Negative Effects of Visual Distraction on Traffic Accidents
- The Probability of Accidents Based on a Statistical Probabilistic Model-

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ABSTRACT: This study analyzes the relationship between the time of visual distraction for a driver, which can be defined as taking one’s eye away from the forward driving view, and the probability of traffic accidents. Using a driving simulator, we investigated the evasive reaction time of 22 drivers to risky events under a visual distraction. We subsequently analyzed the correlation between the evasive reaction time and the occurrence probability of rear-end collision and lane-deviation collision using a statistical probabilistic model, which can quantify the risk of traffic accidents. Based on this relationship, the possibility of reducing the evasive reaction time using a distraction alarm was investigated in order to minimize the probability of collision. The results demonstrate that reducing the distraction time and thus the evasive reaction time below 1.0 s effectively reduced the probability of a rear-end collision to one third compared with the probability without using an alarm system. Moreover, this system was also effective against collisions resulting from lane deviation.

KEY WORDS: safety, accident avoidance, statistical accident analysis, driver model, visual distraction, statistical probabilistic model, risk of traffic accidents [C1]

1. Introduction

Major human errors while driving cars include “distraction,” which is taking one’s eyes away from the road, and “inattentiveness,” which is allowing one’s concentration to deviate from the driving. In recent years, newly developed driving support systems applying advanced sensor and communication technologies have been used to support driving operations and to reduce human errors. Automakers, suppliers, and automotive research institutes have been studying methodologies to estimate collision frequency under specific traffic scenarios (1), including rear-end and head-on collisions at intersections, and to evaluate the effectiveness of driving support systems with sufficient accuracy in terms of reducing traffic accidents. However, there are no satisfactory methodologies to evaluate the quantitative effectiveness in reducing traffic accidents in consideration of the driver behavior. The experimental investigation of variables such as reduced reaction time for the braking operation is a typical evaluation for the effectiveness of driving support systems.

This paper describes a study addressing the quantification of traffic-accident probability, focusing on rear-end collision and lane deviation. The study applies the statistical probabilistic model (5) based on system reliability engineering. We evaluated the evasive reaction time under a visual distraction in a scenario that may trigger rear-end collision or lane deviation. Specifically, this study analyzes the relationship between driver visual distraction time, taking one’s eye from the forward driving view, and the probability of traffic accidents. Moreover, the effect of reducing visual distraction time on the probability of traffic accidents is estimated. First, in a driving simulator, we investigated the evasive reaction time of 22 drivers to risky events, such as the braking reaction time for sudden deceleration of a leading vehicle or steering reaction time to avoid lane deviation, under visual distraction in a driving simulator with the participants of 22 drivers. Subsequently, we analyzed the correlation between the evasive reaction time and the probability of rear-end collision and lane-deviation collision using a statistical probabilistic model. Based on this relation, the effectiveness of reducing the evasive reaction time in minimizing the probability of traffic accidents is discussed.

2. Estimation method regarding the probability of traffic accidents and the effectiveness of driving support

2.1. Preceding studies

The methodologies presuming the effectiveness of accident avoidance assistance systems in terms of collision mitigation which have been reported so far can be classified into three major methods. The first one is a method which used a driving simulator. For example, Homma and others (3) reported a method to evaluate the Forward Vehicle Collision Mitigation Systems, based on the investigation in terms of the braking reaction time of 72 young and elderly drivers. In addition to this investigation, a method using the experiment vehicle equipped with computers for presenting the visual image of obstacles generated by computer graphics to a driver on a proving ground was also reported by Homma and others (4). The second one is how to estimate the accident reduction effect using the event-data recorder on public road. In this method, the frequency of risky driving situation was investigated and the effectiveness of system use for mitigating collision is estimated. For example, Mimuro and others (5) reported that the accident reduction effect using the Collision Mitigation...
Braking reaction time

2.2. Accidents due to inconsistent driving performance

Traffic accidents typically occur when driving performance declines below the necessary level demanded by the traffic environment. Fig. 1 depicts the accident potential when the driving performance declines due to fatigue or sleepiness during long driving periods. In the real world, accidents can easily occur when driving performance declines momentarily due to such things as monotonous driving (inattentiveness) or looking away from the road (distraction), as shown in Fig. 2.

