Implementing Surrogate Safety Measures in Driving Simulator and Evaluating the Safety Effects of Simulator-Based Training on Risky Driving Behaviors

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Received 26 December 2019; Accepted 23 April 2020; Published 19 June 2020

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1.Introduction

The worldwide number of annual fatalities in traffic crashes reached 1.35 million each year, and this number continues to increase steadily in the world [1]. Human errors cause about 90 percent of all road accidents [2], and the majority of human errors involve risky driving. Drivers with risky driving behaviors such as speeding, following other vehicles too closely (tailgating), erratic driving, and violation of traffic laws accounted for about 52% of severe traffic accidents [3]. Moderating risky driving behaviors have been achieved successfully using a variety of approaches that combine education, engineering, and enforcement; this approach to safety is known as the 3E principle [4]. Driver education has been used extensively to reduce risky driving behaviors. It has been reported to be an effective way to reduce traffic accidents by detecting risky driving behaviors and providing appropriate feedback to reduce these behaviors [5]. Risky driving behaviors should be measured and evaluated quantitatively to give appropriate feedback to drivers in order to reduce risky driving behaviors.

Current driver education programs have focused on educating drivers about the skills and attitudes necessary to become a safe driver. Videos and lectures about traffic
regulations and automobile-related knowledge, on-road training, and simulator-based training generally have been used in driver education programs. Videos and lectures help drivers acquire knowledge about driving safely by providing information about traffic regulations and the appropriate operation of automobiles. However, these approaches to teaching drivers have limitations in that they do not help improve the practical skills that are required in on-road driving [6]. On-road training with a driving instructor is an effective method to educate drivers to drive more safely on the road. However, even professional instruction and on-road training cannot address all of the potential crashes of driving because they cannot expose drivers to the various potential collision situations that can occur on the road.

Driving simulators are used extensively as a tool to instruct drivers to drive in a common driving environment as well as in collision situations that would be too dangerous to create in actual on-road driving [7]. The instructor can design various driving scenarios including myriads of road and traffic environments, movements of surrounding vehicles, and collision scenarios. Therefore, driving simulators can be used to give risky drivers repeated training with various collision situations. Driving simulators can be used to measure driving behaviors quantitatively as well as to acquire the trajectory data for surrounding vehicles [8]. However, there are issues concerning the validity of virtual simulations of real driving environments. Current studies have shown that they have similar patterns, but the driving behaviors in driving simulators and on-road driving may not be the same [7, 9]. In other words, driving simulators can be useful tools for educational purposes in driver education programs. In fact, the driving instructors involved in a previous study thought that one-hour simulator training was as effective as three hours of on-road training [10].

Most research on reducing risky driving behaviors based on driving simulators has been conducted with a focus on drivers’ eye movements and the movements of the subject vehicle, i.e., movements such as erratic acceleration and deceleration, speed variation, and lane deviation [11–14]. Since risky driving behaviors cause severe road crashes, it is necessary to evaluate the crash potential in the interactions between the subject vehicle and surrounding vehicles, such as following leading vehicles (car-following) and changing lanes (lane-changing). However, few studies have evaluated the crash potential between the subject vehicle and surrounding vehicles, which would address the interactions between vehicles [15]. This study implemented realistic interactions between the subject vehicle and surrounding vehicles in a driving simulator by applying traffic flow models to the movements of surrounding vehicles. In addition, we examined surrogate safety measures (SSMs), which are used extensively in the field of road safety as useful measures for assessing crash potential or severity even on roads where no actual collisions have occurred. The SSMs can increase our understanding of the situations that cause collisions. In this study, the SSMs were used to evaluate risky driving behaviors in order to evaluate vehicles’ crash potentials.

The aim of this study was to determine whether the SSMs can identify risky driving behaviors in driving simulators and whether the SSMs are effective in improving drivers’ behaviors when the SSMs are used as evaluation measures in the simulator-based training.

2. Literature Review

Risky driving behaviors are defined differently by many organizations and in many studies. Since the motivation of a driver is difficult to determine, risky driving behaviors can only be judged and evaluated based on the motions of vehicles [16, 17]. Risky driving behaviors mean taking risks that endanger the safety of both the driver and other road users [18]. Generally, risky driving behaviors include speeding, noncompliance with traffic laws, tailgating, reckless changing speeds, erratic lane-changing, and threats to other drivers (yelling and horn honking) [3, 16, 19].

