Evaluating Safety Based on Driver Decisions upon Acquiring Signal Change Information

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Abstract: Intersection is one of the accident-prone locations. To avoid accidents at the intersection, it may be important for drivers to observe the flashing green and non-flashing red of pedestrian signals. In this paper, safety level at the signalized intersection having a pedestrian signal is evaluated using laboratory experiment with the driver as subject. This study is based on the assumption that observing the pedestrian signal enables drivers to anticipate change of the signal to yellow. This provides allowance time for the decision to proceed or to stop, thereby leading to improved safety at intersections. Result clearly shows that driver anticipation of a signal change to yellow by observing the pedestrian signal enables the driver of a vehicle to avoid the “dilemma zone”. This improves safety level at the intersection compared to the case where such information is not provided.

Keywords: Safety analysis, Pedestrian signal, Dilemma zone, Driver decision

1. INTRODUCTION

Greater dependence on automobiles has resulted in ever-increasing automobile traffic volumes. As a result, various problems related to road traffic are becoming worse, including increase in number of traffic accidents, perennial traffic congestion, and pollution of living and natural environments by exhaust fumes, noise, and vibration.

In Japan, nearly sixty percent of all traffic accidents each year occur around the vicinity of intersections (National Police Agency, 2009). Roughly sixty percent of all traffic accidents at intersections are rear-end or right-angle collisions. Traffic signals are installed at intersections to prevent traffic accident occurrence. However, even signalized intersections include risks. When a leading vehicle decelerates to stop for a signal change, a following vehicle may accelerate to proceed through and thereby cause a rear-end collision; or, a right-angle collision of intersecting vehicles may occur when a driver cannot respond to a signal change and enters into the intersection.

One method for resolving these problems is the use of “dilemma control” at the intersection. Dilemma control is one method used to make the situation at the signalized intersection safer by modifying the time period of signal. When a vehicle approaches the signalized intersection at the moment when the light signal changes to yellow, the driver of the vehicle finds himself in a situation in which the vehicle could not stop before the intersection, nor proceed into the intersection because of the location and speed of the vehicle at that instant. The vehicle has gotten into what is called a “dilemma zone”. In order to avoid this situation, dilemma control is applied by setting a longer yellow time in order to allow the
vehicle enough time to proceed through the intersection. Dilemma control (Saito, 1994) is implemented during low traffic volume periods to reduce rear-end collisions which may occur during moments when the signal changes to yellow, and right-angle collisions occurring in the case where vehicles enter an intersection when signal indication at all intersection approaches are red. The technique, however, may be difficult to adopt during high traffic volume periods. Moreover, the dilemma zone used for implementing dilemma control, unfortunately, may not always coincide with the actual danger zone (research on this is still in progress).

To avoid accidents in the vicinity of intersections, it is considered important that drivers are able to confirm the change in traffic signal indication at an approach by observing the flashing green and non-flashing red of pedestrian signals, and the remaining wait time displayed by pedestrian signals. Therefore, this study is based on the assumption that observing the pedestrian signal enables the approaching drivers to anticipate the change of the signal to yellow. This provides allowance time for the decision to proceed or to stop, thereby improving safety at intersections. This study also examines the behavior of vehicles proceeding through intersections, and considers the contributions of pedestrian signals to intersection safety by analyzing the driver's decision times.

2. THE RELATION OF THIS STUDY TO PREVIOUS RESEARCH

The present research focuses on the effects of a pedestrian signal on vehicle behavior at the moment when traffic signal indication changes. The context of this study is clarified by reviewing past and more recent related researches.

Research focusing on the reduction of traffic accidents at the intersections when signals change includes research by Kataoka (2005) that analyzes factors affecting a driver's decision to stop at a signalized intersection. The objective road environment of this research is four-leg signalized intersections having at least one road with two lanes in both directions and a dedicated right-turn lane. Analysis is performed based on data for signal change timing, decision results to proceed or stop, the existence of an opposing vehicle turning right, and measurements of speeds in the vicinity of stop lines at the intersection. As a result, it was clearly shown that all vehicles in what is referred to as a "dilemma zone" chose to proceed through. It was also confirmed that a "dilemma/option zone" does not always coincide with a "different zone". Kataoka’s research focuses on the dilemma zone and the option zone, and does not consider the effects of pedestrian signals.

