From RT to POC: Proposal for Computation of Probability of Automobile Accidents from Empirical Reaction Time Distribution

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ABSTRACT
The main aim of this paper is to propose an objective assessment of the likelihood of automobile accidents, by computing probability of collision (POC) from the driver’s reaction time (RT) distribution. Since the driver’s RT distribution is strongly dependent on his/her arousal level, we measured eye-opening rate (EOR) from real-time image analysis of the driver’s eye, and estimated the RT distributions separately for different EORs. To examine the reliability of our proposed method, we conducted an experiment in which RTs and EOR were measured while participants were driving a driving simulator. The results show that, with other parameters constant, the resulting POC is higher for low EOR (e.g., low arousal level), as expected.

Keywords: Reaction time, Probability of collision, Eye-opening rate, Arousal level, Automobile accident.

1. INTRODUCTION
One of the main themes in transportation research is to assess the momentary likelihood of an automobile accident in a given situation, for providing drivers with a safety indicator and, if necessary, a warning. Most of the assessment indexes proposed thus far (time headway, time-to-collision, etc) [1-3] are computed solely from physical parameters, such as driving velocity and distance from a lead car. However, human factors are also involved in automobile accidents. As a new, improved index, Matsuki [4] proposed probability of collision (POC), which takes driver’s reaction times (RTs) into consideration (for details, see the next section). This paper extends Matsuki’s approach, by further taking into consideration the driver’s arousal level. It is well known that RTs and driving performance change with arousal level [5-6]. As an index of arousal level, we use eye-opening rate (EOR) [7] and propose to compute POC from RTs separately for different EOR. We evaluate our proposed method by an experiment in which RTs and EOR are measured simultaneously in a simulated driving situation.

2. PROBABILITY OF COLLISION
POC is defined as the probability of rear-end collision with a car ahead when it stops suddenly [4]. The collision occurs when the stopping distance of the following car $D_{st}$ exceeds the following distance $D_f$, the distance between the rear of the lead car and the head of the following car. $D_{st}$ is expressed with the following car’s velocity $v$, driver’s reaction time $T$, coefficient of friction between tires and roadway $\mu$, and acceleration of gravity $g$, in the following equation:

$$D_{st} = Tv + \frac{v^2}{2\mu g} \quad (1).$$

As we state above, the rear-end collision occurs when

$$D_f < T v + \frac{v^2}{2\mu g} \quad (2).$$

In Equation (2), all variables except $T$ are physical parameters which are measurable at a given moment, whereas $T$ is indeterministic and can only be estimated stochastically. Therefore, $T$ is represented by a stochastic variable $x$, with its probability density function $f(x)$. $F(t)$, the probability distribution for RT, is defined as

$$F(t) = \int_{-\infty}^{t} f(x) dx \quad (3).$$

Rearranging Equation (2), we obtain
EOR is defined as the ratio of the vertical width of driver’s eye-opening at a given moment to the eye-opening width at a high arousal level [7]. The vertical width of eye-opening is the height of palpebral fissure. Although several other indexes of arousal level have been proposed (e.g., EEG, blood flow, cardiac rate) [8-10], a major advantage of EOR is that it is measured non-intrusively. While other indexes require attachment of equipment with the driver’s body, EOR is measured from an image of the driver’s eye taken by a video camera. We have developed a measuring system with a standard personal computer and a commercial digital video camera (30 Hz frame rate) that computes EOR in real time (less than the time for 1 frame, 1/30 second). This temporal resolution is higher than that of other indexes of arousal level. The detail of our measuring system will be given in the next section.

In this paper, we classify EOR values into three ranges, Low (lower than 70%), Mid (from 70 to 95%), and Hi (higher than 95%), and compute POC from RT data separately for those ranges. A previous study has shown that the classification yields sufficient numbers of RT data for each EOR range [7]. Our preliminary investigation has also shown that those three ranges of EOR values are correlated with verbal reports of drowsiness during an RT experiment [11, 12].

4. EXPERIMENT

4.1 Participants
Three males of 23 to 24 years old participated. One of them was the first author. None of them had difficulty in seeing the stimuli used in this experiment.

