Re-Examination of Loss-Time Estimation and Intergreen Time Design for Right-Turn Traffic at Signalized Intersections in Japan

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Abstract: The current loss-time estimation and intergreen time design methods in Japan lack sufficient consideration of the characteristics of right-turn traffic, such as right-turner’s behavior as well as clearing distance and speed under various phases. Utilizing field data, this paper first examined loss-time estimation method under the permissive-and-protected right-turn (PPRT) and protected-only right-turn (PORT) phasing plans. Results showed that the current method is very likely to over-estimate loss time. Two modifications to the current method for the PORT and PPRT phasing plans, respectively, were then proposed to provide more accurate and sophisticated estimation. Meanwhile, intergreen time design method was examined. It was found that the current method tends to generate unnecessarily long all-red times for right-turn traffic as compared with German method. Thus, it is suggested that the applicability of the German method to Japan conditions needs to be investigated to reduce loss time as well as cycle length.

Keywords: Intergreen, Loss time, Right-turn traffic

1. PROBLEM STATEMENT AND OBJECTIVE

Intergreen time is the interval between the end of the green time for one traffic stream and the beginning of the green time for the next. The onset of green conflicting streams is delayed because of intergreen, which leads to loss time. Loss time consists of the sum of the starting response time of the first vehicle and the additional time it took the first several vehicles to discharge (start-up loss), and the time between signal phases during which an intersection is not used by any traffic (clearance loss). It is normally assumed that start-up lost time is approximately equal to the used intergreen time, e.g. 2s. As a result, loss time with a change of phases is regarded as identical to intergreen time between the phases in the planning stage. In Japan, loss time of one cycle \( L \) is roughly determined by equation (1). \( L \) is then used to determine the optimal cycle length given by equation (2) according to the revised edition of Manual on Traffic Signal Control, hereafter called MTSC (JSTE, 2006).

\[
L = \sum_{j} (Y_{j} + AR_{j}) - n
\]  
(1)

Where, \( L \)=loss time of one cycle (s); \( Y \)=yellow time (s); \( AR \)=all-red time (s); \( j \)=a change of phases; \( n \)=number of the change of phases with \( Y \) greater than 4s or \( Y+AR \) greater than 5s.
Note that the compensation to loss time \((n)\) is mainly to account for the extended effective green in the case of fairly long intergreen times.

\[
C = \frac{5 + 1.5L}{1 - \lambda}
\]

(2)

Where, \(C\)=optimal cycle length (s); \(L\)=loss time of one cycle (s); \(\lambda\)=total critical demand ratio.

As illustrated in Figure 1(a), start-up lost time of right-turn traffic under protected-only right-turn (PORT) phasing plan is possibly very small because right-turners are able to predict the start of right-turn green arrow through the previous yellow signal for through and left-turn traffics at the same direction. On the other hand, it has been reported in literature that right-turn vehicles often enter intersections even after the start of the red signal (Kimura et al., 2007; Shikata et al., 2003; Tang and Nakamura, 2007). Therefore, equation (1) may result in an overestimation of loss time of right-turn traffic in the case of PORT.

As illustrated in Figure 1(b), right-turners are able to cross the stop-line and wait inside the intersection to seek suitable gaps in the opposing traffic in the case of permissive-and-protected right-turning (PPRT) phasing plan. In the current signal timing procedure provided in MTSC, a special modification is applied for right-turn traffic under PPRT phasing plan that those vehicles in the waiting area are considered as gained capacity. In other words, that part of right-turn traffic is excluded when calculating demand ratio, and loss time is indirectly compensated by the number of vehicles \(N_s\), \(N_s=1\) veh/cycle for small intersections and \(N_s=2\) for large intersections). For the rest of right-turn traffic, equation (1) is still used for the estimation of loss time. Such a method of assessing loss time, combining equation (1) with the special modification, needs to be scientifically examined because: (1) the first vehicle in the queue can move right after the clear of the last opposite through vehicle, without the need to wait for the onset of right-turn green arrow; (2) the start of the first vehicle before the stop-line is delayed due to the discharge of the queued vehicles inside intersection (Shikata et al., 2003); (3) right-turners often run red lights as stated earlier.

