Analysis of Avoid Entering Dilemma Zone by Acquiring Information on Signal Change Timing

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Abstract: Road intersections are accident-prone locations for traffic. To avoid accidents in the vicinity of intersections, vehicles should avoid entering dilemma zone. In this paper, a model formula was compiled that represents vehicle movement at a signalized intersection to gain an understanding how to ensure safety by making an earlier decision before the signal change to yellow. This formula clearly shows that an earlier decision can result in better safety at signalized intersections by preventing entry to the dilemma zone.

Key Words: safety analysis, dilemma zone, prior decision

1. INTRODUCTION

In Japan, close to 60% of traffic accidents occur at intersections or in their vicinity; and about 60% of traffic accidents at intersections consist of rear-end or right-angle collisions. Installing traffic signals is one countermeasure to traffic accidents at intersections or their vicinity. Even signalized intersections, however, carry the risk of a rear-end collisions due to deceleration and stopping of the leading car combined with the following car's driver accelerating with the intention to pass though the intersection; and of right-angle collisions due to a car entering the intersection and behaving indecisively after the signal change.

Signalized intersections have two hazards. These are the dilemma zone (the range where a vehicle cannot pass through or stop safely at the stop line when the signal changes to red) and the option zone (the range where a vehicle can pass through or stop safely at the stop line when the signal changes to red). Both zones are regarded as dangerous because stopping/proceeding is dependent on the individual driver's judgment. If all drivers made the same decisions in these zones, there would be risk in the option zone, but there would still exist a risk in the dilemma zone. Therefore, avoidance of entering the dilemma zone is likely to contribute to reducing the hazards at signalized intersections.

One preventive countermeasure to entering the dilemma zone is to provide the traffic signals with a dilemma zone control system (Saito, 1994). This system is designed to reduce rear-end collisions just after a signal change to yellow and to minimize right-angle collisions caused by a car entering the intersection during the all-red period in off-peak times. More specifically, it senses the vehicle's speed and location when the signal changes to yellow and adjusts the yellow signal interval accordingly. It has, however, certain problems, such as difficult application during non-off-peak times. Also, the zone covered by this system does not necessarily correspond to the actual danger zone. This is being addressed by the researchers.
To avoid entering the dilemma zone, it appears to be important to some drivers to stop an imminent signal change to yellow by watching the blinking green and red lights of pedestrian signals. In this study, based on a study by Hamaoka et al. (2009), the decision to proceed or stop before a traffic signal turns yellow by acquiring advance information on traffic signal changes might inevitably lead to avoidance of entering the dilemma zone, reduce the moment of hesitation, resulting in safe proceeding or stopping. Based on this assumption, we developed model formulae to examine the times and distances necessary to safely avoid the dilemma zone.

2. DEFINITION OF SAFETY

Perhaps everyone who drives a vehicle has experienced, at least once, a moment of hesitation when deciding to stop or proceed through an intersection when a signal changes to yellow. This hesitation may trigger a rear-end collision or other accident. Each intersection has a zone in which rapid acceleration is needed to proceed through or equally rapid deceleration to stop when a traffic signal changes to yellow. This zone, referred to as the dilemma zone, always requires excessive acceleration or deceleration; and in which indecision is extremely dangerous. This study proposes that advance acquisition of signal change information can enable proceed or stop decision prior to the yellow signal change. This early acceleration/deceleration action can prevent a situation in which the vehicle enters the dilemma zone and hesitates during the stop/proceed decision.