Miyata (2001) focused on vehicle behavior when signals change with consideration of effects from pedestrian signals. The study tested the hypothesis that "for a certain traffic flow, the variation in acceleration and deceleration behavior increases as the length of time is increased between a pedestrian signal changing to a flashing green or a non-flashing red and a vehicle signal turning to yellow or red." The research performed observations of vehicle speeds upstream from the stop line and when crossing the stop line, as well as observations of vehicle behavior such as lane changing of vehicles in approaching intersections. However, the objective of this research was limited to only one intersection having pedestrian signals, and the analysis did not address differences in vehicle behavior according to intersection geometry and the existence of a pedestrian signal.

Based on the research cited above, Goto (2004) performed research comparing differences in vehicle behavior according to intersection geometry and the existence of a pedestrian signal. This research surveys and analyzes intersections both with and without pedestrian signals to clarify the effects of pedestrian signals on vehicle behavior. The results clearly
indicate that the flashing green and non-flashing red of a pedestrian signal prevents indecision of drivers to proceed or stop when the traffic signal turns to yellow. However, the evaluation is based on a assumption that drivers confirm a pedestrian signal when they approach to an intersection that has a pedestrian signal, and there is no reference to the driver decisions after actually confirming a pedestrian signal.

In consideration of the research described above, this study focuses on a comparison of vehicle behavior with and without a pedestrian signal; focuses additionally on individual driver decisions to proceed/stop when the traffic signal changes to yellow; and evaluates safety by acquiring the information of signal change beforehand.

3. THE PERSPECTIVE REGARDING SAFETY AT INTERSECTIONS

Perhaps everyone who drives an automobile has experienced, at least once, a moment of hesitation to stop or proceed through when a signal changed to yellow. This hesitation may trigger a rear-end collision or other accident. Each intersection has a zone for which an excessive acceleration or deceleration is required to either proceed or stop, regardless of the decision, when a traffic signal changes to yellow. This zone, referred to as the dilemma zone, is always characterized by excessive vehicle acceleration or deceleration. When a decision occurs in this zone, the situation becomes extremely dangerous. This study proposes that the acquisition of signal change information beforehand can facilitate a proceed/stop decision prior to the yellow signal change. This early acceleration/deceleration action could prevent a situation where the vehicle enters the dilemma zone and hesitates during the stop/proceed decision. With reference to the Japanese HCM (vi), a safe proceed/stop action is defined to be an action with a non-excessive acceleration (0.2G or 2m/s\(^2\)) and a non-excessive deceleration (-0.3G or -3m/s\(^2\)). This safety criterion is evaluated based on both vehicle behavior at intersections and driver decisions. There is some concern that directing attention to visually confirm a pedestrian signal may cause a decrease of attention to a leading vehicle, thereby increasing the risk of accidents. However, this study seeks to clarify the extent of positive effects on safety enabled by the visual confirmation of pedestrian signals, and such negative effects are excluded from the objectives of this research.

In the case where information of a change in traffic signal indication is acquired prior to a yellow signal, an early proceed/stop decision may be possible, thus the resulting acceleration or deceleration can be made gradually. Figure 1 graphically illustrates an approach for the case where a decision to proceed is made early. In Figure 1, \(A\) represents the travel speed and location when the traffic signal is green; \(B\) represents the travel speed and location when the vehicle signal changes to yellow in the case where the vehicle moves at constant speed without an early decision; and \(C_p\) represents the travel speed and location when a signal changes to yellow in the case where the vehicle makes an early decision and accelerates to proceed through the intersection. As seen from the illustration of these points, a vehicle goes from \(A\) to \(B\) at a constant speed and enters the dilemma zone in the case where the information of the signal change is not acquired. However, in the case where the information of the 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 to yellow. The vehicle therefore has higher speed than that of \(B\), and has moved a longer distance prior to the yellow signal change; and thus, the dilemma zone is avoided.