2.3. Modeling of risk avoidance

2.3.1. Two models for quantifying the probability of traffic accidents proposed by authors

When implementing accident avoidance support systems, it is important to estimate the accident reduction level from using the system. This is necessary to determine the practical-use priority of the system and marketing of the system in terms of its effectiveness. Two types of models have been proposed, namely, the “Time-series reliability model” and “Statistical probabilistic model,” that can quantify the probability of traffic accidents and its reduction level from using a driving support system. The former model can estimate detailed damage variables, such as collision speed, but the development of the model and the time-series simulation require significant effort. Although the latter model cannot estimate variables such collision speed, it can calculate collision probability using only a mathematical function based on the system reliability engineering.

2.3.2. “Time-series reliability model” to estimate the probability of accidents using Monte Carlo simulation

The concept of this simulation model is that an accident occurs when both the driver reliability and environment reliability decline simultaneously for a fixed period. The model for simulating a driver's behavior in terms of cognitive behavior is depicted in Fig. 3. The database or drivers’ evasive behavior surveyed in the driving simulator is used for the time of recovery from the lowered reliability of the driver (depicted with the black bold arrow in Fig. 3). The environmental reliability, including the state variables such as time interval and continuation time of risky traffic events, is estimated and is set based on traffic–accident data. When both reliability factors exceed the accident evasion time simultaneously, an accident occurs. In a case of a rear-end collision, time for collision avoidance (Tca), which is the braking-time margin to avoid the collision, is equal to the accident-evasion time. Tca is estimated by applying a conventional Stopping Distance Algorithm(13) that includes the state variables such as time headway, velocity, and deceleration of each vehicle.

In addition to accident occurrence probability, frequency distribution of collision velocity is presumed quantitatively in this model. In this methodology, the probability of traffic accidents can be obtained through the time-series simulation using the Monte Carlo method.

![Image of driving performance level fluctuation](image1)

**Fig. 1 Fluctuation of driving performance level**

![Image of driving performance level considering short driver distraction time](image2)

**Fig. 2 Fluctuation of driving performance level considering short driver distraction time**

![Image of time-series reliability model](image3)

**Fig. 3 “Time-series reliability model” to estimate the probability of accidents**

2.3.3. “Statistical probabilistic model” for estimating the probability of accidents based on reliability engineering

In addition to the above model, a second methodology has been proposed, which quantifies the probability of accident occurrence based on system reliability engineering, without executing a time-series simulation. System reliability engineering...
is generally used in analysis of electronic systems that have a constant failure rate, which means failure may occur at any time. We applied the system reliability engineering to the analysis of traffic accidents.

Fig. 4 depicts the sequence diagram of a rear-end collision. The horizontal axis in this figure means the time flow when the risk event such as the braking of preceding vehicle started. In this study, we describe the relationship between the continuation time of distraction and accident occurrence probability, using a statistical method based on system reliability engineering, which does not use the above Monte Carlo simulation. The symbols in Fig. 4 are defined as follows.

\[
\begin{align*}
\mu_{11} & : \text{Recovroy rate of driving performance } \text{[1/s]} \\
\mu_{11}^* & : \text{Continuation time that the driver performance is declined } \text{[s]} \\
\lambda & : \text{Declined rate of driving performance } \text{[1/s]} \\
\mu_{11}^* & : \text{Continuation time that the driver performance is not declined } \text{[s]} \\
\mu_{11} & : \text{Recovroy rate of driving performance in error situations } \text{[1/s]} \\
\mu_{11}^* & : \text{Continuation time that the driver performance is declined in error situations } \text{[s]} \\
t_0 & : \text{Time margin before entering an accident area } \text{[s]} \\
\mu_2 & : \text{Rate of accidents } \text{[1/s]} \\
\mu_2^* & : \text{Average time to a collision after entering a risky area } \text{[s]} \\
\end{align*}
\]

(1) Static probability that driving attention drops

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

(2) Probability of an accident after a risky event with a low level of driver attention

It is possible to quantify the probability of collision by the integration of integrated reliability of human-environment with a time span between \(t_0\) and infinity.

