Evaluation of the effectiveness of advanced driving headlights using a driving simulator

Keisuke SUZUKI*, Katsuya GODA*, Shun’ichi DOI*, Toshihiko TSUKADA**, Kazunori HIGUCHI** and Keiichi SHIMAOKA**

*Kagawa University
2217-20 Hayashi-cho, Takamatsu-city, Kagawa 761-0396, Japan
E-mail: ksuzuki@eng.kagawa-u.ac.jp
**Toyota Central R&D Labs., INC.
41-1 Yokomichi, Nagakute-city, Aichi 480-1192, Japan

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Abstract
In this study, a method to evaluate the effectiveness of adaptive driving beam (ADB) to enhance a driver’s perception level for detecting pedestrians in a driving simulator is proposed. First, we investigated a driver's reaction time for applying brakes and the time taken to detect pedestrians stepping out from sidewalks. Next, we evaluated the effectiveness of ADB in terms of likelihood of collision mitigation using this reaction time based on the system reliability concept that we have proposed in previous studies. Using a driving simulator, we verified that it is almost possible to simulate the distribution of illuminance on the road surface by headlights and that it is useful to investigate the reaction time of drivers to detect obstacles such as pedestrians walking on a drive lane during the night.

Key words: Driving support, Recognition timing, Adaptive driving beam (ADB), Collision mitigation, System reliability concept

1. Introduction
Various types of light distribution control technology are being put to practical use to improve a driver’s visibility at night. Newer versions of headlamps have light-emitting diodes (LEDs) arranged in a matrix. Using digital mirror device technology, light distribution can be controlled separately for each headlamp (Elger et al., 2015), (Schmidt et al., 2007). This is an example of using adaptive driving beams (ADB) (Berlitz et al., 2015) which are capable of reducing the glare toward oncoming vehicles (Neumann, 2014), (Bullough, 2015). Using ADB to control light distribution is an example of improving the ability to detect distant obstacles by increasing the degree of visual stimulation through intermittent irradiation to the obstacles. Previous research has focused on shortening a driver’s cognitive reaction time, the time frequency for spot dimming, and optimizing spatial frequency (Kojima et al., 2015), (Shiraki et al., 2015), (Hiratsuka et al., 2015), (Böhm et al., 2009). The evaluation of how driver visibility is affected by these light distribution control technologies is performed, of course, with a night-test course. However, there are constraints caused by the evaluation time frame, weather, etc. that cause issues and lower work efficiency. As such, recent evaluative studies on light distribution control have been conducted using driving simulators (Tanaka et al., 2014), (Morita et al., 2014). Using a driving simulator, the improvement of the working efficiency can be expected because light distribution control can be performed easily. However, reproducing the glare of headlights from oncoming vehicles is difficult, because the illuminance of the light from the projector reflected on the screen is not as bright. Therefore, there are many problems when it comes to reproducing vehicle glare so that the driving experience feels real. Nevertheless, the usefulness of using a driving simulator has been confirmed to a certain degree when evaluating a driver’s cognitive reaction time when vehicle headlights illuminated pedestrians. In our preceding investigations, we were able to perform a qualitative comparison between ADB and a conventional light distribution

apparatus. Therefore, we used this evaluation method for our research. In this paper, we used a driving simulator to compare the difference in driver performance when using high- and low-beams. We conducted various analyses including the reduction in the time that drivers took to recognize pedestrians when using ADB, and whether reaction time for braking could be shortened and by how much. Furthermore, wherever possible, we quantified how accident avoidance equipment reduced accidents, as proposed in prior studies by Suzuki et al. (Suzuki et al., 2012), (Suzuki et al., 2014). Based on these results, the validity of the active safety effect of ADB was considered, as determined using state transition probability models based on system reliability engineering. The purpose of our research is as follows.

1) To implement light distribution controls in a driving simulator environment so that light distribution to oncoming vehicles can be spot-darkened while simultaneously the frequency of the darkening can be arbitrary. Then, we analyze the perception and reaction time of drivers using this simulator when they detect a crossing pedestrian.