4.2 Apparatus
A custom-made driving simulator was used. The simulator consisted of a driver’s seat with a handle (not used here), brake and accelerator pedals, and a 42-inch full-color display (TOSHIBA, REGZA 42C3500) which presented computer graphics simulating the front view of a running car. The graphics was created by a personal computer (DELL, Precision T7400) and image softwares (Microsoft Direct X 9.0, e-frontier Shade 10, and Adobe Photoshop CS3) This computer also controlled experimental timing and RT measurement with an optical time counter. The velocity of the car in the graphics was controlled by the brake and the accelerator pedals. A second computer (order-made PC) received data from those pedals and transmitted them via gigabit Ethernet LAN to the above-mentioned simulator-control computer. Using this data, the simulator-control computer calculated the positions of all materials in the graphics for the next frame. The apparatus for EOR measurement are described in Section 4.5.

4.3 Stimuli
The front view of the simulator showed 2 straight lanes, where the driver’s car ran on the left lane, and a black car driving ahead in the same lane. The driver was not allowed to change lanes or directions. The driver controlled his/her car’s velocity by the accelerator and the brake pedals, and the velocity was expressed by optical flow of the road, side walls, and the sky shown in the front view. The lead car ran at 60 km/h, except when it slowed down suddenly (see below).

The stimulus for the driver to respond was the brake lights of the rear of the lead car. When the lights turned on and the lead car slowed down suddenly, the driver was required to stop the car by stepping down the brake pedal to avoid collision. The presentation timing of the brake lights followed an exponential distribution of the time from a previous presentation of the brake lights, with a mean of 30 sec. Exponential distributions have previously been used to set foreperiods for stimulus presentation in simple RT experiments [13]. In this experiment, there were additional constraints on the stimulus presentation that the brake lights turned on only when the following distance from the lead car was between 5 and 30 m and the driver was stepping on the accelerator pedal. The luminance of the brake lights when they were on and off were 78.8 and 8.62 cd/m², respectively. These values adhere to the motor vehicle safety standard in Japan.

4.4 Procedure
The participants were instructed to keep looking at the rear of the lead car and to hit the brake pedal as soon as the brake lights of the lead car turned on. The time between the presentation of the brake lights and hitting the brake pedals was measured as RT, with millisecond precision. Each session consisted of 20 stimulus presentations, thus 20 RT measurements. Each participant completed 15 sessions.

4.5 EOR measurement
During an experimental session, EOR was measured from images of the participant’s left eye that were taken by a digital video camera (SONY, HDR-SR1) with 56 infrared LEDs which enabled taking images in darkness. The images were captured at 30 Hz with a frame grabber (Cyber Optics, PXC200) on a personal computer (DELL, Precision 690). The spatial resolution of the images was 640 × 480 pixels. To precisely measure eyelid positions in real time, a small reflection sheet (5 mm × 5 mm) was attached to the participant at slightly below the lower eyelid of the left eye, and the lower eyelid position in the captured image was defined relative to the center of the attached sheet. In the image analysis, the area of reflection sheet was extracted first, then the lower eyelid position was calculated. The edge line of the upper eyelid was detected from luminance gradient of the upper eyelid. The upper eyelid position was defined as the intersection of a vertical line drawn from the lower eyelid position with the edge line of the upper eyelid. The distance between the lower and the upper eyelid position was computed and taken as the vertical width of eye opening. It should be pointed out that the vertical width of eye opening computed here is not precisely equivalent to the height of palpebral fissure. However, this does not invalidate the value of EOR per se, because EOR is a relative measure of momentary eye-opening to that measured with the same system and for the same participant at a high arousal level.

Specifically, momentary EOR is computed as the ratio of the
average value of eye-opening over a 1-second time-window to
the eye-opening at high arousal. The eye-opening at
high-arousal is defined as the average eye-opening over 30
seconds at the beginning of each experimental session.

The computer of the EOR measurement system was linked via
gigabit LAN with the computer controlling the driving
simulator (see Section 4.1). The two computers transmitted
synchronization signals between each other, to record
Corresponding EOR and RT.

5. FITTING REACTION TIME MODELS

For each participant, a total of 300 RT data were used to
estimate RT distributions. We fitted to the data ex-Gaussian
distributions [13], which is expressed by the equation
\[
f(t) = \lambda \exp(-\lambda t) \exp \left( \frac{t - \mu}{\sigma^2} \right) \Phi \left( \frac{t - \mu - \lambda \sigma^2}{\sigma} \right)
\]
where \( \Phi(x) \) is standard normal cumulative distribution
function, \( \mu \) is the mean of Gaussian distribution, \( \sigma \) is the
variance of Gaussian distribution, and \( \lambda \) is the inverse of the
mean of exponential distribution. Ex-Gaussian is the
convolution of exponential and Gaussian density functions, and
it has been found to be successful in approximating simple RT
data [13].

