Abstract: The signal change and clearance intervals, more specifically the all-red times, are often set longer than necessary in Japan. Too long all-red times not only increase lost time but also may induce aggressive pass and lead to safety drop. Hence, the objective of this study is to investigate the impacts of intersection geometry, signal control, and traffic conflicts on driver’s start-up behavior during the signal change and clearance intervals. By using extensive field data, stochastic models are developed for estimating the distributions of starting response time (SRT) and acceleration rate of the entering vehicles. A numerical examination is performed to explore the possibility of reducing the length of all-red times when the aforementioned impacts on start-up behavior are incorporated into the calculation procedure. Conclusions support that the minimum required all-red times can be reduced by 1 second.

Key Words: signalized intersection, all-red time, start-up behavior

1. INTRODUCTION

As signalized intersections are usually identified as bottlenecks in terms of safety and efficiency, the design of intersection geometry and signal control requires rather thoughtful treatments. However, the scale of intersection geometry in Japan is often larger than sufficient, due to the current road planning and design philosophy (Tang and Nakamura, 2008). As a result, the signal change and clearance intervals, more specifically the all-red
times, are commonly set longer than necessary at signalized intersections in Japan. A too long all-red time may induce risky behavior of drivers being aware of its abundant length, e.g., aggressive pass and hurry start (Tang and Nakamura, 2009), and meanwhile leads to greater delay due to the rise of lost time. Nevertheless, proper determination of the all-red time is crucial for improved balance of safety and efficiency at signalized intersections.

When designing the all-red time, it is essential to examine the exactly needed time by drivers, while considering the related driver behavior at the change of phases. However, relevant research in this regard is still in a shortage. In particular, the variability of driver behavior associated with intersection geometry and signal control has rarely been investigated so far. Understanding the stochastic character of such driver behavior will enable to accurately predict and estimate the variability of driver behavior during the signal change and clearance intervals, dependent upon intersection geometry and signal control. It also makes possible to determine the exactly required all-red time by drivers.

In view of that, the primary objective of this study is to empirically analyze the impacts of intersection geometry, signal control, and traffic conflicts on start-up behavior of drivers during the signal change and clearance intervals, and model such behavior in a probabilistic way. The second objective of this study is to explore the possibility of shortening the all-red time, while incorporating the above impacts. This research focuses on the through-ahead vehicles released after a protected right-turn (comparable to the left-turn in the United States) phase at typical four-leg signalized intersections. The reason is that permitted-and-protected and protected-only right-turn phasing plans are dominantly applied at four-leg signalized intersections in Japan (Tang et al., 2010), and thus the occurrence likelihood of traffic conflicts as well as conflict severity is significantly high during the subject signal change and clearance intervals.

2. LITERATURE REVIEW

2.1 Design Method of the All-Red Time

It is usual that incompatible traffic movements have to traverse a number of common areas inside the intersection at the change of phases. Such cross-over of incompatible vehicles and/or pedestrians is defined as conflict, and those common areas are defined as conflict points or areas. There are two types of conflicts during the signal change and clearance intervals after a protected right-turn phase indicated by A and B in Figure 1, the analysis subject of this study.

In the figure, the clearing vehicle is defined as the last vehicle that passes the stop-line after the start of the signal change and clearance intervals (the last clearing right-turning vehicle), and the entering vehicle is defined as the first vehicle that enters the intersection (the first entering through-ahead vehicle). \(T_c'\) refers to the stop-line crossing time of the clearing vehicle, regarding the start of all-red as the beginning time. \(T_e'\) refers to the stop-line crossing time of the entering vehicle, regarding the start of green as the beginning time. Travel time of the clearing vehicle from the stop-line to the conflict point is denoted as clearing time \(T_c\), and the same travel time for the entering vehicle is denoted as entering time \(T_e\). Accordingly, the distance between the stop-line and conflict point is defined as clearance distance or entering distance, respectively. A concept of Late Exit Time (LET) is also defined to quantify how late the clearing vehicle exits from the conflict point in this study. It represents the elapsed time from when the all-red time ends up to when the clearing vehicle completely leaves the
conflict point. A positive value translates that the clearing vehicle fails to clear from the conflict point before the start of green for traffic movements on the crossing road, i.e., a late exit (LE).