2) To quantify the probability of collision with a pedestrian during various light distribution conditions using data obtained in the above experiment for braking response times required to avoid collision with the pedestrian.

The positioning of the light distribution control device (Driving beam) considered by the authors is shown in Fig. 1. In the case of using an accident avoidance support system to avoid collision with a crossing pedestrian, it is difficult to maintain a sufficiently high level of sensing reliability. For a time to collision (TCC) with a range of 3 sec or more, the effect of the reduction in trust of the system is low, even if there are false positives or nondetection occurrences. Therefore, recognition support by light distribution control devices such as ADB is believed to be appropriate. With a quicker collision risk detection in a TTC range less than 3 sec, judgment and operation assistance using conventional alarm and information-providing equipment is considered effective. The degree of accident avoidance support using light distribution control is shown in Chapter 4.

2. Evaluation method

2.1 Light distribution control pattern

The light distribution control pattern realized in a driving simulator environment is shown in Fig. 2. The ADB light distribution area was based on the coverage by high-beams, and the area of the oncoming vehicle was shielded depending on that vehicle’s behavior in real time on a two-dimensional plane (vertical and horizontal). In the test conducted using advanced ADB, as illustrated in Fig. 3, in addition to the ADB function, a light distribution control repeatedly performed spot light distribution and darkening of pedestrians in a 2-Hz time frequency while also detecting pedestrians. Optimizing the time frequency of the light distribution and darkening in order to shorten the driver cognition time is a challenge moving forward. The detection area for pedestrians in this experiment was within a range of 100 m from the front of the vehicle headlights. Note that to ensure these light distribution controls simulated reality, researchers involved in the development of light distribution systems were asked to test drive simulators to validate light distribution illumination, areas of illumination, etc. Details concerning illuminance distribution are discussed in Chapter 5.
Fig. 2 Distribution of lighting pattern. The normal ADB light distribution area was based on the coverage by high-beams, and the area of the oncoming vehicle was shielded depending on that vehicle’s behavior in real time on a two-dimensional plane (vertical and horizontal).

Fig. 3 Advanced ADB to enhance the perception of crossing pedestrians. In addition to the ADB function, a light distribution control repeatedly performed spot light distribution and darkening of pedestrians in a 2-Hz time frequency while also detecting pedestrians.

2.2 Scenario

We conducted analyses of the cognitive reaction time when pedestrians were detected far off and braking response time when pedestrians were nearby. In both analyses, the use of the same analysis index for the time to collision (TTC) as an example is preferred. However, for the analysis of collision avoidance of nearby pedestrians, the quantification of the collision occurrence probability was performed, as described in Chapter 4, with braking response times used as an analysis indicator for risk instead of TTC.

2.2.1 Analysis of behavior when detecting distant collision risks

We constructed a driving simulator environment and conducted several scenarios in which pedestrians jump out in front of the subject vehicle, as shown in Fig. 4. We analyzed how drivers responded to distant collision risks. Referencing the ITARDA accident database (ITARDA, 2012), near-miss scenarios were developed similar to the typical pattern for night-time collision accidents with pedestrians. In one scenario, the test participant’s vehicle and the
vehicle in front of it were traveling at 50 km/h. After the oncoming vehicle had passed the pedestrian standing at the side of road, the pedestrian began crossing the street from the rightmost lane at 1 m/s (in typical Japanese scenarios, the participant is driving in the leftmost lane). To avoid having the participants concentrate excessively on the risk events, we developed other scenarios in which no pedestrians jump out. In this dummy scenario, a pedestrian walked along the sidewalk and did not enter the driveway. For every light distribution condition, the experiment drive was set 10 times, with 6 of those set as the real scenario. In this real scenario, a pedestrian actually entered the driveway. The oncoming vehicles appeared every 15 sec - 30 sec, and pedestrians appeared after every four or five oncoming vehicles. The appearance of the pedestrian was set; therefore, the pedestrian began crossing the street with a TTC timing of 5 sec from the vehicle being driven by the participant. The driveway width of one lane is 3.0 m, and the width of the sidewalk is 2.0 m.