In addition, clearance loss time is largely influenced by intergreen time lengths. Unnecessarily long intergreen times might cause large loss times and further unnecessarily
long cycle lengths according to equation (2), which imposes extraordinary delay on drivers and induces red-light-running (Suzuki et al., 2004). The current intergreen time design method in Japan is relatively conservative as compared to other countries such as Germany, and thus easily produces large intergreen times (see details in Section 5). Simultaneously, it disregards the randomness of traffic, and insufficiently accounts for distinct characteristics of right-turn traffic, e.g., comparably low clearing speed and large clearing distance (Kimura et al., 2007).

Thus, the primary objective of this study is to validate the current loss-time estimation method for right-turn traffic under the PPRT and PORT phases through empirical studies, because a small variation of loss time \( L \) can cause a big variation of optimal cycle length \( C \). Also, this study intends to compare the current intergreen time design method in Japan to that of Germany, and further investigate the applicability of the German method in Japan, in order to reduce clearance loss time as well as extremely long cycle lengths (120s~180s) at signalized intersections in Japan (Tang and Nakamura, 2008a).

The rest of the paper is organized as follows: Section 2 reviews the existing research literature and paves the way for the remaining parts. Section 3 explains data collection and reduction. Utilizing the data, Section 4 validates the current loss-time estimation method for the PPRT and PORT phases, and proposes some modifications to the current method. Subsequently, Section 5 compares the all-red time calculations based on Japanese and German methods, respectively, and discusses the applicability of the German method. Section 6 summarizes the conclusions and proposes future work.

2. LITERATURE REVIEW

Past research has investigated the influence of signal display sequence, phasing and timing on loss time. Bonneson (1993) evaluated driver’s starting response time to the leading left-turn indication. No significant difference among five PPLT (protected-permissive or permissive-protected left turn) signal displays was found. Chris Sheffer et al. (1999) compared start-up lost time between lead and lag protected-only phasing. It was found to be better for the locations with lag phasing than with lead phasing. No differences in start-up lost time were found due to the type of PPLT signal display in Noyce et al. (2000). Studies by Tang and Nakamura (2007 and 2008b) showed that signal display sequence has significant effect on starting response time, and signal timing significantly affects clearance lost time as well. There is also some research done in Japan that particularly looked at loss time of right-turn traffic under different phasing. Shikata et al. (2003) compared start-up loss time under PPRT and PORT phases during saturated periods, and found that it goes up by 0.5s with the increase of one vehicle waiting inside the intersection. The whole yellow signal is often completely used, and part of all-red is sometimes used. Ono et al. (2008a) focused on loss time under PORT phase, and found that the observed total loss-time was quite smaller than the estimated value based on equation (1).

On the other hand, intergreen time design has attracted many research interests as well. Arasan et al. (2006) applied three intergreen time design methods, namely, (1) the probabilistic method, (2) the ITE method, and (3) the German method for the heterogeneous traffic situation in India. It was found that the application of the three methods resulted in varying intergreen intervals for any given set of signal phases, and the intergreen interval calculated by probabilistic method is the highest among them. Easa (1993) proposed a reliability-based approach for intergreen time design, which enables the design of intergreen interval for any desired reliability level. In addition, researchers in Japan have been investigating the applicability of the German intergreen time design method in Japan. A study
by Kimura et al. (2003) concluded that the calculated all-red times based on the Japanese method tend to be considerably long if right-turn traffic is concerned. They suggested the adoption of the German method in Japan, concurrently with countermeasures to force drivers to comply with traffic signals. A similar work was also done by Ono et al. (2008a). Tang and Nakamura (2009) that proposed a stochastic safety estimation method for intergreen intervals that was meant to investigate safety benefits when changing intergreen time values based on the Japanese method to the values based on the German method. They supported that safety and reliability may drop if the German method were adopted by simply modifying values without corresponding supplementary measures, e.g., group-based signal control and camera enforcement.