In Japan, the all-red time is determined by Equation (1), according to the current manual (JSTE, 2006). It is basically identical to the method recommended by the Institute for Transportation Engineers in the United States (i.e., ITE method) (ITE, 1998). In Australia, a pretty similar method is also being adopted (AUSTROADS, 2003).

\[ AR = \frac{W}{V} \]  

(1)

Where, \( W \)=clearance distance [m]; \( V \)=approach speed [m/s].

Conventionally, clearance distance \( W \) is the distance between the opposite stop-lines, in order to account for the conflicts between pedestrians and vehicles. For example, all-red time is calculated as 4.5 second under the condition that the distance between the opposite stop-lines is 50m and the approach speed is 40km/h. However, \( W \) can be regarded as the distance between the stop-line and conflict point for the subject signal change and clearance intervals of this study, since such type of conflicts is impossible to occur during that interval. As a result, a smaller all-red time than the one computed by Equation (1) becomes more reasonable and efficient. On the other hand, an even shorter all-red time can be produced by the German method, given by Equation (2) (FGSV, 2003).

\[ I = T_u + T_c - T_e \]  

(2)

Where, \( I \)=length of intergreen times, consisting of yellow, yellow-and-red, and all-red in Germany [s]; \( T_u \)=crossing time [s]; \( T_c \)=clearance time [s]; \( T_e \)=entering time [s].

The first term, \( T_u \), is to account for the crossing time needed by the clearing vehicle to reach the stop-line after the yellow onset. It is usually assumed to be 3s, 4s, or 5s for though-ahead vehicles dependent upon speed limit, and those values are often used as yellow times. The difference of the second and third terms is ordinarily used as the all-red time. Thus, a unique
feature of this method can be recognized that entering time is taken into consideration when
determining the all-red time. Close to the German method, the method in the United Kingdom
accounts for the effects of entering distance in the determination of all-red time (UK
Department of Transport, 2006). A detailed comparison of the current all-red time design
methods across the world was given by Tang and Kuwahara (2009).

2.2 Issues related to the Determination of the All-Red Time

As compared with the Japanese method, the German method that considers entering time is
supposed to be more rational. However, a fundamental hypothesis of the German method is
that the clearing vehicle enters the intersection at the same time as the start of all-red, and the
entering vehicle prepares to move in the mean time of the green onset. It neglects the variance
of stop-line crossing time of the clearing and entering vehicles, indicated by \( T_c' \) and \( T_e' \) in
Figure 1. Hence, safety is not ensured in the case that the clearing vehicle runs a red light
and/or the entering vehicle moves into the intersection earlier than the onset of green. In this
regard, the Japanese method is able to provide additional clearing time and thus helps to
reduce risk under that kind of situations, which is however not always good.

Overall, stop-line crossing behavior of the clearing and entering vehicles seems to be affected
by intersection geometry and length of the all-red time. It is thus essential to incorporate the
effects when designing the all-red time. Particularly, starting response time of the entering
vehicle \( SRT \) in Figure 1, a portion of \( T_e' \), is influenced by exit time of the clearing vehicle
from the conflict point. Thus, it is understandable that the required all-red time varies by
whether or not those impacts are incorporated into the calculation procedure of all-red time.

2.3 Past Research Related to the All-Red Time

The necessity of accounting for stop-line crossing time and its variance when determining the
all-red time has been suggested in past studies. Easa developed a reliability-based approach
for the design of intergreen time (yellow+all-red), considering the variability of starting
response time, clearance speed, and so on (Easa, 1993). Despite driver behavior during the
signal change and clearance intervals was treated as random in his study, there was few
discussions on the possible influencing factors on driver behavior’s randomness. Also,
Wolfermann (2010) stated that it is important for the determination of the signal change and
clearance intervals to incorporate stop-line crossing time of the clearing and entering vehicles,
\( T_c' \) and \( T_e' \), and reduce their uncertainty. However, little empirical evidence on the causes of
driver behavior’s random character was provided in his study.