Driving simulators have been used increasingly for driver education because of the advantages they provide, including the freedom to present drivers with a wide variety of scenarios without any threat to their safety or the safety of other people [20]. Studies on reducing or evaluating risky driving behaviors using driving simulators have investigated mainly risky driving behaviors in terms of the drivers’ reactions and the movements of vehicles. Studies of drivers’ reactions have used the movements of the eyes, the focus of gazes, the duration of glances, and the number of fixations as measures to evaluate drivers’ physical responses to collision situations [11, 14, 21]. These studies have shown that drivers’ perceptions of conflict situations improve after they have had driving education in which eye-tracking systems to improve the ability of novice drivers and older drivers to recognize situations where collisions could occur. Various studies have used response time, pressure on the accelerator, and pressure on the brake pedal to measure drivers’ responses to collision situations and red lights at intersections [12, 13, 22]. Measures related to drivers’ reactions were used mainly to evaluate risk perception rather than to reduce risky driving behaviors.

Most of the studies related to the movements of vehicles have focused on the movements of the subject vehicle, and they evaluated primarily the risky behaviors of the drivers of the subject vehicle, e.g., erratic steering control, speeding, and tailgating. Erratic steering control involves the driver’s sudden and unexpected changes in steering the vehicle or how far the driver allows the vehicle to deviate from the center of its lane. The steering angle, steering reversal rate, lane deviation, and mean lane position have been used in assessing erratic steering control [13, 14, 22–24]. Velocity, mean speed, speed variation, speeding, and acceleration are speeding-related measures that can be used to determine the driver’s compliance with the speed limit and the reckless changing of speed [13, 14, 22, 25]. Evaluations of the gap distance between vehicles and time-to-collision (TTC) with a leading vehicle were made mainly in a car-following situation [15, 22]. However, the gap distance between vehicles and the TTC between the subject vehicle and the leading vehicle cannot take into consideration the accelerations and
decelerations of either vehicle. Also, few studies have considered the potential for crashes between vehicles when they are changing lanes [26].

Most studies have attempted to evaluate the effects of simulator-based training on risky driving behaviors. These studies focused principally on risky driving behaviors related to the movements of the subject vehicle. Since most risky driving behaviors require consideration of the subject vehicle’s interactions with surrounding vehicles, it is essential to evaluate the crash potential with one or more of the surrounding vehicles. However, research considering the interactions between vehicles has rarely been conducted because the movements of surrounding vehicles would not be implemented realistically. This study attempted to introduce the SSMs into a simulator-based training program to evaluate the crash potential between vehicles and to reduce the risky driving behaviors associated with the surrounding vehicles.

3. Methodology

3.1. Framework. This study consisted of three parts: a survey of SSMs and scenario design, a preliminary experiment, and a simulator-based training program (see Figure 1). The SSMs can be classified into measures that consider only the subject vehicle and measures that consider both the subject vehicle and surrounding vehicles. Before the SSMs were used as measures of driving behaviors, it was necessary to test whether the SSMs could detect risky driving behaviors and conservative driving behaviors in a driving simulator. This study conducted a preliminary experiment for the sensitivity analysis of SSMs. The purpose of the sensitivity analysis of SSMs was to ensure that SSMs could detect extreme driving behaviors, i.e., normal, conservative, and risky driving. In a preliminary experiment, each driver was required to engage in one of the three types of driving behaviors (normal, conservative, and risky) in the driving simulator. Finally, this study used a quantitative evaluation based on the SSMs to analyze whether drivers reduced their risky driving behaviors after engaging in the simulator-based training program.

3.2. Survey of Surrogate Safety Measures. Since a simulator-based training requires immediate feedback concerning which driving behaviors are risky in the various driving scenarios, it is crucial to be able to calculate the SSMs used in the simulator-based training within a short time after driving in the driving simulators. This study reviewed numerous studies about road safety in order to investigate the SSMs that can be used in simulator-based training, and 31 SSMs were selected as alternatives. Since 11 of the SSMs were challenging to calculate instantaneously in driving simulators or unsuitable in evaluating driving behaviors, 20 out of the 31 SSMs were selected as implementable SSMs. For example, the Crash Index is a measure concerning the severity of a potential crash, and it is presented in the form of the kinetic energy of the crash [27]. It is challenging to translate kinetic energy values into an easily understandable account of the risk associated with a given participant’s driving behaviors. Thus, this study excluded the Crash Index from the implementable SSMs and selected implementable SSMs as measures that can be explained easily to the drivers in simulator-based training.