Comparing normal adaptive driving beam (ADB) with high-beams shows no major difference in how a driver recognizes a pedestrian because both have the same irradiation distance to a pedestrian. The only difference in normal ADB is that an oncoming vehicle is not illuminated in real time. When using advanced ADB, the irradiation to a pedestrian is highlighted by a flashing frequency of 2 Hz. The visual stimulus to the driver for detecting a pedestrian crossing the driveway is the most intense when using advanced ADB.

2.2.2 Analysis of behavior when detecting nearby collision risks

The position of the vehicle is shown in Fig. 4. Immediately after the oncoming vehicle has passed, the pedestrian began to cross the street from the rightmost lane at 1 m/s. To avoid having the participants concentrate excessively on the risk events, we developed other scenarios in which no pedestrians jump out. In this dummy scenario, a pedestrian walked along the sidewalk and did not enter the driveway. For every light distribution condition, the experiment drive was set 10 times, with 6 of those set as the real scenario. In this real scenario, a pedestrian actually entered the driveway. The oncoming vehicles appeared every 15 sec – 30 sec, and pedestrians appeared after every four or five oncoming vehicles. The appearance of the pedestrian was set; therefore, the pedestrian began crossing the street with a TTC timing of 2.3 sec from the vehicle being driven by the participant.

2.2.3 Regulating risk level with pedestrians

In all scenarios, the distance between vehicles traveling in the opposite lane was random, and the time with which
the pedestrian was expected to begin crossing the road could not be anticipated. However, the vehicle between the participant’s vehicle and the oncoming vehicle was controlled so that it was constant, as well as the point at which the pedestrian begins walking. The participants were also instructed to keep the speed of their own vehicle at 50 km/h.

2.2.4 Sub-task

In all scenarios, the participant was asked to perform a mental arithmetic task (Uchida - Kraepelin test) using a number presented on the front screen of the driving simulator near their forward gazing point so that we could set up the driving without a hypersensitive reaction to risk event.

2.3 Evaluation index

2.3.1 Analysis of behavior when detecting distant collision risks

Experiment participants were taught to operate a switch on the steering wheel when they recognized a pedestrian on driveway. The collision prediction time was analyzed on the basis of the timing with which they pressed the switch. In addition, the degree of psychological burden during driving was evaluated by asking the participants to complete the NASA Task Load Index (NASA-TLX) assessment tool to obtain a mental workload score.

2.3.2 Analysis of behavior when detecting nearby collision risks

Experiment participants were taught to avoid collision by braking when they saw a pedestrian and felt the risk of collision, as they would when actually driving. We analyzed the braking response times from the time when the pedestrian appeared on the driveway until the driver began to brake. The degree of psychological burden while driving was not evaluated. Because the time from when the pedestrian appeared until the driver braked was extremely short compared to the time when pedestrians appeared far away until the driver braked. It was difficult to evaluate the degree of psychological burden while driving during different light distribution patterns when detecting nearby collision risks.

2.4 Experiment participants

Informed consent was obtained from the participants, 13 young men with an average age of 22.2 years. Conditions and protocols of the experiments were performed under the scrutiny of the Kagawa University Engineering Experiment Ethics Committee.

2.5 Experiment sequence

After a 15-min practice session, an analysis of behavior at each light distribution control pattern was performed, and finally, a questionnaire for quantifying the psychological burden during driving using the NASA-TLX assessment tool was prepared. The total experiment duration was set so that each participant would not take more than 1 h and 30 min.