Meanwhile, the effects of all-red time on red-light-running (RLR) behavior have gained
extensive research attentions. Retting et al. (1997) studied the effects of signal timing design
on red light compliance as a result of an increase in change intervals to values recommended
by the Institute of Transportation Engineers (ITE). The study showed that increasing the
length of the yellow time following the ITE recommendations significantly decreased the
chance of RLR, and the length of the all-red interval did not seem to affect RLR. Schattler et
al. (2003) examined driver behavior at the test sites where the change and clearance intervals
have been re-calculated according to ITE guidelines, and at the control sites. The RLR at the
test and control sites didn’t exhibit a significant difference. Datta et al. (2003) compared the
red light violation characteristics of intersections with all-red interval and those without all-
red intervals. They supported that significantly lower red light violations and an extraordinary
reduction in right-angle and injury at the intersections with all-red intervals.

Furthermore, the impacts of aggressive pass of the clearing vehicle on start-up behavior of the
entering vehicle have been implied by many researchers, e.g., Tang and Nakamura (2009), Schattler et al. (2003), Schattler and Datta (2004), Mori and Mitsui (2005), and Sasaki et al. (2009). However, the relationship between the impacts and intersection geometry, the all-red time, and other factors was not sufficiently investigated in their studies.

### 2.4 The Objective of This Study

In summary, the impacts of intersection geometry, the all-red time, and late exit on the stop-line crossing behavior have not been implicitly addressed in the existing research. Hence, the primary objective of this study is to empirically analyze and stochastically model start-up behavior of the entering vehicle, while concerning those impacts. Furthermore, this study aims at understanding the relationship between starting response time and acceleration rate as well as entering time, and numerically examining the exactly required all-red times when those impacts and relationships are incorporated in the calculation procedure of all-red time.

### 3. SITE DESCRIPTIONS AND DATA COLLECTIONS

#### 3.1 Outline of the Observed Intersections

In total, 17 approaches at 6 intersections located in Nagoya City, Japan were selected and observed to collect traffic signal control parameters and driver behavior utilizing video cameras. In order to cover various traffic conditions, the selected intersections are distinct in terms of signal control and geometric design. Table 1 outlines the subject approaches and intersections, among which Atsuta-jingu intersection was operated under a dual-lagging protected-only right-turn phasing plan, and the other intersections were operated under a permitted-and-protected right-turn phasing plan (Tang et al., 2010). The intergreen time \((Y + AR)\) here is inserted after the end of the protected right-turn phase. As noted from this

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**Table 1 Outline of the observed intersections**

<table>
<thead>
<tr>
<th>Intersection</th>
<th>App.</th>
<th># of lanes</th>
<th>Intersection size(^{(1)}), [m]</th>
<th>Setback of the stop-line(^{(2)}), [m]</th>
<th>Cycle length, [s]</th>
<th>(Y^{(3)}), [s]</th>
<th>(AR^{(4)}), [s]</th>
<th>Survey time</th>
<th>Sample size(^{(5)}), [veh]</th>
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</thead>
<tbody>
<tr>
<td>Hiroji 1</td>
<td>NB</td>
<td>2</td>
<td>49.6</td>
<td>16.5</td>
<td>120</td>
<td>3</td>
<td>2010/2/24</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>3</td>
<td>38.9</td>
<td>15.5</td>
<td>(9:00~11:00)</td>
<td>4</td>
<td>7:00-10:00</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EB</td>
<td>3</td>
<td>52.8</td>
<td>13.6</td>
<td></td>
<td>5</td>
<td>2008/6/27</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>7:30-11:00</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Sunadabashi</td>
<td>NB</td>
<td>3</td>
<td>37.0</td>
<td>12.9</td>
<td>120~150</td>
<td>5</td>
<td>2008/6/27</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EB</td>
<td>3</td>
<td>52.8</td>
<td>13.6</td>
<td></td>
<td>4</td>
<td>7:30-11:00</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Suemoridori</td>
<td>SB</td>
<td>3</td>
<td>60.4</td>
<td>19.5</td>
<td>140</td>
<td>2</td>
<td>2008/11/18</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>3</td>
<td>13.8</td>
<td>59</td>
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<td>5</td>
<td>9:00-12:00</td>
<td>59</td>
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</tr>
<tr>
<td></td>
<td>WB</td>
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<td>18.0</td>
<td>45</td>
<td></td>
<td>5</td>
<td>2009/10/13</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EB</td>
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<td>88</td>
<td></td>
<td>5</td>
<td>7:30-10:20</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>Taikoudori 3</td>
<td>SB</td>
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<td>2008/1/18</td>
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<td>NB</td>
<td>4</td>
<td>23.3</td>
<td>2008/12/30</td>
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<td>9:00-12:30</td>
<td>78</td>
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<tr>
<td>Nishiohsu</td>
<td>SB</td>
<td>5</td>
<td>75.6</td>
<td>30.2</td>
<td>160</td>
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<td>NB</td>
<td>5</td>
<td>8.1</td>
<td>2009/7/21</td>
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<td>7:00-10:00</td>
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</tr>
<tr>
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<td>EB</td>
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<td>25.3</td>
<td>5</td>
<td></td>
<td>5</td>
<td>7:00-10:00</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Atsuta-jingu</td>
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<td>5</td>
<td>50.4</td>
<td>9.4</td>
<td>153~160</td>
<td>3</td>
<td>2009/7/21</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>5</td>
<td>8.1</td>
<td>7:00-10:00</td>
<td></td>
<td>5</td>
<td>2009/7/21</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>4</td>
<td>9.0</td>
<td>7:00-10:00</td>
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<td>5</td>
<td>2009/7/21</td>
<td>70</td>
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<tr>
<td></td>
<td>EB</td>
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<td>8.7</td>
<td>7:00-10:00</td>
<td></td>
<td>5</td>
<td>2009/7/21</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