The implementable SSMs were divided into “Relating to the subject vehicle” and “Relating to surrounding vehicles,” depending on whether or not the SSMs related to interactions with surrounding vehicles. The SSMs relating to the subject vehicle can be calculated without any interactions with surrounding vehicles (nos. 1 to 9 in Table 1). The SSMs relating to surrounding vehicles consider interactions with surrounding vehicles, such as car-following situations and lane-changing situations (nos. 10 to 20 in Table 1). The gap distance in the car-following situation (no. 10) was used to confirm the validation of driving errors between the driving simulator and on-road driving [7]. The time-to-collision (TTC, no. 12) was used for studies in which driving behaviors in critical situations were compared [15, 22, 35]. However, the gap distance and the TTC between the subject vehicle and the leading vehicle have the limitation that the difference between the acceleration of the subject vehicle and the deceleration of the leading vehicle cannot be considered. This study used modified TTC (no. 13) and deceleration rate to avoid crash (no. 14) to evaluate the crash potential by considering the difference between the acceleration of the subject vehicle and the deceleration of the leading vehicle in situations where the subject vehicle is following the leading vehicle. The study in which the driving behaviors were analyzed in the lane-changing situation used the gap distance (no. 16 and no. 17) with the surrounding vehicles in a target lane [26]. This study adopted the SSMs (nos. 13, 14, 19, and 20) that had not been used to reduce risky driving behaviors in existing driving education programs to assess the crash potential between the subject vehicle and surrounding vehicles properly. The contribution of this study is to secure the effectiveness of driver education by capturing interactions between a subject vehicle and surrounding vehicles based on the simulator-based training using SSMs and then ultimately induce the prevention and reduction of road accidents.

The SSMs consist of measures with a single outcome for the dataset and measures with continuous outcomes calculated at every time step of the dataset. Accumulated speeding (AS), speed uniformity (SU), speed variation (SV), acceleration noise (AN), and lane deviation were measured with a single outcome and calculated after completing the driving scenarios. Measures with continuous outcomes should be transformed into a single representative value in order to evaluate how risky the drivers’ driving behaviors were.

A single representative value of SSMs can be obtained either as the maximum (minimum) value of total outcomes, such as Max S, i.e., the maximum velocity in a conflict situation [33] or as the ratio of conflicts defined as exceeding the threshold value of each measure [27, 36]. This study adopted the minimum value as the representative value for SSMs related to lane-changing situations (see nos. 15 to 20 in Table 1). The method to define the threshold value for
### Table 1: Description of implementable surrogate safety measures.

<table>
<thead>
<tr>
<th>Relation with surrounding vehicles</th>
<th>No.</th>
<th>Surrogate safety measure</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relating to the subject vehicle</td>
<td>1</td>
<td>Accumulated speeding (AS)</td>
<td>kph</td>
<td>The normalized relative area (per unit length) bounded between the speed profile values higher than the speed limit and the speed limit line [28]</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Speed uniformity (SU)</td>
<td>kph</td>
<td>The normalized relative area (per unit length) bounded between the speed profile and the average speed line [28]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Speed variation (SV)</td>
<td>kph</td>
<td>The standard deviation of the speed</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Acceleration (%)</td>
<td>m/s²</td>
<td>The acceleration of the subject vehicle</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Deceleration (%)</td>
<td>m/s²</td>
<td>The deceleration of the subject vehicle</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Acceleration noise (AN)</td>
<td>m/s²</td>
<td>The root mean square deviation of the acceleration [29]</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Lane deviation</td>
<td>m</td>
<td>The rotational velocity around the z-axis of the subject vehicle [31]</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Yaw rate (%)</td>
<td>°/s</td>
<td>The number of lane change manoeuvres completed</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Lane change (%)</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Relating to surrounding vehicles</td>
<td>10</td>
<td>Gap distance (%) (GD)</td>
<td>m</td>
<td>The longitudinal distance along a travelled way between one vehicle’s leading surface and another vehicle’s trailing surface [32]</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Proportion of stopping distance (%) (PSD)</td>
<td>—</td>
<td>The ratio of the distance available for manoeuvring to that of the necessary stopping distance to a projected point of collision [33]</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Time-to-collision (%) (TTC)</td>
<td>sec</td>
<td>The time interval required for one vehicle to strike another object if both objects continue on their current paths at their current speed [32]</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Modified TTC (%) (MTTC)</td>
<td>sec</td>
<td>The time interval required for one vehicle to strike another object if both objects continue on their current paths at their current speed and acceleration [32]</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Deceleration rate to avoid crash (%) (DRAC)</td>
<td>m/s²</td>
<td>The deceleration required by the following vehicle to come to a timely stop or attain a matching lead vehicle speed to avoid a rear-end crash [34]</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Min_Front_GD</td>
<td>m</td>
<td>The minimum value of gap distance (GD) with leading vehicle of current lane in lane-changing situation</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>Min_Lag_GD</td>
<td>m</td>
<td>The minimum value of gap distance (GD) with lag vehicle of target lane in lane-changing situation</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>Min_Lead_GD</td>
<td>m</td>
<td>The minimum value of gap distance (GD) with leading vehicle of target lane in lane-changing situation</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>Min_Front_TTC</td>
<td>sec</td>
<td>The minimum value of time-to-collision (TTC) with leading vehicle of current lane in lane-changing situation</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Min_Lag_TTC</td>
<td>sec</td>
<td>The minimum value of time-to-collision (TTC) with lag vehicle of target lane in lane-changing situation</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Min_Lead_TTC</td>
<td>sec</td>
<td>The minimum value of time-to-collision (TTC) with leading vehicle of target lane in lane-changing situation</td>
</tr>
</tbody>
</table>
counting the number of conflicts in each of the SSMs was derived from the existing literature [37]. The 85th percentile value of total participants’ driving data distribution was used as the threshold for SSMs for which higher values indicated more risky driving behaviors (acceleration (%), yaw rate (%), lane change (%), gap distance (%), and proportion of stopping distance (%)). For SSMs for which lower values indicated more risky driving behaviors (deceleration (%), time-to-collision (%), modified TTC (%), and deceleration rate to avoid crash (%)), the 15th percentile value of total participants’ driving data distribution was used as the threshold.