3. Test results

3.1 Analysis of behavior when detecting distant collision risks

In the experiment investigating driving behavior when detecting distant collision risks, we asked the participants to press the switch on the steering wheel. We evaluated the effect of reducing the recognition time using normal ADB and advanced ADB. In Fig. 5, an example of the analysis of the collision prediction time (time to collision, TTC) for the timing of recognizing distant pedestrians is shown. The results of significant-difference testing using a multiple comparison test (Bonferroni) are shown in the figure. Evaluation results are shown for conditions for which the significant difference level was 5% or less (*). No significant differences between conditions other than those shown have been confirmed. The results when using normal ADB and high-beams showed a similar tendency, and the cognition timing became quicker compared to results when using low-beams. In normal ADB, the distribution range of a headlight beam to a pedestrian is same as that of high beams. Therefore, both normal ADB and high beams require the same amount of time in recognizing distant pedestrians. Cognition timing was further sped up when the pedestrians at intersections were intermittently darkened and irradiated at 2 Hz (using advanced ADB). The results show that pedestrian recognition using a distant visual search can be supported with light distribution control. Specifically, the extent of accident reduction when using advanced ADB is discussed on the basis of the results of the analysis for cognitive reaction time in the following scenarios in which the pedestrian crossing was nearby and the collision risk was high.
Fig. 5 Braking timing in terms of TTC when detecting pedestrians when detecting distant collision risks. The results when using ADB and high-beams showed a similar tendency, and the cognition timing became quicker compared to results when using low-beams. Cognition timing was further sped up when the pedestrians on the driveway were intermittently darkened and irradiated at 2 Hz (using advanced ADB).

The results of the NASA-TLX assessment, showing the degree of psychological burden, are shown in Fig. 6. Because the data population was less when there were 13 participants, a statistically significant difference test was not conducted. Psychological burden was at the lowest value when advanced ADB was used. A questionnaire was given to participants after the experiments that used advanced ADB. The participants often answered that they could begin braking operations at an earlier timing due to a high-inducing effect of seeing pedestrians on the driveway, which lowered the participants’ workload when they searched crossings visually.

Fig. 6 Evaluation of mental work-load at each lighting control based on NASA-TLX when detecting distant collision risks. Psychological burden was at the lowest value when advanced ADB was used. A questionnaire was given to participants after the experiments that used advanced ADB. The participants often answered that they could begin braking operations at an earlier timing due to a high-inducing effect of seeing pedestrians at intersections, which lowered the participants’ workload when they searched crossings visually.

3.2 Analysis of behavior when detecting nearby collision risks

As mentioned earlier, the ability to detect pedestrians is the same for both normal ADB and high beams. In this section, we will evaluate the advantages of advanced ADB. In Fig. 7, an example of the analysis of braking response times from the time a pedestrian appeared to the time the participant began braking is shown. The results of significant-difference testing using a multiple comparison test (Bonferroni tests are shown in the figure. Significant differences between all conditions were clarified, including cases where the total significance level was 1% (**). Without conducting an investigation of using normal ADB, the findings for the use of advanced ADB are compared to conventional irradiation patterns. The results showed that when using advanced ADB, the braking response times to
avoid collision with pedestrians have been shortened. When using advanced ADB, the headlight beam is distributed to
a pedestrian with a flashing frequency of 2 Hz. Therefore, the evasive brake reaction time to avoid a collision with the
pedestrian is reduced. Based on this reduction in brake reaction time, we will quantify the effects of advanced ADB on
reducing accidents.

In the experiment investigating driving behavior when detecting nearby collision risks, we analyzed the evasive
brake reaction time and deceleration to avoid collision with a pedestrian crossing the driveway. Consequently,
regarding the deceleration level to avoid collision, the braking level at each condition was almost same. The average
deceleration was 6.9 m/s² at each condition of driving beam. In a quantification of collision probability mentioned in
chapter 4, we will use this value to estimate “to,” which is the time margin before entering the collision area.