Note: (1) the distance between the opposite stop-lines; (2) the distance between the stop-line and crosswalk’s edge of the crossing road; (3) yellow time; (4) all-red time; (5) number of through-ahead vehicles used for the analysis of start-up behavior.

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3. SITE DESCRIPTIONS AND DATA COLLECTIONS

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table, most of the intersections have long all-red time from 4 to 5 s, and the all-red time is set 5 s even at such a relatively small size intersection as Sunadabashi. Video cameras were placed at high buildings nearby the subject intersections, and finally at least three hours of video survey was successfully conducted at each intersection.

3.2 Data Reduction for the Analysis of Start-up Behavior

Necessary information regarding traffic operation and driver behavior was extracted from the video files, by the use of an image processing software developed by the authors (Suzuki and Nakamura, 2006). Vehicle trajectories captured by different video cameras were firstly synchronized and integrated, and Kalman smoothing technique was then used to reduce the measurement errors of coordinates and calibrate the vehicle trajectories. Driver behavior data for the clearing vehicle includes the crossing time at the stop-line and conflict point, the clearance distance, and late exit time (LET) as defined earlier in Figure 1. As for the entering vehicle, starting response time (SRT), crossing time at the stop-line and conflict point, starting position, and the entering distance were measured. SRT is the elapsed time from the green onset to the start of the entering vehicle’s move, and a negative value represents that the entering vehicle has already started to move before the onset of green, i.e., a hurry start. Meanwhile, the vehicles with SRTs greater than 5s or less than -5s were excluded from the analysis, and the vehicles with a starting position far away from the stop-line as well. Figure 2 shows an interface of the image processing software used in this study, George 3.3, and may provide the readers with ideas on how the above parameters were collected from the video files.

Figure 2 The image-processing software used for data reduction in this study, George 3.3

As illustrated in Figure 1, two patterns of conflicts may occur during the signal change and clearance intervals, indicated by A and B respectively. The potential collision position is the right-back of the last right-turning vehicle and the right-front of through-ahead vehicle for conflict pattern A. It is center-back of the right-turning vehicle and center-front of through-ahead vehicle for conflict pattern B. Considering the significance of impacts on the entering
vehicle, only the conflicts with larger LETs were selected in the analysis, among which 56.9% of the valid samples are from conflict pattern A.