If change information on a traffic signal is acquired prior to a yellow signal, an early proceed or stop decision may be possible; and therefore the resulting acceleration or deceleration can be made more gradually. Figure 1a graphically illustrates the situation where a decision to proceed is made early. In this Figure 1a, A represents a car's speed and location when the traffic signal is green; B represents its speed and location when the signal changes to yellow if the vehicle is moving at constant speed without a prior decision; and C_P represents its speed and location when the signal changes to yellow if the vehicle's driver has made a prior decision and accelerates. Broken lines represent the proceeding line and stopping curve; the former indicates that if a vehicle is on this line when a signal changes to yellow, it can exit the intersection just as the signal changes to red, while the latter indicates that if a vehicle is on this curve when a signal changes to yellow, it can stop by the time the signal changes to red. In other words, a vehicle located in the area above (to the left of) the line when the signal changes to yellow can pass through the intersection by the time the signal changes to red, whereas a vehicle located in the area below (to the right of) the line cannot. Similarly, a vehicle located in the area below (to the right of) the curve when the signal changes to yellow can stop, whereas the vehicle located in the area above (to the left of) the curve cannot. The proceeding line was calculated from the travel distance during a yellow signal duration of 3 seconds, while the stopping curve was calculated using the travel distance to a complete stop as well as the travel distance during a reaction time to signal change of 1 second.

As seen from the illustration of these points, a vehicle moves from A to B at a constant speed and enters the dilemma zone if no information on the imminent signal change is acquired. However, if information on the imminent signal change is acquired and a decision is made to proceed, the vehicle accelerates from A to reach C_P when the traffic signal turns yellow. The vehicle therefore has a higher speed than that of B, and has moved a longer distance prior to
the yellow signal change: the dilemma zone is thus avoided.

Similarly, Figure 1b graphically illustrates the situation where a decision to stop is made early. In Figure 1b, A represents the car's speed and location when the traffic signal is green; B represents its speed and location when the traffic signal changes to yellow if the vehicle moves at a constant speed without making an early decision; and $C_S$ represents the speed and location when the traffic signal changes to yellow if the vehicle makes an early decision and decelerates. As seen from the illustration of these points, a vehicle goes from A to B at a constant speed and enters the dilemma zone if no information on the signal change is acquired. However, if signal change information is acquired and a decision is made to stop, the vehicle decelerates from A to $C_S$ when the traffic signal changes to yellow. Therefore, the vehicle has a lower speed than that of B, and has moved a shorter distance prior to the change of the yellow signal; and thus, the dilemma zone is avoided.

**Figure 1 Effects on safety of making a decision before the signal change**

Based on the concept above, model formulae were developed to evaluate the safety of avoiding the dilemma zone.

3. RELATIONSHIP BETWEEN THIS AND PREVIOUS STUDIES

In this section, previous relevant studies are reviewed to define the position of this study.

Hayashi et al. (2005) investigated the safety of accident-prone intersections where there had been numerous rear-end and right-angle accidents, and focused on the dilemma control system, or a traffic control system that is effective in preventing accidents, to estimate its effects after installation. The results showed there to be a high probability of right-angle collisions, because a vehicle that is traveling between stop lines of studied intersection at an average speed is in the intersection after the end of an all-red period. The speeds at two surveyed locations, where a dilemma detector was installed close to the center of the dilemma zone, differed markedly. This indicates that the speed at the surveyed location might not accurately represent the speed at the moment of signal change. However, there is no reference to avoiding entry of the dilemma zone.

Uno (2002) used a fuzzy tracking model to examine traffic distribution with a shortened reaction time through a simple simulation. His results showed that a reduction in reaction time
of vehicles was likely to contribute to improvements in the stability and safety of traffic distribution. This is an investigation focusing on the occurrence and resolution of traffic congestion: therefore, avoidance of entering the dilemma zone is naturally not referred to.

In this context, Nakamura et al. (2006) conducted a study to compare vehicle behavior at various types of intersections with and without pedestrian signals. In this study, the analysis from the viewpoint of the difference in speed and acceleration in vehicle behavior between decisions to proceed or stop with and without pedestrian signals revealed that some drivers rely on pedestrian signals in decision making, and that relying on pedestrian signals to predict signal change can lead to increased safety owing to there being enough time to decide whether to proceed or stop. This study revealed that drivers relied on pedestrian signals when deciding to proceed or stop.