Similarly, Figure 2 graphically illustrates an approach for the case where a decision to stop is made early. In the Figure 2, \(A\) represents the travel speed and location when the traffic
signal is green; $B$ represents the travel speed and location when the traffic signal changes to yellow in the case where the vehicle moves at a constant speed without making an early decision; and $C_S$ represents the travel speed and location when the traffic signal changes to yellow in the case where the vehicle makes an early decision and decelerates to stop. As seen from the illustration of these points, a vehicle goes from $A$ to $B$ at a constant speed and enters the dilemma zone in the case where the information of the signal change is not acquired. However, in the case where 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 a decision to proceed prior to the signal change

Figure 2. Effects on safety of a decision to stop prior to the signal change

4. SAFETY ANALYSIS BASED ON DRIVER DECISIONS

Using experiments, evaluation of the effect on safety in acquiring information on change of traffic signal indication related to driver decision to proceed/stop entering the dilemma zone is performed for two cases: (1) information of the signal change to yellow is acquired beforehand, and (2) information is not acquired. Additionally, decisions based on a “countdown” method (an alternative way of providing information instead of using the pedestrian signal) are studied. In the countdown method, time remaining (in seconds) before the next signal change is made available. This experiment used video image simulation to provide the same road and running conditions to all drivers. The drivers watched video images of running into the dilemma zone (see Figure 4) and made decisions to proceed into the intersection or to stop by raising flags held by either hand (left: stop, right: proceed). To duplicate actual conditions as much as possible, the video images used in the experiment were actual video images taken from a moving vehicle, with signal information added. Furthermore, the positions of the screen and the experiment participant were adjusted so that the video images appeared in actual size to the participant.
Table 1 illustrates an overview of the experiment. Regarding the representations of decision times, the start of the yellow signal is represented by 0; a decision prior to the start (hereinafter referred to as "early decision") is represented by a negative value; and a decision after the start (hereinafter referred to as "late decision") is represented by a positive value.

<table>
<thead>
<tr>
<th>Date</th>
<th>Dec. 14, 2006 to Dec. 21, 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>40 persons, aged 20 - 24, licensed drivers for one to six years (30 males, 10 females)</td>
</tr>
<tr>
<td>Number of video image patterns</td>
<td>{with/without Pedestrian signal, and Countdown} x {40 / 50 / 60 / 70 / 80 km/h} = 15 patterns</td>
</tr>
<tr>
<td>Data acquired</td>
<td>(1) Proceed/stop decision</td>
</tr>
<tr>
<td></td>
<td>(2) Decision time (Yellow signal start = 0)</td>
</tr>
<tr>
<td></td>
<td>(3) Ease of decision</td>
</tr>
</tbody>
</table>

4.1 Method of Analysis

The experiment performed employs simulation using video image to focus on the decisions made by a driver when the driver enters a dilemma zone during vehicle operation.

The extent of avoidance of the dilemma zone is clarified for the case where the driver acquires the information of the signal change beforehand. Verification analysis is performed to show if obtaining information of the signal change beforehand enables the driver to avoid the dilemma zone and make proceed/stop decisions at a signalized intersection with a safety margin for both action and psychological considerations. Moreover, information acquisition methods are also addressed. The experiment considers two methods, pedestrian signal or countdown, to give advance information on the change of traffic signal indication. Differences among three traveling environments are compared by focusing on results such as the decision time, ease of decision, and acceleration. The 3 environments are: (1) the lack of a warning by signal change information (without pedestrian signal), (2) the existence of a warning by signal change information (with pedestrian signal), and (3) the existence of a warning (countdown).

4.2 Driver Decision

Herein, differences regarding the proceed/stop decisions of drivers are analyzed. First, the extent of changes in decision time due to different running conditions is clarified. This
experiment uses five levels of travel speeds from 40km/h through 80km/h at 10km/h intervals. Analysis of variance (ANOVA) is conducted in order to confirm the similarity of distribution among the decision time in each speed. Table 2 shows the ANOVA result for 6 cases such as without pedestrian signal (stop/proceed), with pedestrian signal (stop/proceed) and countdown (stop/proceed).