4. ANALYSIS OF START-UP BEHAVIOR OF THE ENTERING VEHICLES

4.1 Starting Response Time
As an example, Figure 3 presents the observed distribution of SRTs with and without LE of the clearing vehicle at Sunadabashi and Nishiohsu, where start-up (entering) vehicles are passenger cars only. As shown in the figure, there is a sharp rise nearby the range of 0.7-0.8s that is approximately equal to the perception-and-reaction time of an ordinary human being, $\tau$. Therefore, those SRTs smaller than $\tau$ represent the drivers who started to move earlier than the green onset as they have anticipated the start of green via the prior signal change and clearance intervals, i.e., hurry-start drivers. On the other hand, those SRTs greater than $\tau$ represent the drivers who complied with traffic signals and started to move after the onset of green, i.e., not hurry-start drivers.

At Sunadabashi, a small intersection, the percentage of hurry-start vehicles is remarkable in the case of no LE, around 30%, while it drops to about 15% in the case of LE because of the delayed start for the avoidance of possible collisions. At Nishiohsu, a large intersection, no significant difference in SRT between with and without LE is found. It translates that start-up behavior may not be significantly affected by LE of the clearing vehicle at the large-scale intersections. A possible explanation is that the entering driver is aware of that the clearing driver would have left the conflict point before his or her arrival provided a comparably long entering distance, and thus the entering driver tends to ignore the LE vehicle and starts to move as usual. Similar tendency was also observed at the other intersections.

Based on the results above, the distribution of SRTs was modeled by those influencing factors discussed previously. After a comprehensive review of existing distribution functions and theoretical consideration of SRT’s characteristics, Weibull was eventually chosen to be the distribution of SRTs. As shown in Equation (3), it has three distribution parameters, shape $\alpha$, scale $\beta$, and location $\gamma$. Each of them was estimated by influencing factors such as intersection geometry, signal control, and traffic conditions. More specifically, explanatory variables include the distance between the opposite stop-lines, set-back of the stop-line, the entering distance ($x_{SE}$), late exit time ($x_{LET}$), length of the all-red time ($x_{AR}$), signal phasing plan...
(dummy variable: the permitted-and-protected right-turn phasing plan or the dual-lagging protected-only right-turn phasing plan), and vehicle type (dummy variable, \( x_{\text{heavy}} \): passenger car or heavy vehicle). Based on statistical tests, basic structure of the final model is described by Equation (4a)-(4c), and the estimated coefficients are presented in Table 2.

\[
f(t) = \frac{\alpha}{\beta} (1 + \frac{\gamma}{\beta})^{\beta - 1} \exp(-\frac{t + \gamma}{\beta})
\]

(3)

\[
\alpha = a_0 + a_{\text{heavy}} x_{\text{heavy}}
\]

(4a)

\[
\beta = b_0 + b_{\text{Se}} x_{\text{Se}} + b_{\text{AR}} x_{\text{AR}} + b_{\text{protected-only}} x_{\text{protected-only}}
\]

(4b)

\[
\gamma = c_0 + c_{\text{LET}} x_{\text{LET}}
\]

(4c)

Where, \( a_0, b_0, \) and \( c_0 \)=constants; \( a_{\text{heavy}}, b_{\text{AR}}, b_{\text{protected-only}}, \) and \( c_{\text{LET}} \)=coefficients.

<table>
<thead>
<tr>
<th>Table 2 Estimated coefficients of the SRT estimation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables</td>
</tr>
<tr>
<td>( \alpha )</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>( \beta )</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>( \gamma )</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>( \rho^2 )</td>
</tr>
<tr>
<td>Sample size</td>
</tr>
</tbody>
</table>

Vehicle type was found to significantly affect shape parameter \( \alpha \), and the variance of SRT tends to be bigger for heavy vehicles. In addition, scale parameter \( \beta \) has a negative relationship with the entering distance, which suggests that the larger the entering distance is, more likely the driver makes a hurry start. The entering distance has a stronger relationship with \( \beta \) than intersection size as well as set-back of the stop-line. It implies that the physical distance to the clearing vehicle is a critical influencing factor to start-up behavior of the entering vehicle. Dummy variable, signal phasing plan, was found to be significant as well, and the cumulative distribution curve tends to shift to the right side and its variance increases in the case of the dual-lagging protected-only right-turn phasing plan. This may be explained by that drivers may not be familiar enough with the complex signal displays under such a phasing plan, and thus might experience greater perception-and-reaction time; on the other hand, since its phase sequence is stable, such difference in SRT could be neglected for commuters who have accustomed to the complicated signal displays. Due to the existence of these two driver populations, the variance of SRT became more apparent. It was also found that LET is negatively related to the location parameter \( \gamma \). It indicates that the later the clearing vehicle leaves the conflict point, the greater start-up behavior of the entering vehicle.
is delayed.