3.3. Driving Simulator and Scenario Design. The driving simulator used in this study was mounted on a six-degree-of-freedom motion system, with a size of 3500 × 3500 × 3500 mm. The visual system for the driving simulator consisted of three 43-inch full HD LED monitors, providing a 150-degree field of view with a resolution of 5760 × 1080 pixels and a 60 Hz refresh rate. The virtual environment with various driving conditions was represented through the three monitors, with rear-view and side-view mirrors visible on the center monitor and side monitors, respectively (Figure 2(a)). The vehicle dynamics were validated based on the real motion of the Hyundai Sonata.

A part of the street grid in Seoul was implemented in a virtual environment in order to enhance the reality of the driving environment. The total length of the designed route in the scenario was 10.1 km, including freeway (2.3 km), urban roads (6.0 km), and rural roads (1.8 km) (Figure 2(b)). The freeway consisted of the main freeway segment with a posted speed limit of 110 kph and an off-ramp. The urban roads included ten signal intersections located every 200–400 m on a four-lane two-way road with a speed limit of 60 kph. The rural roads were either two- or four-lane, two-way roads with a speed limit of 80 kph.

The movements of surrounding vehicles significantly determine the mental load and ability to drive a vehicle. If the movements of the surrounding vehicles were not real enough, there is a possibility that drivers will drive a vehicle differently than they would in actual driving, meaning that the results and conclusions obtained from the simulation would not be applicable in actual driving. Many studies using driving simulators have been limited in expressing realistic movements because the movements of the vehicles were very strictly controlled to assess the drivers’ abilities in certain crash situations [38]. Therefore, if the movements of the surrounding vehicle are unrealistic and strictly controlled irrespective of the movements of the subject vehicle, it would be difficult to expect the reduction of risky driving behaviors in actual driving on the road through simulator-based training. In order to implement the realistic interactions with surrounding vehicles, traffic flow models (i.e., a car-following model, a lane-changing model, and a gap-acceptance model) were modeled based on video data and vehicle trajectory data, and then, they were applied to the movements of the surrounding vehicles. Using the traffic flow models had the additional benefit of showing different movements in each trial, thereby increasing the sense of reality and preventing participants from adapting to the scenario [38]. The generalized model of car-following was estimated with data obtained from random vehicles on the West-Hanam IC and the West-Icheon IC of the Jungbu Highway [39]. The lane-changing model was implemented based on the vehicle trajectory data measured by nine video cameras in the upper 400 m section of the Middle East IC of the Seoul Ring Expressway for discretionary and mandatory lane-changing. The parameters of a logit model were estimated with the gap distance and the speed of the subject vehicle as independent variables. The logit model was estimated for the gap-acceptance model at the intersection. Data were collected using video cameras at six intersections in Seoul to estimate the parameters of the gap-acceptance model, and the data included the time gap, type of vehicle, and traffic volume. This study estimated the parameters of the logit models for an unprotected left turn, an unprotected right turn, and a roundabout using collected data.