3. DATA COLLECTION AND PROCESSING

To observe the actual loss time of right-turn traffic under the PPRT and PORT phases, filed surveys were undertaken at two large-scale intersections with high right-turn traffic demand, namely, at Hibiya and Aoyama-ichome, located in Tokyo metropolitan area. As shown in Figure 2, these two intersections have different phasing but similar geometric characteristics as well as identical yellow and all-red times for the subject traffic movements, right-turn traffic of approach I at Hibiya and right-turn traffic of approach III at Aoyama.

The surveys were conducted under good weather conditions in 2007 and 2008, using video cameras from high buildings near the intersections. Three hours of video recording during saturated periods at each site were used for this study. Necessary data were then extracted from the videotapes by a lab-developed software with a resolution of 1/30s, except for geometric parameters. Data processing work was done mainly to obtain right-turn vehicle passing time at the stop-lines and conflict points inside the intersections as indicated in Figure 2, in addition to traffic volumes and signal timing parameters. Passing and arrival time at the stop-lines and conflict points of the conflicting through traffics were also recorded for intergreen time calculations in Section 5.

4. REEXAMINATION OF LOSS-TIME ESTIMATION

4.1. Calculations of the actual start-up and clearance loss times

According to the revised edition of MTSC, only the first several vehicles experience start-up loss time. In this study, the first three vehicles in the queue were considered based on past studies (Shikata et al., 2003; Ono et al., 2008a). Start-up lost time \( L_s \) is thus calculated by equation (3). Clearance lost time \( L_c \) is computed by equation (4).

\[
L_s = \left( \frac{H_1 + H_2 + H_3}{3} - \frac{H_s + \ldots + H_n}{n-3} \right) \times 3
\]

Where, \( H_i \) = time headway of \( i^{th} \) vehicle passing the stop-line in the queue (s); \( n \) = total number of queued vehicles. Note that \( H_1 \) refers to the time period from the onset of the green signal to the passing of the vehicle at stop line of the first queued vehicle before the stopline in the case of PPRT phase.

\[
L_c = Y + AR - T_c
\]
Where, $Y$=yellow time (s); $AR$=all-red time (s); $T_e$=entry time of the last cleared vehicle after the start of intergreen (s). Note that it equals to 0 if a vehicle enters after the end of all-red.

Figure 2. Signal timings and geometric characteristics at the two observed intersections

4.2. Comparison between the observed actual loss time and the estimated loss time

Table 1 presents the calculated and estimated loss times of right-turn traffic movements at the two subject intersections based on the above conventional method and the method proposed later. $L_s$ and $L_c$ were -0.4s and 3.27s respectively at Hibiya intersection, while -2.86 s for $L_s$ and 2.87s for $L_c$ were observed at Aoyama-Ichome. As a result, the actual total loss time at
Hibiya intersection was 2.87s. At the Aoyama-Ichome intersection, it was 0.01s without considering the compensation gained from the vehicles in the waiting area. However, if the current method, i.e. equation (1), were adopted, the estimated total loss time would be 4.00s for both of the two intersections because the yellow and all-red were 2s and 3s. It is clear in the table that the current method considerably overestimated loss time both in the cases of PORT and PPRT.

<table>
<thead>
<tr>
<th></th>
<th>M($L_s$), s</th>
<th>M($L_s'$), s</th>
<th>E($L_s$), s</th>
<th>M($L_e$), s</th>
<th>M($L_e'$), s</th>
<th>E($L_e$), s</th>
<th>E($L_e'$), s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hibiya</td>
<td>-0.40 (21)</td>
<td>/</td>
<td>/</td>
<td>3.27(24)</td>
<td>2.87</td>
<td>4.00</td>
<td>/</td>
</tr>
<tr>
<td>Aoyama</td>
<td>-2.86(15)</td>
<td>-0.27(23)</td>
<td>-2.40</td>
<td>2.87(21)</td>
<td>0.01</td>
<td>4.00</td>
<td>0.37</td>
</tr>
</tbody>
</table>