In our preliminary investigation, we used other sets of RT data
and compared the fitting of reaction time models to the data [11,
12]. The models fitted were log-normal (Gaussian), gamma,
Gumbel, Weibel, Wald, and ex-Gaussian, all of which are often
used to approximate RT data. The comparison was made with
Akaiake Information Criteria (AIC) [14] and estimation error
variance. For both criteria, ex-Gaussian yielded the best fit to
the data.

Ex-Gaussian also provided good fit to the present sets of data.
The fitting was performed separately for three ranges of EOR
values (Hi, Mid, Low; see Section 3) for each participant.
First, probability density was obtained from each set of RT data
by Gaussian kernel estimate [15]. Kernel estimate is computed
by the following equation,
\[
\hat{f}_T(t) = \frac{1}{Nh_N} \sum_{i=1}^{N} \phi \left( \frac{T_i - t}{h_N} \right)
\]
where \( T_i \) is i-th RT, \( N \) is total number of RT, \( h_N \) is the band
width. The function \( \phi(x) \) has to meet the condition that all
\( x \in D \):
\[
\int_D \phi(x) dx = 1, \phi(x) \geq 0
\]
Specifically, Gaussian kernel estimate uses the Gaussian
distribution for \( \phi(x) \):
\[
\phi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2}
\]
The band width \( h_N \) follows Silverman’s method [16]
\[
h_N = \frac{0.9}{N^{0.2}} \min \left( \frac{q_3 - q_1}{1.349}, \frac{1}{s} \right)
\]
where \( q_1 \) and \( q_3 \) are the first and third quartiles, and \( s \) is the
standard deviation of the RT data.

Next, ex-Gaussian (Equation 6) was fitted to the density. Fig.1
shows the result for one participant, RT data and best-fitting
curves separately for three ranges of EOR. Table 1 shows the
estimates of parameters for the best-fitting curves. The results
for the other two participants (not shown) were equally good.

Fig. 2 shows the averages of RT data and the sum of the
best-fitting estimates of \( \mu \) and \( 1/\lambda \) to the data. Since \( \mu \)
and \( 1/\lambda \) are means of Gaussian and exponential terms of
ex-Gaussian distributions, their sum corresponds to the mean
of ex-Gaussian. The figure shows excellent correspondence
between the data and the best-fitting distribution in terms of
mean.

<table>
<thead>
<tr>
<th>EOR</th>
<th>( \lambda )</th>
<th>( \mu )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi</td>
<td>0.011</td>
<td>713.2</td>
<td>64.6</td>
</tr>
<tr>
<td>Mid</td>
<td>0.012</td>
<td>746.0</td>
<td>69.1</td>
</tr>
<tr>
<td>Low</td>
<td>0.004</td>
<td>714.6</td>
<td>72.9</td>
</tr>
</tbody>
</table>

6. COMPUTING POC

Using the best-fitting ex-Gaussian distributions as \( f(x) \) in the
operation explained in Section 2, we computed POC separately
for different EOR ranges for each participant. Fig. 3 presents
the results for one participant (the same person as Figs. 1-2 and
Table 1) with the following distance $D_F$ set at 20 m. It is seen in the figure that POC is higher for lower EOR. When the velocity is 44 km/h, for example, POC is 0.68 for Hi, 0.79 for Mid, and 0.85 for Low. This indicates that the likelihood of collision with the car ahead is higher as the driver’s arousal level becomes lower, as expected. The other participants showed similar results.

Fig. 3  POC computed from best-fitting ex-Gaussian density distributions when $D_F$ is 20m

7. CONCLUSIONS

The experimental data suggest that our proposal for the objective assessment of the likelihood of automobile accidents, that is, the computation of POC from RT distributions for different EOR values, is quite promising. We have developed a real-time EOR measurement system which also realizes real-time computation of POC, and the system works reasonably well for the driving simulator. We are planning to test this system for real cars, in the hope that POC will be used as a new index of safety driving.

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9. REFERENCES

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