In the analysis, most of the observed intersections have a 5s of all-red time for the subject signal change and clearance intervals, and the impacts of the all-red time on SRT could not be specified due to the sample’s bias on relatively long all-red times. The model could be improved in this aspect by including samples of short all-red times in future.

Figure 4 compares the estimated and the observed SRTs. A permitted-and-protected right-turn phasing plan and passenger car for the entering vehicles were assumed when estimating SRT according to the developed models. In order to assess the model accuracy, comparison was conducted within a certain range of value in the entering distance and the late exit time because these values are different among each observed SRT. The area between the two curves in the figure indicates the estimated SRTs, correspondent to LETs in the range of 0~5s and the entering distances in the range of 15~30m. It can be seen that SRT is fairly scattered within the range close to the ordinary perception-and-reaction time, 0.7~0.8s. As discussed earlier, the driver population of SRT > \( \tau \) complies with traffic signals and starts to move after the onset of green. The other driver population of SRT < \( \tau \) may not completely follow traffic signals and decide start-up time according to the position of the clearing vehicles, along with their perception of the green onset time via the prior signal change and clearance intervals for the crossing road. Consequently, they probably begin to move earlier than the start of green. These two driver populations might have distinguished the observed distributions of SRTs, and a single distribution function, Weibull, is not capable of fully describing the mixed SRTs’ variability. The basic model structure needs to be improved at this aspect in future.

4.2 The Relationship between Start-up Time and Acceleration Rate

Figure 5 presents the measured average acceleration rates of the entering vehicles, which was used to analyze driver behavior of the entering vehicles from the starting position to the conflict point. The average acceleration rate was calculated according to the distance and travel time from the starting position to the conflict point. It should be noted that acceleration rate of an individual entering vehicle may not be stable but follow a log-normal distribution, as suggested by Wolfermann (2010). However, considering that arrival time and instantaneous speed at the conflict point are more important information for the analysis of this study, the
fluctuation of acceleration rate of an individual entering vehicle was assumed to be static in this study. Meanwhile, it is worth mentioning that a few extremely large acceleration rates greater than 3m/s² can be found in the figure as well, which could be attributed to the measurement errors.

It is clear in the figure that SRTs of those hurry-start vehicles (SRT<0.7s) descend as the average acceleration rates drop. On the other hand, SRTs of those vehicles complying with traffic signals (SRT>0.7s) mostly distribute within a range of 1~3m/s², and its variance tends to decrease with the rise of LET. Moreover, the average acceleration rates fluctuate remarkably when SRTs are close to the perception-and-reaction time, 0.7s. The fluctuation can be attributed to the existence of the late exit vehicles and the effects of drivers' individual difference.

Being aware of the facts above, SRTs were divided into two populations both described by Normal distribution, by taking 0.7s as the threshold value for further analysis. Distribution parameters were modeled by SRT and LET respectively for the two populations, and the estimated coefficients are presented in Table 3. It was found that mean of the average acceleration rates is negatively associated with SRT for hurry-start drivers, i.e., the population of SRT<0.7s. Also, both mean and variance of the average acceleration rate decrease as LET goes up for not hurry start drivers, i.e., the population of SRT>0.7s. The results suggest that those hurry-start vehicles adjust their acceleration rates based on the onset time of green, while the other vehicles adjust their acceleration rates according to LET of the clearing vehicles.
5. NUMERICAL EXAMINATION OF THE REQUIRED ALL-RED TIME

The calculation method of all-red time in Germany, given in Equation (2), is based on the difference in arrival time of the entering and clearing vehicles at the conflict point, and is unable to account for the randomness of start-up behavior, i.e., the variability of acceleration rates and SRTs among drivers. Two cases, without (Case I) and with (Case II) considering such randomness of start-up behavior, are defined in this study to compare the minimum required all-red times with the calculated values based on the German method. The possibility of reducing length of all-red times by incorporating it in the calculation procedure was also explored through a numerical study. For the sake of conflict severity, only conflict pattern A shown in Figure 1 was included in the following numerical examination.