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

\[
= \frac{\mu_2}{\mu_{11}^* + \mu_2} e^{-\mu_{11}^* t_0}
\]

(2) Probability of an accident

\[
\omega_f = Q_f \omega_{t0} p_1
\]

(3) Probability of an accident

\[
\omega_{t0} : \text{Probability of risky traffic situations } \text{[times/hour]}
\]

3. Investigation of risk avoidance behavior

3.1. Scenario and secondary task during driving

In a driving simulator experiment, we set up scenarios in which rear-end collision or lane-deviation collision would be generated. Each scenario was selected randomly such that the participant could not predict which scenario would occur. To increase the reality of the experiment, the running velocity and the deceleration of the leading car were set based on investigations using an event data recorder\(^{(13)}\) that recorded actual near-miss incidents. In this experiment, the time headway was set to 3 s. This is a reasonable value for simulating a drive that triggered a visual distraction in a pre-test of this investigation. The scenario of a rear-end collision is shown in Fig. 5. The timing of the slowdown of the leading car was set assuming that the participants would not notice it. In the lane deviation scenario, a front wheel angle equivalent to a steering wheel angle of 2.5 degrees was added without moving the steering wheel. The steering wheel angle was set assuming that the participants would not notice it. The lane deviation scenario is shown in Fig. 6. In this experiment, a straight road with a width of 3.0 m was used, and the operator of the experiment controlled the timing of the steering adjustment such that the participants could not notice the steering. Each participant experienced this scenario ten times.

The contents of the experiment were presented to 22 experienced drivers, and they consented to participate in the investigation. The standard deviation of the age and the average age were ±0.96 years and 23.5 years, respectively.

Owing to the time constraints of the experiment, it was very unlikely that a rear-end collision or lane-deviation collision would occur in a driving simulator experiment. Therefore, the drivers were assigned a secondary task to induce a visual distraction to simulate the rear-end condition. During the experiment, the participants were asked to input a destination into a car navigation system that was mounted on the lower part of the instrument panel. The driving scene is shown in Fig. 7.
3.2. Scenario and secondary task during driving

Fig. 8 shows the accumulated frequency distribution investigated in the driving simulation for the drivers’ evasive reaction time to rear-end collision under visual distraction. In this figure, it is shown that the 63%ile, which is used for the statistical analysis (1/µ1) in eq. (2), is 1.67 s. This means that 63% of drivers were able to begin the braking operation within 1.67 s while performing the secondary task. In this model based on system reliability engineering, 63%ile is a representative value in terms of the recovery time during a visual distraction. In the exponential function explaining the reliability level of driver and environment shown in eq. (2), the 63%ile in the accumulated frequency-distribution is equal to the average of all of the data. This is a representative value for explaining the phenomena in the system reliability engineering. In this study, the reaction time for braking or steering and the frequency of distraction was represented using this 63%ile.

Fig. 9 shows the drivers’ evasive reaction time to lane-deviation collision under visual distraction. In this figure, it is shown that the 63%ile is 2.03 s.

4. Frequency estimation of rear-end collision and lane-deviation collision

4.1. Frequency estimation

Tables 1 and 2 show the parameters for estimating the frequency of rear-end collision and lane-deviation collision, respectively.

To estimate the time margin before entering a collision area, the Stopping Distance Algorithm was used. Tca, which is the accident evasion time before entering the collision area, is given by the following.

\[
T_{ca} = \frac{1}{2} V_2 \left( \frac{1}{\alpha_1} - \frac{1}{\alpha_2} \right) + \frac{y}{V_2^2}
\]

(4)

\[Tca \text{ : Time for collision avoidance [s]}\]
\[V_2 \text{ : Velocity of following car [m/s]}\]
\[\alpha_1 \text{ : Average of deceleration of the leading car [m/s}^2]\]
\[\alpha_2 \text{ : Average of deceleration of following car [m/s}^2]\]
\[y \text{ : Distance between two cars [m]}\]