(Note: M()=measured; E()=estimated; E($L_e$)=estimated loss time by the conventional method; E($L_e'$)=estimated loss time by the proposed method; (#)=valid sample cycles)

The major reason for the overestimation at Hibiya is that start-up loss time ($L_s$), -0.40s, was much smaller than the used intergreen which was 1.75s. $L_s$ remarkably dropped as the first vehicle started to move before the start of the green arrow signal, i.e. during the yellow interval for through and left-turn traffics. It implies that the simple assumption of treating start-up loss time equal to the used intergreen may not be always correct and therefore needs to be modified according to phase-switching patterns. The overestimation at Aoyama-Ichome could be mostly attributed to the observation that right-turners could immediately move forward after the opposing traffic becomes apparently clear, instead of waiting for the onset of the right-turn green arrow. As there was 4s of yellow signal before the right-turn green arrow, a large part of the yellow signal must have been used by right-turn traffic. On the other hand, the measured start-up lost time of the vehicles before the stop-line was 2.27s, which was significantly lower than the -0.40s measured $L_s$ at Hibiya. It indicates that the start of the first vehicle before the stop-line was delayed due to the waiting vehicles ahead of it, an observation which is supported by a research on the subject (Shikata et al., 2003).

Moreover, it was found that the used intergreens at the two intersections, 1.75s and 2.13s, seemed to be very close to the yellow interval, 2s. It indicates that the compensation to loss time, i.e. $n$ in equation (1), may not be necessary in some cases even when the total intergreen time lengths are fairly long, e.g., greater than 5s. More deep analyses on drivers’ behavior with the change of phases should be performed in order to properly determine under what situations and how much loss time should be compensated.

As far as start-up loss time ($L_s$) is concerned, to overcome the drawbacks of the current method, a possible modification for the PORT case could be to supplement certain amounts of time to $L_s$ whenever there is a yellow interval signal displayed before the green arrow. The amount of supplemented time to $L_s$ should be dependent on the lengths of intergreen times before the right-turn green arrow, as well as the arrival time of the last cleared opposite through vehicles at the conflict points. To determine it, widespread observations and empirical studies in Japan are required. For simplicity, 1~1.5s might be suitable based on past research (Tang and Nakamura, 2007) and policy documents (AASHTO, 2004) which supported that starting response time and start-up loss time with predictable information, e.g., green onset in the case that a red-and-amber signal is displayed before the start of green, are approximately 1~1.5s smaller than those with unpredictable information.

The other modification to the current method for the PPRT case could be to apply a time-based start-up loss time estimation method, instead of simply treating the vehicles inside intersections as gained capacity (vehicle-based method). Figure 3 shows a time-space diagram for deriving $L_s$ in the case of PPRT. Based on that, the vehicles entered during cycle green can be directly considered as shown in equation (5), without the need to use the vehicle-based
concept.

Figure 3. A time-space diagram for deriving start-up lost time in the case of PPRT phase

\[ L_s = L_s' - \frac{d}{v_f} \]  

(5)

Where, \( L_s \) = start-up loss time regarding stop-line as reference (s); \( L_s' \) = start-up lost time regarding stop-bar of waiting area as reference (s); \( d \) = distance between the stop-line and stop bar of waiting area (m); \( v_f \) = free flow speed (m/s).

To validate the proposed method, \( d \) and \( v_f \) at Aoyama-Ichome intersection were measured and found to be 15.5m and 7.50m/s respectively. The measured \( L_s' \) at the intersection was 0.27s. As can be seen in Table 1, the calculated \( L_s \) was 2.40s, which is quite close to the measured value, 2.86s, based on the time-space diagram. On the other hand, if the current method were adopted, gained capacity (\( N_s \)) would be determined as 2 veh/cycle owing to the scale of Aoyama-Ichome intersection. Thus, the compensation to loss time would be 4s, assuming a saturation headway of 2s. As \( L \) estimated by the current method, \( E (L) \) in Table 1, is equal to 4s, the actually assessed loss time becomes 0s (4s-4s), almost the same as the measured value, namely, 0.01s. It seems that the current loss-time estimation method along with the modification of \( N_s \) could be accurate enough. However, in practice the main factor to determine intersection scale is the number of approach lanes instead of the distance \( d \). MTSC does not provide a specific way to determine intersection scale and leaves the decision to traffic engineers. Due to that, large errors in the estimation of loss time may take place if wrong decisions on intersection scale were made, i.e. \( N_s=1 \) or \( N_s=2 \). However, the proposed method is able to straightforwardly and sophisticatedly assess loss time according to \( d \) and \( v_f \), eliminating the additional decision on the value of \( N_s \).