![Fig.7 Braking reaction time after the onset of crossing pedestrian when detecting nearby collision risks. The results showed that when using advanced ADB, the braking response times to avoid collision with pedestrians at intersections have been shortened.](image)

### 4. Quantification of collision probability based on system reliability engineering

Based on the analysis results obtained from the experiment regarding the response time during tests when
pedestrians presented an occurrence of possible risk, we quantified the accident reduction results using the methods for
the quantification of collision probability based on system reliability theories, as reported by Suzuki et al. (2014) in
their prior research. The examination was performed using braking response-time data from testing scenarios in which
pedestrians were nearby.

The recognition level of the pedestrian from a driver was investigated in this experiment. In order to analyze the
accident reduction effect by advanced headlights, such as ADB, the cognitive characteristic of the approach vehicles
seen from the pedestrian should also be analyzed. As the beginning of this research has described, it is difficult to
evaluate the glare of a headlight using a driving simulator. About the ease of noticing of the approach vehicles by
irradiation by an advanced headlight seen from the pedestrian, investigation in an actual test course is indispensable. In
this investigation, since these are not analyzed, it is a future subject.

When we quantify the effects, it may be important to discuss the possibility of malfunctions in detecting a
pedestrian. As a first step of the study, we only focus on the effects of advanced ADB on reducing accidents when the
system operates properly.

#### 4.1. Outline of model for quantification of collision occurrence probability

Using a concept of accident occurrence probability featuring a multi-combined system from the system reliability
engineering field, Suzuki et al. who is an author of this study proposed a method to estimate the degree of the reduction
in accidents when using driver-support devices designed to assist in accident avoidance. They named this method the
“state transition probability model.” Fig. 8 includes a timing diagram showing fluctuations in driver driving
performance and the driving environment condition. As shown in the diagram, in conditions in which driving
performance is decreased, regardless of whether or not a dangerous event occurs, attempts to avoid a collision will fail
and a collision accident will occur when driving performance does not recover.
A definition of symbols is as follows:

- \( \mu_{11} \): Probability of a condition in which driving performance decreases \([1/\text{s}]\)
- \( 1/\mu_{11} \): Duration of a condition in which driving performance decreases \([\text{s}]\)
- \( 1/\lambda_1 \): Duration of a condition in which driving performance does not decrease \([\text{s}]\)
- \( 1/\mu_{11}^* \): Time until pedestrian is noticed \([\text{s}]\)
- \( t_0 \): The delay time from when the collision is started \([\text{s}]\) (Time span when the collision never happen)
- \( 1/\mu_2 \): Average time to a collision after entering a collision area \([\text{s}]\)
- \( Q_f \): Probability of decreased driver awareness

\[
Q_f = \frac{1/\mu_{11}}{1/\mu_{11} + 1/\lambda_1}
\]

![Diagram showing state transition probabilistic model](image)

Fig.8 Concept of state transition probabilistic model. As shown in the diagram, in conditions in which driving performance is decreased, regardless of whether or not a dangerous event occurs, attempts to avoid a collision will fail and a collision accident will occur when driving performance does not recover.

When based on system reliability engineering, the recovery rate for reduced driving performance in the event of a dangerous situation can be expressed using Equation (1).

\[
e^{-\mu_{11}^* t}
\]

The probability of an accident occurring \(t_0\) sec later can be expressed using Equation (2).

\[
e^{-\mu_2(t-t_0)}
\]

Because the collision probability is \(\mu_2\) when driving performance decreases, the probability of an accident occurring in \(t_0\) sec \((p_1)\) can be given as demonstrated by Equation (3). By expanding Equation (3), Equation (4) can finally be obtained. For details regarding the derivations of the equations, refer to prior research by Suzuki (Suzuki et al., 2012), (Suzuki et al., 2014).

\[
p_1 = \int_0^\infty e^{-\mu_{11}^* t} e^{-\mu_2(t-t_0)} \mu_2 dt
\]

\[
= \frac{\mu_2}{\mu_{11}^* + \mu_2} e^{-\mu_{11}^* t_0}
\]
4.2 Quantification of accident occurrence probability