In this estimation, the average deceleration of the following car was set between 4.00 m/s² and 8.00 m/s². In the scenario described in Fig. 5, the Tca ranges from 3.00 to 3.90 s under this deceleration. The minimum Tca is equal to the time margin before entering a collision area (t₀), as shown in Fig. 4. The maximum Tca is equal to \(t_0 + 2/\mu_2\). Therefore, the average time to a collision after entering a collision area, \((1/\mu_2)\), is 0.450 s.
In this analysis, $1 / \lambda$ meaning the distraction frequency per hour was set up as one. This is based on the preceding study of authors regarding the driving performance decline. Further analysis regarding its accuracy should be investigated. In this section, $1 / \mu_{i1}$ meaning the time between the onset of visual distraction and the initiation timing of braking/steering of driver was set up longer than $1 / \mu_{i1}$ meaning the time between the onset of risky event and the initiation of driver behavior. The time difference between two values was around 0.25 s. This is based on the recorded video-image of driving behavior. The time difference for rear-end collision was set up as 0.23 s and set up as 0.27 s for the lane deviation. Regarding the $\omega_{a}$ meaning the frequency of risky event was set up as once per hour for rear-end collision, and once per three hours for lane deviation. The value for each was estimated based of the investigation report by JARI on highways in metropolitan area. The further validation for the value should be carried out, because each value has significant effect on the frequency of accidents.

Table 1. Parameters for rear-end collisions

| Parameter       | Value     | Content                                                                 |
|-----------------|-----------|-------------------------------------------------------------------------|
| $1 / \lambda$   | 1 [h]     | 63% of the drivers may have one distraction per hour                     |
| $1 / \mu_{i1}$  | 1.90 [s]  | Time for declined driving performance                                    |
| $Q_{f}$         | 5.27E-4   | See eq. 1                                                               |
| $\hat{\mu}_{i1}$ | 1.67 [s]  | See Section 3                                                            |
| $\omega_{a0}$   | 1 [h]     | Risky situations occur once per hour                                     |
| $t_{0}$         | 3.00 [s]  | Time margin before entering a collision area                            |
| $1 / \mu_{2}$   | 0.450 [s] | Average time to a collision after entering a collision area              |

The results are as follows:

1. Frequency of a dangerous situation when the driver is distracted

$$Q_{f} \omega_{f0} = 5.27 \times 10^{-4}$$

This indicates that, on average, a driver will encounter a risky situation where a rear-end collision could occur once every 1,900 h. The frequency is much higher than the frequency of rear-end collisions. This result agrees with Heinrich’s Law that states that there are many near-miss events before an accident.

2. Probability of a rear-end collision in a dangerous situation

$$p_{1} = \frac{\mu_{2}}{\mu_{i1} + \mu_{2}} e^{-\mu_{i1} t_{0}}$$

$$= \frac{1}{1 + \frac{0.450}{1.67}} e^{-0.36} = 0.132$$

3. Frequency of a rear-end collision when the driver is inattentive

$$\omega_{f} = Q_{f} \omega_{a0} \frac{\mu_{2}}{\mu_{i1} + \mu_{2}} e^{-\mu_{i1} t_{0}} = 6.94 \times 10^{-5}$$

To estimate the time margin before entering an area of lane-deviation collision, the actual time margin that was determined in a driving-simulator study was used. To quantify this time margin, we determined the threshold of collision to the obstacles in a lane deviation as 0.750 m. This is based on the lateral margin of the traffic lane and implies that the vehicle collides with the obstacles when the level of lane deviation is longer than 0.750 m. In the driving simulator investigation, the time margin to avoid the collision with an obstacle on the roadside ranged from 6.00 to 7.80 s after the input of the disturbance. Therefore, the average time to a risk after entering a risky area is 0.900 s.

| Parameter       | Value     | Content                                                                 |
|-----------------|-----------|-------------------------------------------------------------------------|
| $1 / \lambda$   | 1 [h]     | 63% of the drivers may have one distraction per hour                     |
| $1 / \mu_{i1}$  | 2.30 [s]  | Time for declined driving performance                                    |
| $Q_{f}$         | 6.39E-4   | See eq. 1                                                               |
| $1 / \mu_{i1}$  | 2.03 [s]  | See Section 3                                                            |
| $\omega_{a0}$   | 1/3 [h]   | Risky situations occur once every three hours                            |
| $t_{0}$         | 6.00 [s]  | Time margin before entering a risky area                                 |
| $1 / \mu_{2}$   | 0.900 [s] | Average time to a risk after entering a risky area                       |

The results are as follows.