Table 2. Result of the analysis of variance

<table>
<thead>
<tr>
<th></th>
<th>Without Pedestrian signal</th>
<th>With Pedestrian signal</th>
<th>Countdown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>stop</td>
<td>proceed</td>
<td>stop</td>
</tr>
<tr>
<td>Intragroup</td>
<td>0.10</td>
<td>4.21</td>
<td>0.96</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Intergroup</td>
<td>0.23</td>
<td>1.47</td>
<td>2.16</td>
</tr>
<tr>
<td>Variance ratio</td>
<td>43</td>
<td>141</td>
<td>138</td>
</tr>
<tr>
<td>F-statistics (significant level: 0.05)</td>
<td>2.59</td>
<td>2.44</td>
<td>2.44</td>
</tr>
</tbody>
</table>

From this table, 5 out of 6 results are shown that the distributions are not different in the 5% of significant level. Therefore, it could be thought that the distributions might be almost the same. This gives basis for summing up the number of responses for each of the travel speeds. On the other hand, decision times exhibit differences for the existence of the information and for the methods of informing the change of the yellow signal at each travel speed, regardless of speed. Therefore analysis of decision time is performed for all cases of travel speeds. Figure 5 illustrates distributions of decision times for each of the 3 traveling environments. The solid line in the center divides the Figures into regions before and after the signal changes to yellow.

![Figure 5](image_url)

**Figure 5. Distributions of decision time**

The Figures show that acquisition of advance information of the signal change enables a proceed/stop decision prior to the change of the traffic signal, and this also shows that the driver tends to decide to stop. It can be concluded that enabling early decisions allows drivers...
to avoid the dilemma zone and reduces entries into the intersection by excessive acceleration. In the trends of the distributions in Figure 5, it is particularly significant that some drivers made risky decisions, i.e., they required a long decision time. The video image is set to evaluate decisions when the driver entered to the dilemma zone, and therefore a decision after the signal changes to yellow is extremely dangerous.

The participants requiring one or more seconds to make a decision after the traffic signal changes to the yellow are referred to herein as "decision delayers." The attributes of these participants were analyzed. Table 3 illustrates the ratio of decision delayers who use a vehicle infrequently. An infrequent driver is defined in this study as a participant who uses a vehicle less than once per week. The percentage of infrequent drivers is 15% (6 people out of 40). Table 3 reveals that higher percentages of the decision delayers are infrequent drivers. Moreover, it is also possible to consider that a driver's experience in the traffic conditions by regular driving may affect proceed/stop decisions in the dilemma zone.

Table 3. Percentages of participants with delayed decisions who are infrequent drivers

<table>
<thead>
<tr>
<th>Decision time</th>
<th>Proceed</th>
<th>Stop</th>
<th>Proceed</th>
<th>Stop</th>
<th>Proceed</th>
<th>Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s or more</td>
<td>16%</td>
<td>43%</td>
<td>43%</td>
<td>50%</td>
<td>33%</td>
<td>40%</td>
</tr>
<tr>
<td>2s or more</td>
<td>60%</td>
<td>50%</td>
<td></td>
<td></td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>3s or more</td>
<td>75%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Distribution of decision time in Figure 5 clearly shows that acquisition of change information enables early decisions. To clarify the ease of making a decision in the case where change information is acquired, the relationship between results of interviews regarding as the ease of decisions made for each experimental video image and the actual early or late decision times were examined for each information acquisition method (Figure 6). Responses of interviews are collected for the different travel speeds, yielding a total of 200 responses (40 participants x 5 speed patterns).

Although 99 participants responded that decisions were difficult without signal change information, 170 responses stated that signal change information allowed easier decisions. It is clear therefore that signal change information assists decision-making. Furthermore, 78 responded that decisions were difficult when making a late decision without signal change information. It may be that, in the case where early decisions are possible, avoidance from the dilemma zone is possible, while in the case where early decisions are not possible, drivers enter the dilemma zone and further hesitation by drivers occurs.