Using the state transition probability model previously described, it is possible to estimate the effects of using advanced ADB on reducing accidents based on the analysis results for braking response times. The state transition probability model is based on system reliability engineering and uses a quantitative value of the 63%ile. Shown in Fig. 9 is a cumulative frequency distribution for the analysis results of the braking response times (shown in Fig. 7) during the scenarios in which pedestrians appeared at intersections. The cumulative frequencies for braking response times during light distribution control conditions are shown in Fig. 9. The $1/\mu_{ii}$ in Equation (1) is 1.39 sec for low-beams, 1.23 sec for high-beams, and 1.12 sec for advanced ADB. This means that 63% of drivers start braking within 1.12 sec when using advanced ADBs and that a decrease in braking response times of 0.27 sec has been achieved when comparing response times when using low-beams. Table 1 shows the feature quantities for the behavior of drivers when they attempt to avoid a collision with pedestrians during light distribution control conditions.

![Fig.9 Evasive braking reaction time for state transition probabilistic model. The state transition probability model is based on system reliability engineering and uses a quantitative value of the 63%ile. This Fig.9 shows a cumulative frequency distribution for the analysis results of the braking response times. The cumulative frequencies for braking response times during light distribution control conditions are shown. The $1/\mu_{ii}$ in Equation (1) is 1.39 sec for low-beams, 1.23 sec for high-beams, and 1.12 sec for advanced ADB.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low-beams</th>
<th>High-beams</th>
<th>Advanced ADB</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/\lambda_{i}$</td>
<td>$3.60 \times 10^{3}$ [s]</td>
<td>$3.60 \times 10^{3}$ [s]</td>
<td>$3.60 \times 10^{3}$ [s]</td>
<td>Duration of a condition in which driving performance does not decrease [s] 63% of the drivers may have distraction once per hour</td>
</tr>
<tr>
<td>$1/\mu_{ii}$</td>
<td>1.50[s]</td>
<td>1.50[s]</td>
<td>1.50[s]</td>
<td>Duration of a condition in which driving performance decreases [s]</td>
</tr>
<tr>
<td>$Q_{f}$</td>
<td>$4.16 \times 10^{-3}$</td>
<td>$4.16 \times 10^{-3}$</td>
<td>$4.16 \times 10^{-3}$</td>
<td>Probability of decreased driver awareness Probability to face risky situation when the driver’s attention level is low</td>
</tr>
<tr>
<td>$1/\mu_{ii}^{*}$</td>
<td>1.39 [s]</td>
<td>1.23 [s]</td>
<td>1.12[s]</td>
<td>Time until pedestrian is noticed 63%ile of braking reaction time to avoid a risky driving situation</td>
</tr>
<tr>
<td>$\omega_{f_{max}}$</td>
<td>1.00 [/h]</td>
<td>1.00 [/h]</td>
<td>1.00 [/h]</td>
<td>Risky situations occur once per hour</td>
</tr>
<tr>
<td>$t_{a}$</td>
<td>2.30[s]</td>
<td>2.30[s]</td>
<td>2.30[s]</td>
<td>The delay time from when the collision is started [s] Time margin before entering a collision area</td>
</tr>
<tr>
<td>$1/\mu_{ii}$</td>
<td>1.00[s]</td>
<td>1.00[s]</td>
<td>1.00[s]</td>
<td>Average time to a collision after entering a collision area</td>
</tr>
</tbody>
</table>
1 Temporal probability when encountering a close call situation in conditions where the driver is distracted

\[ Q_f, \omega_{f0} = 4.16 \times 10^{-4} \] (5)

This means that when driving at night for 2,400 h, there was one occurrence of a dangerous situation in which there was a possibility of a collision with pedestrian.