5. REEXAMINATION OF INTERGREEN TIME DESIGN

5.1. The difference in intergreen time design between Japan and Germany
The intergreen time calculation method in Japan is notably different from that in Germany. In both of the two nations, the calculation of yellow time is based on the dilemma zone theory. However, when determining all-red time, stop-line is regarded as a reference for vehicle clearance in Japan, while clearance is defined as the clearing vehicle completely passes conflict area in Germany, according to the Guidelines for Traffic Control, RiLSA (FGSV, 2003), as illustrated in Figure 4. All-red times are thus computed by equations (6) and (7), respectively.

![Figure 4. Difference in all-red time calculation between Japan and Germany](image)

\[ AR = \frac{W}{V_c} \]  
(Japan) \hspace{1cm} (6)

\[ AR = t_c - t_e \]  
(Germany) \hspace{1cm} (7)

Where, \( AR \)=all-red clearance interval (s); \( W \)=distance between the opposite stop-lines (m); \( V_c \)=clearing speed of the last discharged vehicle in the previous phase (m/s); \( t_e \)=clearing time of the last discharged vehicle in the previous phase (s); \( t_c \)=entering time of the first discharged vehicle in the next phase (s).

Note that the last vehicle’s clearing can be considered as cruise process with a uniform speed. However, the first vehicle’s entering can be treated as having a starting response time right after the onset of green, and an acceleration period till reaching the conflict point. Also, starting response time can be considered as zero if the first vehicle makes a hurried start before the onset of green. Thus, \( t_e \) and \( t_c \) in German method can also be expressed by equations (8) ~ (10). The difference as explained above produces comparably long all-red times in Japan provided identical conditions. Knowing this difference, the German concept has been already introduced in the revised MTSC. However, it has not yet been widely applied in practice so far.

\[ t_c = \frac{S_c + W_c + L}{V_c} \]  
(8)

Where, \( S_c \)=clearing distance (m); \( W_c \)=width of conflicting area (m); \( L \)=vehicle length (m).

\[ t_e = \tau + \sqrt{\frac{2S_e}{a}} \]  
(Non-hurry start case) \hspace{1cm} (9)
Where, \( S_e \) = entering distance (m); \( \tau \) = starting response time (s); \( a \) = acceleration rare (m/s\(^2\)).

\[
t_e = \frac{-V_0 + \sqrt{V_0^2 + 2aS_e}}{a}
\]

(Hurry start case) \( (10) \)

Where, \( V_0 \) = initial speed of the first entering vehicle in the case of hurried start (s).

### 5.2. Comparison between the calculated all-red times of Japanese and German methods

Using the reduced data from the two observed intersections, which were composed mainly of clearing and entering time \((t_c\) and \(t_e\)), all-red times were calculated based on Japanese and German methods, respectively. Note that \( t_e \) refers to the clearing time from conflict point when adopting the German method, while it refers to the clearing time from stop-line at the exit approach, i.e. \( W/V_c \), when adopting the Japanese method. Considering the time to reach conflict points, through traffic movements of approach IV and II at Hibiya and Aoyama-Ichome, respectively, were identified as the critical conflicting movements with the subject right-turn traffic movements. For each intersection, there were three critical conflict points (CP) totally, labeled as CP1, CP2 and CP3 by the lane number of through traffic movement; \( t_c \) and \( t_e \) were measured by each conflict point and stop-line at the exit approach, and presented in Table 2 together with valid sample vehicles.