For the experiment that uses pedestrian signal to give signal change information, 58 responded that decisions were easy even though late decisions were made. This result seems to indicate that if change information is obtained beforehand even when the driver has entered in the dilemma zone, hesitation is relieved in making the decision at the intersection. For the countdown method, participants commented that the information provided using the method is less useful in making a decision as compared to using pedestrian signal, for both early decisions and late decisions. This comments might have been due to factors such as appearance of the video image, way of setting the video image, and uncomfortable feelings of the participants due to the lack of experience from this kind of experiment.
The safety effect of a signal change is analyzed based on the prediction of actions after a decision. The ratios of vehicles with high-risk decisions are ascertained by calculating the accelerations from the decisions of proceed/stop, decision times, and the initial speeds; and by comparing the threshold values to indicate a dangerous acceleration or deceleration.

Based on the decisions to proceed/stop and the decision times obtained above, required accelerations to proceed through a designated distance, or required decelerations to stop within a designated distance were calculated for various decision times. For a vehicle that proceeds, the acceleration required to proceed through the intersection was calculated using the interval from the decision time to the time of change to the red signal. For a vehicle that stops, the deceleration required to stop at the stop line was calculated using the interval from the decision time to the time of change to the red signal. Based on these values, the required acceleration or deceleration was determined by utilizing each proceed/stop decision and decision time. In this study, a dangerous situation is considered as 2 m/s$^2$ or more for acceleration and -3 m/s$^2$ or less for deceleration.

For a vehicle that proceeds, given that the size of intersection is 30m and interval of yellow is 3 seconds, equation (1) can be set up utilizing three variables $V_0$ - the speed at the time of decision, $a_a$ - acceleration of the vehicle, and $t$ - elapsed time of vehicles just proceeding through the intersection.

\[
\int_0^{3t} (V_0 + a_a t) dt = (3 + t)V_0 + 30
\]

Equation (2) is derived by solving this equation (1) for $a_a$.

\[
a_a = \frac{60}{(3 + t)^2}
\]
For a vehicle that stops, the stop must be made within the three-second yellow interval, and therefore $a_d$ in equation (4) is derived by solving equation (3).

$$-V_0^2 = 2a_d(3+t)$$

$$a_d = \left\{ \begin{array}{l} \frac{V_0^2}{2(3+t)} \end{array} \right.$$  

In the above equations, $t$ shows the early decision time (s) and $V_0$ shows the travel speed (m/s).

Figures 7 and 8 illustrate the relationship between the decision time and the acceleration $a_a$ and the deceleration $a_d$. Accelerations and decelerations are determined by the formulas shown above. The dashed lines in the Figures delineates non-excessive acceleration or deceleration. These Figures illustrate the extent of the effects of the passage of the decision time on acceleration when proceeding, and on deceleration when stopping. These Figures also indicate the timing at which a decision is needed to provide safety.

In Figure 7, an acceleration exceeding $2m/s^2$ indicated by the dashed line is considered to be an excessive acceleration, and therefore an early decision of 2.5 seconds or more beforehand is necessary to proceed safely. Furthermore, this Figure illustrates that a later decision correspondingly would require sudden acceleration. It may be concluded from this result that in the case where a decision to proceed is made, a decision must be made significantly prior to the yellow signal change.

In Figure 8, a deceleration less than $-3m/s^2$ illustrated by the dashed line is considered to be an excessive deceleration. For low speeds, an early decision enables the driver to stop safely; but for high speeds, even in the case where an early decision is made, a decision shortly before the signal change requires a sudden deceleration. However, the speed is reduced from the initial travel speed by the time the signal changes to yellow, and therefore an intention to stop exists beforehand; and thus it can be said that a major risk is not involved in
the deceleration of this case.

Based on the acceleration and deceleration values required to proceed through or to stop within the respective specified distances as predicted from the decision times, the ratios of high risk vehicles for each pattern are determined. In this study, high-risk vehicle is defined as the drivers with risk taking behavior that tend to run with the large absolute value of acceleration and deceleration. Figure 9 illustrates the ratio of high-risk vehicles for each speed. The Figure indicates that the high-risk vehicles are fewer when information is acquired. Figure 10 illustrates the reduction ratios of high-risk vehicles for each method of providing information, i.e., pedestrian signal or countdown, by using the ratio of high-risk vehicles for no signal change information as the reference. This Figure shows that, with the exception of only 60km/h, the reduction ratios are greater for higher speeds than those for lower speeds when a pedestrian signal is used. Additionally, the magnitude of the speed reduction for higher speeds may indicate that the acquisition of signal change information provides an impetus to drivers at dangerously high speeds to come to a stop; and it also may indicate an effect of reducing the number of high-risk vehicles that enter the dilemma zone at high speeds.