2 Probability of a collision with pedestrian in a close call condition in which there is a possibility of a collision occurring

\[ p_1 = \int_0^\infty e^{-\mu_1 t} e^{-\mu_2 (t-t_0)} \mu_2 dt = \frac{\mu_2}{\mu_1 + \mu_2} e^{-\mu_2 (t-t_0)} = \frac{1}{1.39+1} e^{-1.10 \times 10^{-4}} \] (6)

3 Probability of a collision occurring in conditions in which the driver is distracted

\[ \omega_f = Q_f, \omega_{f0} P_1 = 4.58 \times 10^{-5} \] (7)

This means that if the driver drives a total of 200 hours at night in a year, the probability of a collision with a pedestrian who suddenly runs out into the street will occur once in approximately 110 years.

In other words, if it is assumed that the average driver operates a vehicle for 50 years over the course of their lifetime, it can be assumed that the event of being in a collision with a pedestrian who suddenly runs out into the street will be experienced by approximately one in two drivers. More detailed discussion is necessary regarding accident occurrence probabilities under actual driving conditions.

Regardless of the quantification of accident occurrence probability under these actual driving conditions, the methods for quantifying the effects of advanced ADB has on reducing accidents is discussed in the remainder of this paper, and it is the main objective of this paper.

The above is a discussion regarding estimation for the probability of a collision with pedestrian in a close-call condition in which there is a possibility of a collision occurring when using advanced ADB. In other words, when making determinations using the value for \( p_1 \), the probability of an accident occurring when using advanced ADB is 39% lower than when using low beams. It will be necessary to perform an adequate verification by increasing the number of test subjects and by performing a larger number of driving scenarios to quantify the effects on reductions in collision risks with pedestrians.

In this section, the derived probability of collision with pedestrian at nighttime is compared with the actual accident statistics from the national traffic assessment database and traffic accidents database of Japan (MLIT, 2013).

1 Accident statistics

- Travelling distance of all traffic on the national roads of Japan per year; \( 1.33 \times 10^{11} \) km
- Ratio between travelling distance on the national roads of Japan at day time and night time; 69:31

Therefore, travelling distance of all traffic at night time; \( 1.33 \times 10^{11} \times 0.31 = 4.12 \times 10^{10} \) km

- Ratio of fatalities of pedestrians among all accidents including (Ishikawa, 2009); 3%
- Number of fatalities of pedestrians at night time per year; 1,717

2 Estimated number of accidents using the model

- Average speed; 50 km/h
- Traveling hours: \( 4.12 \times 10^{10} / 50 \text{km/h} = 8.24 \times 10^8 \) hours

Consequently,

- Number of estimated accidents; \( 4.58 \times 10^{-5} \times 8.24 \times 10^8 = 3.77 \times 10^4 \)
Number of estimated fatalities; $3.77 \times 10^4 \times 0.03$

$$=1.13 \times 10^3$$

The result is almost close to the actual accident statistics data shown above.

In these evaluations, each of the values for the state variables was determined based on the statistical probabilistic model mentioned above. In this model, $\omega_{0}$, which represents the probability of risky traffic situations, was assumed to be once per hour. Also, $1/\lambda_{1}$, which represents the duration of a condition in which driving performance does not decrease, was assumed to be one hour. These values require validation.

Moreover, it is important to continue the discussion on the validity of subjective drivers. In this research, 13 young drivers participated in the driving simulator investigation. How should we consider the behavior for all drivers, including senior drivers? Should we conduct the experiments with participants whose ages are in the range of 20 to 80? It is well known that the variation in operational characteristics of senior drivers is significant. Therefore, the statistical confidence interval for the accident occurrence probability (error of estimated accident probability) becomes large. For this reason, as a first stage, the authors analyzed the operational characteristics for young drivers with collision avoidance with pedestrians.

5. Distribution of illuminance using a driving simulator

Because the illumination intensity of the projector light reflected on the simulator screen can never be as powerful as that of actual headlights, it goes without saying that some level of realism is lacking when driving simulators are used to evaluate the glare of light distribution systems. However, although a subjective estimate was given regarding driver visibility when pedestrians or other vehicles are bombarded with light from the light distribution system of the vehicle, adequate verification was performed by researchers in this field and an evaluation was obtained that was extremely close to the actual driving environment.