Therefore, in this study, model formulae to avoid entering the dilemma zone were developed through decision-making prior to traffic signal changes by checking pedestrian signals on signal change to yellow when drivers are pressed to decide whether to proceed or stop to examine if the dilemma zone can be safely avoided.

4. MODEL FORMULA FOR AVOIDANCE OF THE DILEMMA ZONE

Current representative measures to avoid entering the dilemma zone include the dilemma zone control described above in the Introduction. There are no other practical measures. In this study, prior acquisition of information on signal changes using pedestrian signals was investigated as a preventive measure. This preventive measure, allowing the best use of the existing road structure, can be applied to many kinds of intersections with pedestrian signals without any changes in the current system or need for new equipment.

In developing model formulae, distance $L_0$ from the stop line on traffic signal change and speed $V_0$ were assumed to be located within the dilemma zone (the shaded area between the proceeding line and stopping curve) (Figure 2a). It was assumed that a prior decision was made based on preset conditions, assuming constant speed $V_0$ regardless of current signal indication. Figures 2b and 2c show the relationship between speed, time, and distance, respectively, when a decision is made before the traffic signal changed to yellow.

A prior decision is assumed to be made $t$ seconds before traffic signal changes to yellow; therefore, the point of [I] is the distance of $V_0t$ from $L_0$. [I], [II], and [III], respectively, show the points where the decision is made and the traffic signal changes to yellow and red. $Y$ is the point when the traffic signal changes to yellow, and $W$ is the length of the intersection. Also, [II] is the point of 0 seconds, and [I] and [III], respectively, are $t$ seconds before and $Y$ seconds after the change to yellow. The distance between [I] and [II] is calculated by multiplying speed, $V_0$, by time $t$.

Regardless of prior or posterior decision, a decision is made to proceed or stop. Model formulae for the decision to proceed and the decision to stop were therefore developed and tested.
4.1 Decision to Proceed

In this subsection, a model is developed for the relationship between distance from the stop line $L$ and speed $V$ when the traffic signal changes to yellow in the case of a decision to proceed. The condition "a vehicle travels at a certain rate of acceleration until it has passed through the intersection when the traffic signal changes to red" was taken to be the decision to proceed. Figures 3a and 3b show the relationship between speed, time and distance, respectively, for the decision to proceed. [I], [II] and [III] in these Figures represent the same as above. The distance between [I] and [II] was assumed to be $L_1$ for ease of calculation. $Y$ and $W$ may vary depending on the intersection, $L_0$ and $V_0$ are preset values, and $L$ and $V$, $t$, and $L_1$ are variables. $Y$, $W$, $L_0$, $V_0$, $L$, and $V$ can be used in formula $L-V$, a goal formula, where $t$ and $L_1$ cannot be used; therefore, these two parameters used for calculation are replaced with $Y$, $W$, $L_0$, $V_0$, $L$, and $V$ as necessary.
4.1.1 Speed when the traffic signal changes to yellow
As shown in Figure 3a, $V$, which represents speed when the traffic signal changes to yellow, is determined by initial speed during decision and acceleration. Acceleration $'a'$ is calculated using target speed $'V'_r$ when the traffic signal changes to red, initial speed $'V_0'$ on decision, and distance $'V_{0t} + L_0 + W'$ that shows the distance between locations on decision and the end of the intersection) are as follows:

$$a = \frac{V'_r^2 - V_0^2}{2(V_{0t} + L_0 + W)} \quad (1-1)$$

For this equation, target speed $'V'_r$ when the traffic signal changes to red is required to determine acceleration $'a'$. Therefore, speed $'V'_r$ on traffic signal changes to red when a decision is made $t$ seconds before signal change and a vehicle travels at an acceleration $'a'$ is expressed as the following Formula 1-2:

$$V'_r = V_0 + \int_{0}^{t} a \ dt = V_0 + a(Y + t) \quad (1-2)$$

Therefore, acceleration $'a'$ required for a vehicle to have passed through the intersection when the traffic signal changes to red depending on the decision $t$ seconds before traffic signal change is expressed as the following Formula 1-3:

$$a = \frac{V'^2_r - V_0^2}{2(V_{0t} + L_0 + W)} = \frac{(V_0 + a(Y + t))^2 - V_0^2}{2(L_0 + V_{0t} + W)} = \frac{2(L_0 - V_0Y + W)}{(Y + t)^2} \quad (1-3)$$