Figure 9. Ratio of high-risk vehicles of high-risk vehicles

4.4 Analysis of the Timing of Warnings Prior to Yellow Signal Changes

In this section, the relationships regarding the location from the stop line and speed of a vehicle when the signal changes to yellow is examined. The experimental video images themselves are set in a state of entering the dilemma zone; and therefore actions are predicted, regarding the locations and speeds traveled when the signal changes to yellow, only for the case of an early decision. Earlier decision times enable the vehicle to proceed or stop with a corresponding ample amount of time, and therefore the dilemma zone can be avoided.

Figure 11 illustrates a plot of the location from the stop line and the speed when the signal changes to yellow for each decision time by dividing the time of the decision prior to the yellow signal into 0.2 second intervals from the "yellow line" (0.2 < t < 6.0) for each proceed/stop decision, with the dilemma zone added. Here, the location L from the stop line when the signal changes to yellow is expressed in equation (5) using a yellow interval of 3 seconds, for a speed at the time of the decision of $V_0$ and an early decision time of t seconds.
\[ L = 3V_0 - \frac{at^2}{2} \]  

(5)

The travel speed \( V \) is similarly expressed by equation (6).

\[ V = V_0 - at \]  

(6)

In the formulas above, \( t \) shows the decision time (s), \( V_0 \) shows the travel speed (m/s), and \( a \) shows the acceleration or deceleration (m/s\(^2\)).

Figure 11 represents decisions that are made earlier as the distance increases from a "proceed line" for both proceeding and stopping; and it is evident that an earlier decision made prior to the yellow signal change results in a correspondingly greater distance from the dilemma zone, a smoother acceleration or deceleration, and more time for proceeding or stopping.

When a decision to stop is made, even in the case where an early decision is made prior to the yellow signal, a decision shortly before the yellow signal will not enable the vehicle to avoid the dilemma zone. However, the speed has been reduced from the initial speed setting by the time the signal changes to yellow, and therefore the intention to stop exists beforehand; and thus it can be said that a major risk is not involved concerning the vehicle entering the dilemma zone in this case. Figure 11 illustrates that, when a decision to proceed is made, the acceleration exceeds the threshold value of 2m/s\(^2\), which is considered to be dangerous, unless the decision time is 2.5 seconds or more; and therefore it can be said that even in the case where a decision to proceed is made, it is necessary to make the decision at a stage significantly prior to the yellow signal change.
5. CONCLUSIONS

This study evaluates the safety of acquiring signal change information based on both vehicle behavior at intersections and driver decisions. As a result, it was clearly shown that anticipation of a signal change to yellow by using a pedestrian signal enables a vehicle to avoid the dilemma zone; and the safety at the intersection when the signal changes to yellow is thereby better than the case where such information is not provided. Furthermore, an experiment was performed for providing signal change information by a countdown method as an alternative to the signal change information of a pedestrian signal; but problems remain concerning display methods and settings. A trend of high dependence on anticipating the signal change using a pedestrian signal was clearly shown, which indicates a high risk at intersections having different pedestrian signal indication cycles for a flow of traffic, such as signals with irregular turn or clearance intervals, or non-synchronized pedestrian-vehicle signals. To eliminate such risks, studies of methods for providing signal change information not affected by indication cycles for a flow of traffic are considered necessary.

On the other hand, there is the discussion that the variation of driver behavior tends to disperse and brings the danger situation if he gets the information of traffic signal beforehand. However, the result of this experiment shows that the driver tends to stop when he gets the information beforehand (Figure 5). There is a need to discuss more about the effectiveness of getting the information of the change of traffic signal from the viewpoint of safety.

REFERENCES


