude the stability of PfI with respect to changes of network's size. In other words, it was able to conclude that analysis of small part of network, 1 km^2 in this case, is sufficient to evaluate PfI of the network as long as signals are controlled by consistent strategies over the entire network.

6.4.2 Comparison of PfI between weekday and weekend

Utilizing the conclusion of sensitivity analysis, PfIs on weekday (Tuesday) and weekend (Sunday) were compared with a 1-km2-area shown in Figure 10. Another survey was conducted on Sunday afternoon, from 12:00 - 13:00, and a 5-minute-clip was recorded at each intersection.

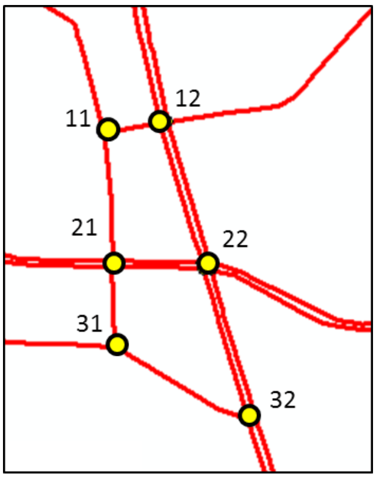


Figure 10. Small network used for comparing signal control on weekend and weekday

Average delay time of real situation on Tuesday and Sunday calculated by the model was 44.8 seconds and 33.9 seconds, respectively. Optimal signal settings – common cycle length and offsets, delay time at optimized situation and PfIs on weekday and weekend are displayed in Table 4 and Table 5.

Table 4. PfIs on weekday

Common cycle (s)	os12	os21	os22	os31	os32	Delay	PfI
58	58	14	25	33	24	27.5	39%
52	0	8	21	20	13	27.6	38%
69	51	57	34	57	66	28.3	37%
60	13	28	26	39	37	27.7	38%

Table 5. PfIs on weekend

Common cycle (s)	os12	os21	os22	os31	os32	Delay	PfI
56	2	14	13	23	21	18.1	47%
67	67	13	21	37	25	19.0	44%
59	51	46	50	55	54	18.6	45%
51	7	9	40	29	6	18.7	45%

※osXY: offset at intersection XY

The result in Table 4 shows that by using suggested common cycle length, green-splits and offsets, a PfI of more than 30% in Bunkyo-ku's network in off-peak hours on weekday can be achieved. Comparing the results shown in Table 4 and Table 5, it can be seen that PfI of the network on weekend is approximately 10% higher than that on weekday, which indicates that there would be more rooms to improve signal controls on weekend. In the other words, it implies that traffic signals on weekend are operated with less effort than those are on weekday. In fact, signal controls are usually biased. Peak hours are mainly focused while off-peak hours, which are much longer, are handled with less concern. With this result, the issue can be clearly recognized, particularly in the case of Japan.

7. CONCLUSIONS

In this research, Potential-for-Improvement (PfI), a new index, was introduced for quantifying the inefficiency of operations of current infrastructure and signal control of an urban network. PfI was calculated by the difference between network's performance, in terms of travel delay time, under current situation and that under a better situation of signal settings. Using PfI, the significant difference when optimizing multiple signal control's parameters can be quantified, which can help select appropriate approach of optimization for a network. Also, PfI helps quantify efforts of delay reduction in a network. By using suggested optimal cycle length, green-splits and offsets, a PfI of more than 30% in Bunkyo-ku's network in off-peak hours was discovered. Moreover, it unveiled that PfI of the network on weekend is 10% higher than that on weekday. These results highlight the inefficiency of signal control in off-peak hours as traffic in off-peak hours, especially on weekend, is being controlled far differently from its best performance from the perspective of travel delay. Thus, more attention should be paid on managing signal control in off-peak hours to offer better service for urban travelers.

By simplifying input data, this methodology provide a handy tool, yet successfully quantified consistent PfIs under various situations. It shows possibility to be applied in evaluating and comparing signal controls' strategies using PfI as an index.

In order to reduce the errors of delay time, further considerations may be needed to improve the model to fully capture the effect of network configurations on it, e.g. effect of road's width on lane changing behaviors or speed variation on links. Also, currently, GA has given a stable PfI for each scenario, but still a convergent optimum signal setting was not reached. In other to provide a clear indication for improvement of traffic control or to precisely define the optimal situation of the network, it would be essential to show a convergent optimum signal setting.

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