Speed $'V'$ when the traffic signal changes to yellow when a vehicle travels at acceleration $'a'$ depending on the decision $t$ seconds previously is expressed as the following Formula 1-4:

$$V = V_0 + \int_{0}^{t} a \ dt = V_0 + at \quad (1-4)$$

Substitution of Formula 1-3 into Formula 1-4 provides the following Formula 1-5:
4.1.2 Distance from the stop line when the traffic signal changes to yellow

As shown in Figure 3b, L, which represents the distance from the stop line when the traffic signal changes to yellow is determined by \(L_1\), and \(L + L_1 = L_0 + V_0t\) is established. Distance ‘\(L_1\)’ between the locations where a decision was made \(t\) seconds before and a vehicle’s position when the traffic signal changes to yellow is expressed as the following Formula 1-6:

\[
L_1 = \int_0^t (V_0 + at)\,dt = V_0t + \frac{1}{2}at^2 \tag{1-6}
\]

According to the equation \(L + L_1 = L_0 + V_0t\), distance from the stop line ‘\(L\)’ when the traffic signal changes to yellow in the case of decision \(t\) seconds before is expressed as the following Formula 1-7:

\[
L = (L_0 + V_0t) - L_1 = L_0 - \frac{1}{2}at^2 \tag{1-7}
\]

Substitution of Formula 1-3 into Formula 1-7 provides the following Formula 1-8:

\[
L = L_0 - \frac{(L_0 - V_0Y + W)}{(Y + t)^2}t^2 \tag{1-8}
\]

4.1.3 Solving the V-L function

Solving Formula 1-5 for \(t\) provides the following Formula 1-9:

\[
t = \frac{(L_0 + W - VY) \pm \sqrt{(L_0 + W - 2VY + V_0Y)(L_0 + W - V_0Y)}}{V - V_0} \tag{1-9}
\]

Substitution of Formula 1-9 into Formula 1-8 provides the following Formula 1-10:

\[
L = L_0 - \frac{(L_0 + W - VY) \pm \sqrt{(L_0 + W - 2VY + V_0Y)(L_0 + W - V_0Y)}}{2} \tag{1-10}
\]

Formula V-L is compiled based on Formula 1-10. Solving Formula 1-10 for \(V\) provides the following Formula 1-11:

\[
V = V_0 + \frac{2(L - L_0) \pm 2\sqrt{(L - L_0)(V_0Y - L_0 - W)}}{Y} \tag{1-11}
\]

From this formula, it is found that if a decision is made at the same time, the higher the speed, the farther the vehicle travels. In other words, distance from the stop line ‘\(L\)’ is smaller than \(L_0\). Therefore, calculated Formula L-V is the following Formula 1-12:
4.2 Decision to Stop

In this subsection, a model is developed for the relation between distance 'L' from the stop line and speed 'V' when the traffic signal changes to yellow in the case of a decision to stop. The condition that a vehicle continues to decelerate until it stops completely at the stop line when the traffic signal changes to red is taken as the decision to stop. Figures 4a and 4b show the relationships between speed, time, and distance, respectively, for the decision to stop. [I], [II], and [III] in these Figures indicate the same as above. The distance between [I] and [II], similar to that for the decision to proceed, was assumed as \( L_1 \) for ease of calculation. \( Y \) may vary depending on the intersection, \( L_0 \) and \( V_0 \) are preset values, and \( L, V, t, \) and \( L_1 \) are variables. \( Y, L_0, V_0, L, \) and \( V \) can be used in Formula 1-L-V, a goal formula, whereas \( t \) and \( L_1 \) cannot. These two parameters used for calculation are therefore replaced with \( Y, L_0, V_0, L, \) and \( V \) as necessary.