The figure below shows the evaluation results of the road surface illumination intensity in a virtual space where it was possible to control light distribution using a driving simulator that we developed. The figure shows the results of analysis performed on the illumination intensity distribution of light reflected off the road surface by the light distribution system. Fig.10 shows the results of measuring the illumination intensity distribution when light is distributed by the driving simulator using a luminance meter. Specifically, a luminance meter was placed upon a tripod that was located at the eye-level of the driver to measure the illumination intensity distribution of the asphalt road surface projected on the screen in front. When ADB is used when an oncoming vehicle approaches nearby, the light distribution from the oncoming vehicle was reduced as it was distributed. In the settings of the driving simulator test previously discussed in which the probability of an accident occurring was quantified, comparisons of road surface illumination intensities in actual usage environments were made for the illumination intensity at the location where a pedestrian appeared. As a result, when High Intensity Discharge (HID) headlights were used, the level of illumination intensity at the location where the nearby pedestrian appeared (6m to the left and 32 m ahead) was 2.0 cd/m$^2$ when using low beams and 12 cd/m$^2$ when using high beams. The level of illumination intensity at the distant location where a pedestrian appeared (4 m to the left and 70 m ahead) was 3.0 cd/m$^2$ when using high beams. This is equivalent to the road illumination intensity of the driving simulator, as shown in Fig. 10. In other words, although it is difficult to replicate the glare of oncoming vehicles when using a driving simulator, the simulator is effective in replicating the actual illumination environment of the road surface necessary to estimate the response time for recognizing the presence of pedestrians when direct light is distributed by the headlights.
Fig. 10 Distribution of illuminance on the road surface. Although it is difficult to replicate the glare of oncoming vehicles when using a driving simulator, the simulator is effective in replicating the actual illumination environment of the road surface necessary to estimate the response time for recognizing the presence of pedestrians when direct light is distributed by the headlights.

6. Summary

Using the driving simulator, we constructed an environment that can simulate an advanced light distribution system. The environment allows analysis to be performed to determine whether the amount of time for recognizing pedestrians can be shortened in using ADB when compared to conventional light distribution control systems, and if so, to what degree. Moreover, using the state transition probability model based on reliability engineering as proposed in our prior research, the methods for quantifying the probability of collisions with pedestrians was examined on the basis of each light distribution control condition. The following is an example of the quantitative evaluation results:

1) Timing for the recognition of distant collision risks (Average TTC values ± standard deviation)
   - Low-beams: 2.48s ± 0.482s
   - High-beams: 3.90s ± 0.566s
   - Normal ADB: 3.73s ± 0.377s
   - Advanced ADBs: 5.47s ± 0.543s

2) Degree of psychological burden when visually searching for pedestrians at distant intersections
   (Average NASA-TLX mental work load score ± standard deviation)
   - Low-beams: 74.0 ± 7.91
   - High-beams: 54.6 ± 15.0
   - Normal ADB: 58.0 ± 14.8
   - Advanced ADBs: 46.6 ± 18.8

3) Braking response times for nearby collision risks (50%ile)
   - Low-beams: 1.34s
   - High-beams: 1.20s
   - Advanced ADB: 1.11s

4) Characteristics when avoiding collisions with nearby pedestrians (with the collision probability while using low beams as the standard)
   - High-beams: 24% decrease
   - Advanced ADB: 39% decrease
5) Reproducibility of light distribution using a driving simulator

As a result of estimating the illuminance distribution when light is distributed on the road surface, an equivalent illuminance is shown for the actual environment and the driving simulation environment. Moreover, it can be said that the driving simulator is effective in replicating the actual illumination environment of the road surface necessary to estimate the response time for recognizing the presence of pedestrians when direct light is distributed by the headlights.

References