<table>
<thead>
<tr>
<th>CP</th>
<th>CP1</th>
<th>CP2</th>
<th>CP3</th>
<th>Stop-line</th>
<th>CP1</th>
<th>CP2</th>
<th>CP3</th>
<th>Stop-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_c ) (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5%</td>
<td>2.65</td>
<td>3.01</td>
<td>3.51</td>
<td>6.12</td>
<td>2.77</td>
<td>3.27</td>
<td>3.67</td>
<td>7.24</td>
</tr>
<tr>
<td>15%</td>
<td>3.24</td>
<td>3.70</td>
<td>4.23</td>
<td>6.69</td>
<td>3.00</td>
<td>3.47</td>
<td>4.01</td>
<td>7.56</td>
</tr>
<tr>
<td>50%</td>
<td>4.02</td>
<td>4.63</td>
<td>5.03</td>
<td>7.60</td>
<td>3.38</td>
<td>3.88</td>
<td>4.43</td>
<td>7.90</td>
</tr>
<tr>
<td>85%</td>
<td>4.91</td>
<td>5.50</td>
<td>5.97</td>
<td>8.60</td>
<td>4.20</td>
<td>4.92</td>
<td>5.44</td>
<td>8.40</td>
</tr>
<tr>
<td>95%</td>
<td>5.59</td>
<td>6.18</td>
<td>6.65</td>
<td>9.07</td>
<td>5.34</td>
<td>5.95</td>
<td>6.45</td>
<td>9.18</td>
</tr>
<tr>
<td>#</td>
<td>55</td>
<td>47</td>
<td>42</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| \( t_e \) (s) |     |     |     |           |     |     |     |           |
| 5%     | 3.02| 2.74| 2.68| /         | 3.45| 3.14| 3.23| /         |
| 15%    | 3.29| 3.25| 3.12| /         | 3.53| 3.64| 3.42| /         |
| 50%    | 3.81| 3.69| 3.62| /         | 4.04| 4.00| 3.97| /         |
| 85%    | 4.75| 4.51| 4.61| /         | 4.61| 4.72| 4.45| /         |
| 95%    | 5.74| 4.98| 4.96| /         | 4.86| 5.77| 4.97| /         |
| #      | 55  | 31  | 42  | 39        |

It was found that the most critical CP was CP3 at both of the intersections, the conflict point correspondent to the most inside through lane. Figure 5 then presents the calculated all-red times based on the German method at Aoyama-Ichome and Hibiya, with different percentile values of \( t_c \) and \( t_e \) at CP3. For Aoyama-Ichome intersection, it is evident that the used all-red time in reality indicated in the figure, 3s, is almost equal to the value correspondent to the extreme case, 95 percentile of \( t_c \) and 5 percentile of \( t_e \) at Aoyama intersection. If 50 percentile values of \( t_c \) and \( t_e \) were applied, the calculated all-red is 0.5s. To ensure safety, a relatively high percentile value of \( t_c \) and low percentile value of \( t_e \) should be used. If 85 percentile value of \( t_c \) and 15 percentile value of \( t_e \) recommended by Kimura et al. (2003) and Ono et al. (2008a) were applied, the calculated all-red becomes 2s. In the case of Hibiya intersection, the used all-red time was still greater than most of the values calculated based on the German method. The value correspondent to the top case was 4s, while it was
2.8s for 85 percentile value of $t_c$, for 15 percentile value of $t_e$, and 1.4s for 50 percentile values of $t_c$ and $t_e$.

Figure 5. Calculated all-red times based on different percentile values of clearing time ($t_c$) and entering time ($t_e$) at CP3 and the German method

In Germany, average values of $t_c$ and $t_e$ are normally recommended in the calculation of intergreen in the current practice (FGSV, 2003). Following this principle, all-red time can be reduced by almost 2.5s at Aoyama-Ichome intersection and 1.6s at Hibiya intersection. Assuming that the same reduction could be applied to the other phases and all-red times were fully included in the clearance loss time, 10s and 6s can be reduced from the total loss time within one cycle for Aoyama-Ichome and Hibiya, respectively, which would approximately lead to a 20s-reduction of cycle length according to equation (2). The shortened cycle length could bring a substantial decrease of control delay for drivers (Ono et al., 2008b). Even if the 85 percentile value of $t_c$ and 15 percentile value of $t_e$ were applied, the all-red time at Aoyama-Ichome could still be decreased by 1s.