5.1 Calculation Procedure of the All-Red Time

a) The required all-red time without considering the randomness of start-up behavior

For Case I, the 85th percentile value of the observed clearance time and the 15th percentile value of the observed entering time were used in the calculation of the required minimum all-red time for safety reason, based on Equation (2).

\[ AR_{\text{min}} = T_{c85} - T_{e15} \]  

(5)

Where, \( AR_{\text{min}} \): the minimum required all-red time [s]; \( T_{c85} \): the 85th percentile value of the observed clearance time [s]; \( T_{e15} \): the 15th percentile value of the observed entering time [s].
b) The required all-red time with considering the randomness of start-up behavior

Figure 6 presents the calculation procedure for Case II. In the first step, clearance time ($T_c$) is randomly generated based on the estimated distribution of $T_c$ from empirical results, and predict late exit time (LET) of the clearing vehicle, while assuming an initial value of all-red time ($AR$) as zero. SRT is then probabilistically determined in terms of the predicted LET and the entering distance ($S_e$) based on Table 2. Afterwards, the model presented in Table 3 is adopted to decide the average acceleration rate ($a$) and compute entering time ($T_e$) based on Equation (6). The distribution of $T_e$ can be estimated by repeating the previous steps many times (5,000 runs in this study), and the 15th percentile value of $T_e$ is finally used to calculate the minimum required all-red time according to Equation (5). In general, the interaction between the clearing and entering vehicles was taken into consideration when calculating the all-red time in Case II.

$$T_e = \sqrt{\frac{2S_e}{a}}$$

Where, $T_e$: entering time [s], $S_e$: entering distance [m], and $a$: acceleration rate [m/s²].

5.2 Numerical Results

Following the above procedure, the calculated all-red times for Case I and Case II respectively are presented in Figure 7. As significant sample size is essential when estimating the percentile values of $T_c$ and $T_e$, the figure only presents the comparison results at the subject approaches with enough sample sizes. It is shown that the calculated all-red times for Case II are appropriately 1s shorter than those for Case I at all the approaches. At the east-bound (EB) approach of Atsutajingu intersection, the difference between Case I and Case II is close to 0.9s, which is likely due to the relatively small clearance time and late exit time (LET) at the subject approach.
6. CONCLUSIONS AND FUTURE WORKS

Taking the through-ahead vehicles released after a protected right-turn phase as the study subject, this paper empirically investigated influencing factors on start-up behavior of drivers during the signal change and clearance intervals, and further developed a probabilistic estimation model for such behavior that accounts for the interaction between the clearing and entering vehicles. Results showed that starting response time of the entering vehicle is strongly related to late exit time of the clearing vehicle, and however the relationship becomes weak when the entering distance is comparably long. In addition, the calculated all-red times based on the German method could be reduced by 1 second, if incorporating the interaction between the clearing and entering vehicles into the calculation procedure of all-red time.

The impacts of the all-red time on start-up behavior were unable to be specified, due to the limitation of the observed approaches mostly with the same length of all-red, 5s. In future, those intersections with relatively short all-red times will be included in the observation so as to improve the model with the increased sample size. Moreover, in the presented study, clearance time is purely based on the empirical results, and a model interpreting stop-line crossing behavior of the clearing vehicle, e.g., aggressive pass, remains absent. Thus, the relationship between the stop/pass choice behavior and clearance time at the change of phases demands to be further analyzed. At present, a vehicle trajectory estimation model is being developed by the authors (Suzuki et al., 2009), which is able to account for the variability of conflict point’s positions. Integrating the above models into the presented model will enable the development of a more quantitative evaluation method for both efficiency and safety during the signal change and clearance intervals at signalized intersections.

Finally, it deserves to mention that the results presented in this paper not only provide us with more insights into more rational all-red time design, but also allow for the development of more powerful microscopic simulation models for the purpose of safety evaluation. Since the models developed in this paper looked into the interaction mechanism between the clearing
and entering vehicles at the change of phases, and are thus also transferable to other countries.

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