### 4.2.1 Speed when the traffic signal changes to yellow

As shown in Figure 4a, \( V \), which represents speed when the traffic signal changes to yellow, is determined by initial speed \( V_0 \) on decision and deceleration \( \alpha \). Deceleration \( \alpha \) can be calculated similarly to that for the decision to proceed. The target speed when the traffic signal changes to red is 0. Therefore, deceleration \( \alpha \), which is needed for stopping at the stop line when the traffic signal changes to red after the decision was made \( t \) seconds before, is expressed as the following Formula 2-1:

\[
\begin{align*}
\alpha &= \frac{V_r^2 - V_0^2}{2(L_0 + V_0 t)} \\
&= \frac{-V_0^2}{2(L_0 + V_0 t)}
\end{align*}
\] (2-1)
Speed \( V \) when the traffic signal changes to yellow when a decision was made \( t \) seconds before the signal change and a vehicle travels at an acceleration \( 'a' \) is expressed as the following Formula 2-2:

\[
V = V_0 + \int_0^t a \, dt \\
= V_0 + at 
\]  

(2-2)

Substitution of Formula 2-1 into Formula 2-2 provides the following Formula 2-3:

\[
V = V_0 - \frac{V_0^2}{2(L_0 + V_0 t)} \cdot t 
\]  

(2-3)

4.2.2 Distance from the stop line when the traffic signal changes to yellow

As shown in Figure 4b, \( L \), which represents distance from the stop line when the traffic signal changes to yellow is determined by \( L_1 \), and \( L + L_1 = L_0 + V_0 t \) is established. Distance \( 'L_1' \) between the points where a decision was made \( t \) seconds before and a vehicle's position when the traffic signal changes to yellow is expressed as the following Formula 2-4:

\[
L_1 = \int_0^t (V_0 + at) \, dt \\
= V_0 t + \frac{1}{2} at^2 
\]  

(2-4)

According to the equation \( L + L_1 = L_0 + V_0 t \), distance \( 'L' \) from the stop line when the traffic signal changes to yellow in the case of decision \( t \) seconds before is expressed as the following Formula 2-5:

\[
L = (L_0 + V_0 t) - L_1 \\
= L_0 - \frac{1}{2} at^2 
\]  

(2-5)

Substitution of Formula 2-1 into Formula 2-5 provides the following Formula 2-6:

\[
L = L_0 + \frac{V_0^2}{4(L_0 + V_0 t)} \cdot t^2 
\]  

(2-6)

4.2.3 Solving the \( V-L \) function

Solving Formula 2-3 for \( t \) provides the following Formula 2-7:

\[
t = \frac{2L_0(V_0 - V)}{V_0(2V - V_0)} 
\]  

(2-7)

Substitution of Formula 2-6 into Formula 2-7 provides the following Formula 2-8:

\[
L = L_0 + \frac{L_0(V_0 - V)^2}{V_0(2V - V_0)} 
\]  

(2-8)
Formula V-L is compiled based on Formula 2-8. Solving Formula 2-8 for V provides the following Formula 2-9:

\[
V = \frac{L \pm \sqrt{L(L - L_0)}}{L_0} V_0
\]

Since \( V \) is smaller than \( V_0 \) since deceleration takes place after the decision to stop, also, if the decision was made at the same time, the lower the speed, the shorter the distance the vehicle travels. In other words, distance from the stop line \( 'L' \) is higher than \( L_0 \). Therefore, calculated Formula L-V is the following Formula 2-10:

\[
V = \frac{L - \sqrt{L(L - L_0)}}{L_0} V_0
\]