On the other hand, it deserves mention that the observed percentile values of $t_c$ at stop-line mostly ranged between 6~9s, due to the comparably long clearing distance. They were approximately 1.5 times similar to the $t_c$ at CP3, and 2~3 times similar to the observed all-red, 3s. The findings suggest that the all-red times should at least double even if the lowest percentile value were applied when adopting the Japanese intergreen time design concept presented in equation (6). The reason why 3s was used at the subject intersections could be that the police had adjusted the all-red times according to the German concept since the publication of the revised MTSC, or inaccurate clearing speeds were used for the calculation of all-red times before.

In summary, there is much potential to reduce the all-red times in Japan if a the German method were adopted, by which clearance loss times as well as cycle lengths can be considerably shortened, i.e. mobility benefits can be gained. However, safety must be ensured when decreasing all-red time. As mentioned earlier, a previous study by Tang and Nakamura (2009) indicated that safety as well as reliability may drop if all red times based on the Japanese method were simply changed according to the values based on the German method without supplementary countermeasures. The countermeasures could be near-side signal setting pattern, camera enforcement, and even the application of the more flexible group-based signal control. Therefore, carefully investigating the applicability of the German method is very essential for the current practice in Japan.

6. CONCLUSIONS AND FUTURE WORKS
This study first empirically analyzed loss time of right-turn traffic under PPRT and PORT phasing plans, based on field data collected at two large intersections. The results showed that the current loss-time estimation method used in Japan easily overestimates loss time both in the cases of PPRT and PORT, due to the hurried start of right-turners under such phasing plans. The results also indicated that the start of the vehicles before the stop-line in the case of PPRT was considerably delayed due to the existence of other vehicles in the waiting area, which has been suggested by Shikata et al. (2003). This study thus proposed two modifications to the current method. One is to compensate 1~1.5s to the loss time in the case of PORT when there is a yellow interval displayed before the green arrow. The other is to use a time-based start-up loss-time estimation method, instead of the conventional vehicle-based method. The proposed time-based method has also been demonstrated to be able to directly account for the entered vehicles before the onset of green arrow and thus provide more sophisticated estimation.

Furthermore, the current intergreen time design method in Japan was examined for right-turn traffic by the use of field data. It was found that the current method tends to produce unnecessarily long all-red times as compared to the German method. On the average, 2s could be shortened for the observed right-turn traffic at the subject intersections, by applying the German method and its principle of selecting percentile values of clearing and entering time. Also, the observed clearing times at stop-line ($W/V_c$) were around 1.5 times same as clearing time at the critical conflict point, and 2~3 times similar to the used all-red time. All-red times should at least double even if the lowest percentile value of $W/V_c$ were applied when adopting the Japanese method. Therefore, it is very essential to investigate the applicability of the German method in Japan in order to reduce loss time and extremely long cycle lengths at signalized intersections, partly caused by the unnecessarily long all-red times (Tang and Nakamura, 2008a).

However, this study is only based on the data from two intersections. To validate and reinforce the conclusions presented above, more empirical studies need to be done. The influence of the proposed modifications to loss-time estimation on signal timing parameters needs to be investigated for a variety of traffic conditions. In addition, regardless of Japanese or German intergreen design method, these completely rely on the single values of the input variables, such as clearing speed, $V_c$, and entering acceleration rate, $a$, without considering the variability and correlations of such input variables. However, past studies have suggested that those variables are often random (Easa, 1993; Tang and Nakamura, 2009). Therefore, a stochastic approach for intergreen time design method, which enables to consider the randomness of traffics, needs to be developed in order to design intergreen times more efficiently in terms of capacity and safety. This work is presently being done by the authors.

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