1. Frequency of dangerous situations when driver is distracted

$$Q_{f} \omega_{f0} = 2.13 \times 10^{-4}$$

This indicates that, on average, a driver will encounter a dangerous situation with lane-deviation collision once every 1,600 h.

2. Probability of a lane-deviation collision in a dangerous situation:

$$p_{1} = \frac{\mu_{2}}{\mu_{i1} + \mu_{2}} e^{-\mu_{i1} t_{0}}$$

$$= \frac{1}{1 + \frac{0.900}{2.03}} e^{-0.36} = 0.0361$$

3. Frequency of lane-deviation collision when driver is inattentive

$$\omega_{f} = Q_{f} \omega_{a0} \frac{\mu_{2}}{\mu_{i1} + \mu_{2}} e^{-\mu_{i1} t_{0}} = 7.69 \times 10^{-6}$$

This indicates that an average driver will cause a collision triggered by a lane-deviation collision once every 100 years, assuming that they drive their car for 500 h each year. That is, one driver out of three will cause a lane-deviation collision once in their lifetime while reacting to obstacles on roadside.

4.2. Comparison with accident statistics

In this section, the derived frequency of rear-end collisions and lane-deviation collisions are compared with the actual accident statistics from the national traffic assessment database and traffic accidents database of Japan.
(1) Rear-end collision

(a) Accident statistics
Travelling distance of all traffic on the national roads of Japan per year: 1.33×10^11 km
Number of accidents: 231,677

(b) Estimated number of accidents using the model
Average speed: 40 km/h
Traveling hours: 3.32×10^9 h (1.33×10^11 km / 40 km/h)
Consequently, Number of estimated accidents: 6.94×10^7 × 3.32×10^9 = 2.30×10^11

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

(2) Lane-deviation collision

(a) Accident statistics
Number of accidents: 25,884

(b) Estimated number of accidents using the model
Estimated accidents number: 7.69×10^4 × 3.32×10^9 = 2.55×10^11

The result is close to that of the actual accidents statistics 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, ω0, which represents the probability of risky traffic situations, was assumed to be once per hour in the case of rear-end collision and once per three hours in the case of lane-deviation collision. These values require validation.

Moreover, it is important to continue the discussion on the validity of subjective drivers. In this research, 22 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 little variation.

5. Effectiveness of estimation of distraction alarm

A system that detects driver distraction or a drowsiness condition and triggers an alarm is under development. In this section, the effectiveness of using distraction alarms in minimizing traffic accidents is estimated.

Fig. 10 shows the estimated frequency result using 1/μ11* as a parameter in Fig. 4. In this part of study, a parameter of 1/μ11* meaning shown in the horizontal axis meaning the evasive reaction time was changed and the probability of collision was estimated through the above ω9 which means the frequency of a rear-end collision. It is shown that when the reaction time is shortened to 1.00 s from 2.03 s, which was determined in the driving simulator study, the probability of a lane-deviation collision will be nearly zero.

Fig. 11 Relationship between evasive reaction time to avoid rear-end collision under visual distraction and the probability of collision

6. Conclusions

6.1. Quantification of the probability of accidents

Rear-end collision
In this study, the probability of rear-end collision was quantified as 6.94×10^7. This indicates that an average driver will cause a rear-end collision once every 30 years. This implies that all drivers will cause a rear-end collision at least once in their lifetime. Using this probability, the frequency of rear-end collisions on Japanese national roads can be estimated as 2.30×10^11 per year. This is close to the actual number of rear-end collisions (231,677) based on traffic databases.

Lane-deviation collisions due to obstacles on the roadside
In this study, the probability of rear-end collision was quantified as 7.69×10^9. This indicates that an average driver will cause a collision triggered by a lane-deviation collision once every 100 years. In other words, one driver out of three will cause a lane-deviation collision due to obstacles on roadside once per lifetime. Using this probability, the frequency of lane-deviation collision on Japanese national roads can be estimated as 2.55×10^11 per year. This is close to the actual number of lane-deviation collisions (25,884) based on traffic databases.
6.2. Relationship between distraction and accident-occurrence probability

When visual distraction can be shortened to 1.00 s using distraction alarm equipment, rear-end collisions can be reduced to about one third compared with the probability when the equipment is not used. For lane deviation, the collision with an obstacle can be reduced to nearly zero.

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