4.3 Verification using the model formulae

We now discuss avoidance of the dilemma zone is using the model formulae developed for the decision to proceed or stop. Figure 5 shows the functions of proceeding or stopping as defined by the model formulae. To simplify, the Figure shows an example of how various vehicles can be present in the dilemma zone. When a decision is made prior to the traffic signal changes to yellow, reaction toward stopping occurs earlier than the change; therefore, reaction time when the traffic signal changes to yellow is 0. In other words, the stopping curve that defines the dilemma zone is expressed as a formula that ignores reaction time. The stopping curve in this Figure is therefore calculated based on the distance needed to stop. The proceeding line is already described as above. The curve for proceeding in the Figure indicates at what speed and at what location a vehicle is traveling when the traffic signal changes to yellow if a prior decision is made to proceed. Similarly, the curve for stopping indicates at what speed and at which location a vehicle is traveling when the traffic signal changes to yellow in the case of a prior decision to stop.

Given the assumptions for developing the model formula, a vehicle can pass through or stop when the traffic signal changes to red. Even so, a vehicle may be present in the dilemma zone when the traffic signal changes to yellow due to constant acceleration/deceleration. Even if a vehicle were able to avoid entering the dilemma zone, sudden acceleration/deceleration may be needed (hereinafter "critical acceleration/deceleration"), indicating that avoidance of the dilemma zone will not necessarily provide safe transit or safe stopping. Although a prior decision is impossible unless the traffic signal change is foreseen, this model formula was developed in disregard of the range of prior decision time \( t \). Therefore, the range of \( t \), or how much earlier a decision can be made, should be taken into consideration. The time needed, therefore, to safely avoid entering the dilemma zone when the traffic signal changes to yellow is examined within the limited range of \( t \).
5. SAFE AVOIDANCE OF THE DILEMMA ZONE ACCORDING TO THE MODEL FORMULAE

In this section, critical acceleration/deceleration is determined, and the range of t is limited to examine the time needed for safely avoiding the dilemma zone. For this purpose, an intersection was assumed to have a width W of 30 m and duration of yellow signal Y of 3 seconds. The blinking green of pedestrian a signal that allows a prior decision starts 6 seconds before the traffic signal changes to yellow.

In the above-developed model formulae, using acceleration/deceleration fixed at a less unnatural critical value (3.0 m/s\(^2\) for acceleration and -2.0 m/s\(^2\) for deceleration), time and distance needed for acquiring information on signal change are tested by calculating intersections among formulae. The model formula (Formula 3-1) for acceleration fixed to a constant critical value was obtained by substituting \(a = 3\) into Formulae 1-4 and 1-7 that had been solved as simultaneous equations. In the same manner, the model formula (Formula 3-2) for deceleration fixed to a constant critical value was obtained by substituting \(a = -2\) into Formulae 2-2 and 2-5 that had been solved as simultaneous equations.

\[
V = V_0 + \sqrt{6(L - L_0)} \quad (3-1)
\]
\[
V = V_0 - 2\sqrt{(L - L_0)} \quad (3-2)
\]

Figure 6 shows various curves for a vehicle with \(V_0\) of 16.7 m/s (60 km/h) and \(L_0\) of 53 m in the dilemma zone at a constant critical acceleration/deceleration value. It also shows the above-developed model formulae (Formulae 1-12 and 2-10) and the dilemma zone. In this Figure, the proceeding line at a critical acceleration shows that, regardless of the possibility of passing through, at what speed and at which location a vehicle is traveling when the traffic signal changes to yellow at a fixed critical acceleration value, acceleration higher than the critical is needed by a vehicle in the area above (to the right of) the curve. Similarly, the stopping curve at a critical deceleration indicates that, regardless of the possibility of stopping, at what speed and on which location a vehicle is traveling when the traffic signal...
changes to yellow at a fixed critical deceleration value, deceleration higher than the critical is needed for a vehicle in the area below (to the left of) the curve. The proceeding line and stopping curve are already described as above. Table 1 shows the time and the distance from the stop line on prior decision calculated using calculated intersections. Capital letters indicate the same items in the Table and Figure.

Table 1 and Figure 6 show that when a decision to proceed is made 0.00-1.30 seconds in advance, the dilemma zone cannot be avoided, or, if possible, acceleration higher than critical is needed to pass through. In the case of stopping for which various formulae have the same intersection, it is indicated that a decision to stop 0.00-0.99 seconds early cannot prevent entry of the dilemma zone. Therefore, a decision should be made at least 1.30 seconds before the traffic signal changes to yellow to pass through at a safe acceleration after the traffic signal changes to yellow.

Also, a decision should be made at least 0.99 seconds before the signal change to yellow to stop at a safe deceleration. Taking into consideration the reaction time after acquiring information on traffic signal change, information should be acquired additionally 1 second (decision to proceed, 2.30 seconds; decision to stop, 1.99 seconds) earlier.

Table 1 Respective intersections in Figure 6

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Location (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: proceed and proceed at the critical acceleration</td>
<td>1.30</td>
</tr>
<tr>
<td>B: proceeding line and proceed at the critical acceleration</td>
<td>0.22</td>
</tr>
<tr>
<td>C: proceed and proceeding line</td>
<td>0.15</td>
</tr>
<tr>
<td>D: stop and stop at the critical deceleration</td>
<td>0.99</td>
</tr>
<tr>
<td>E: stopping curve and stop at the critical deceleration</td>
<td>0.99</td>
</tr>
<tr>
<td>F: stop and stopping curve</td>
<td>0.99</td>
</tr>
</tbody>
</table>
The time and distance needed for acquiring information on signal change in advance is then examined by calculating intersections among formulae at a fixed critical decision time (5 seconds before the traffic signal changes to yellow, or 1 second after the green blinking of pedestrian signals begins, assuming that pedestrian signals are used for the decision with a reaction time of 1 second). The model formula (Formula 4) at a fixed critical decision time, which is the same for both proceeding or stopping, was obtained by substituting \( a = 3 \) into Formulae 1-4 (2-2) and 1-7 (2-5) that were solved as simultaneous equations.

\[
V = V_0 + \frac{2(L_0 - L)}{5}
\]  

(4)

Figure 7 shows various curves for a vehicle traveling at 60 km/h at a fixed critical decision time. It also shows the above-developed model formulae (Formulae 1-12 and 2-10) and dilemma zone. In this Figure, the decision time line indicates the speed needed for a vehicle to be passing a certain point when the traffic signal changes to yellow when the decision is made 5 seconds previously. If the diver decides to proceed, the Figure indicates that a vehicle is in the area above the decision time line on signal change to yellow. In the case of decision to stop, the signal change to yellow is located below the decision time line. Table 2 shows prior decision time and the distance from the stop line on the decision based on calculated intersections. Capital letters are shared between the Table and Figure.

The Table and Figure show a case where a prior decision needs to be made much earlier, even if the dilemma zone can be avoided. They also show that a prior decision to proceed 0.00-0.15 seconds before does not allow avoidance of the dilemma zone, while a decision 5 seconds or more before does not allow acquisition of information on traffic signal change. Prior decision to stop 0.00-0.99 seconds before does not allow avoidance of the dilemma zone, while a decision 5 seconds or more before does not allow acquisition of information on traffic signal changes. Therefore, to pass through the intersection while avoiding the dilemma zone, a decision should be made 0.99-5.00 seconds before. To stop, a decision should be made 0.15-5.00 seconds before.
Table 2 Time and location for intersections in Figure 7

<table>
<thead>
<tr>
<th></th>
<th>Time (sec)</th>
<th>Location (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: proceed and decision time</td>
<td>5.00</td>
<td>136</td>
</tr>
<tr>
<td>B: proceeding line and decision time</td>
<td>0.77</td>
<td>65.8</td>
</tr>
<tr>
<td>C: proceed and proceeding line</td>
<td>0.15</td>
<td>55.4</td>
</tr>
<tr>
<td>D: stop and decision time</td>
<td>5.00</td>
<td>136</td>
</tr>
<tr>
<td>E: stopping curve and decision time</td>
<td>2.269</td>
<td>90.8</td>
</tr>
<tr>
<td>F: stop and stopping curve</td>
<td>0.987</td>
<td>69.4</td>
</tr>
</tbody>
</table>

Safe proceeding or stopping assuming a prior decision is examined by superposing decision time on the above-calculated critical acceleration/deceleration for proceeding or stopping. Figure 8 shows proceeding or stopping depending on critical acceleration/deceleration and decision time.

According to the Figure, to avoid entering the dilemma zone by making a prior decision, the decision to proceed or stop should be made by the time (0-5 seconds before traffic signal changes to yellow) that subcritical acceleration/deceleration is needed. To proceed at a safe acceleration while avoiding the dilemma zone when the traffic signal changes to yellow, the decision should be made 1.30-5.00 seconds before, whereas to stop at a safe deceleration, the decision should be made 0.99-5.00 seconds before. Given the reaction time after acquiring information for foreseeing traffic signal change, information should be acquired at least 1 second earlier (2.30-6.00 seconds before for proceeding, 1.99-6.00 seconds before for stopping).

6. CONCLUSIONS

In this study, it is assumed that information on signal change acquired in advance by watching pedestrian signals could contribute to increase the safety because driver could have additional time to decide his action (pass/stop) if he could get information of signal change. Model
formulae were developed to test for avoidance of the dilemma zone, even under conditions such as varied yellow signal interval, different vehicle speeds, intersection width, and the duration of green blinking of pedestrian signals. In developing the model formulae, assumptions such as proceeding or stopping when the traffic signal changes to red and moving at a constant acceleration/deceleration were made to limit vehicle behavior after signal changes. For some of these assumptions, a vehicle can proceed or stop if the traffic signal changes to red, but cannot avoid entering the dilemma zone if the traffic signal changes to yellow due to traveling at a constant acceleration/deceleration. Meanwhile, in some cases, supercritical acceleration/deceleration is needed, even when the dilemma zone can be avoided. In this study, the range of decision times was not taken into consideration; therefore, the model formulae were developed to indicate that a prior decision is made without acquisition of information on traffic signal change being acquired.

To solve this problem, avoidance of the dilemma zone was examined at a constant critical acceleration/deceleration, assuming that the vehicle is traveling at 60 km/h at a point that is 53 m away from an intersection with a width of 30 m and duration of yellow traffic signal of 3 seconds to limit the range of decision times. Our results suggest that a decision should be made 1.30-5.00 seconds before the traffic signal changes to yellow to avoid entering the dilemma zone at a subcritical acceleration, and that a decision should be made 0.99-5.00 seconds before the traffic signal changes to yellow to avoid entering the dilemma zone at a subcritical deceleration. While prior decision time for this situation (0.99 sec.) seems to be small, distance traveled in the speed of 40km/h is about 11m, and then this prior decision time is important for the driver to avoid entering dilemma zone. Critical situation could not occur without warning, therefore it is important to catch the transition all the time and check the situation whether it is danger or not.

This study identified the variables needed to avoid entering the dilemma zone under certain conditions, including the distance from which a yellow signal is visible and its duration. However, there are some possibly unsafe cases, such as a avoiding the dilemma zone by proceeding at high speed. It is important to determine appropriate safe values under various conditions. Under actual traffic conditions, there are various patterns, such as stopping before the traffic signal changes to red and brief accelerations/decelerations followed by movement at constant speed. In the future, model formulae that can be applied to actual traffic should be developed by establishing the conditions of these various patterns. By solving these issues, installing traffic signal with countdown could be best way to inform the signal change to the driver. Traffic signal that has countdown information is installed in many countries such as Thailand, Turkey and so on. I think it is time to install in Japan as the safety countermeasure to avoid entering dilemma zone.

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