3.4. Preliminary Experiment for Extreme Driving Behaviors with SSMs. This study conducted a preliminary experiment to analyze the sensitivity of SSMs for extreme driving behaviors. Before participating in the preliminary experiment, the participants were shown how to control a driving simulator and performed one to three minutes of practice driving to prevent simulator sickness and to adapt to the virtual environment of the driving simulator. To use the SSMs that could measure the crash potential of surrounding vehicles in a driving simulator, the sensitivity analysis of the SSMs was required to determine whether they could capture risky driving behaviors. In this study, the experimental methods that had been used in previous studies were used to analyze the sensitivity of the SSMs to extreme driving behaviors. Past participants were involved in a study of extreme driving behaviors that compared the difference in fuel consumption depending on driving behaviors and compared the difference in the performance of an urban network on driving behaviors [40, 41].

Participants in the preliminary experiment were asked to drive “normally,” “conservatively,” or “riskily.” In normal driving, the participants drove the way they usually drive. In the conservative driving condition, the participants were asked to maintain a greater safe following distance, accelerate and decelerate as gently as possible, and keep their speed under the speed limit. In risky driving, the participants were required to complete their driving route within 10 minutes rather than the typical 15 minutes, to follow the leading vehicle more closely than the recommended safe distance, and to change lanes and the speed of the vehicle erratically.

3.5. Simulator-Based Training to Improve Driving Behaviors. This study used SSMs that statistically could capture risky and conservative driving within the simulator-based training conducted by the Korea Transportation Safety Authority (KOTSA). The simulator-based training consisted of three parts, i.e., driving before the intervention, intervention
Before the intervention, the participants drove an introduction drive for 1 to 3 minutes to become accustomed to the control of the driving simulator and the virtual environment. Subsequently, they drove the driving scenario as they usually would do, allowing the instructor to examine the extent of their risky driving behaviors.

The intervention consisted of two parts: feedback with a video replay of the driver’s driving and a commentary video. The instructors provided feedback to the participants concerning how risky they drove in terms of six risky driving behaviors, i.e., speeding, reckless changing speed, rapid acceleration and deceleration, erratic steering control, tailgating, and erratic lane-changing. The speeding, reckless changing speeds, rapid acceleration and deceleration, and erratic steering control only assessed the movements of the subject vehicle. In contrast, the tailgating and erratic lane-changing assessed the crash potential with the surrounding vehicles in the normal driving environment. In typical drivers’ education programs, the instructor evaluates the drivers’ driving behaviors based on the movements of the subject vehicle and the crash potential with the surrounding vehicles in specific situations (i.e., speeding, reckless changing speeds, rapid acceleration and deceleration, and erratic steering control). In the simulator-based training using the SSMs of this study, the instructor informed the drivers the risky driving behaviors, including situations in which they were following a vehicle and changing lanes in a common driving environment and were riskier than other drivers. In other words, the contribution of this study is to evaluate the movements of the subject vehicle as well as the interactions between vehicles by identifying the risky driving behaviors such as tailgating in car-following situations and erratic lane-changing in lane-changing situations. Also, the instructor educated the drivers about safe methods for driving on the road to reduce the crash potential between the vehicles. In the commentary video, videos of actual crashes attributable to each of the six risky driving behaviors were shown to encourage safe driving.

After the feedback session at the end of the intervention, the drivers were asked to drive again so that their driving behaviors could be observed in order to determine whether their driving behaviors had been improved; i.e., whether their risky driving behaviors were reduced. The instructor showed the participants how much their driving had improved in terms of the frequency of six risky driving behaviors and to encourage safe driving.

3.6. Participants. For this study, we posted advertisements and recruited 43 participants for the preliminary study. Out of the 43 participants, 12 participants dropped out of the experiment due to simulator sickness, leaving 31 participants, i.e., 21 males and 10 females. The average age of the participants was about 36 years old, and the average driving experience of participants was almost 13 years.

Existing research on simulator-based training was mainly conducted with novice, elderly, and commercial drivers [13, 20, 23, 42, 43] because drivers in these three groups tend to have higher accident rates, making them the primary targets for improving risky driving [44–46]. Participants in the simulator-based training were recruited separately from the three driver groups by posted advertisements. Out of 69 participants, 11 participants dropped out of the experiment due to simulator sickness, leaving 58 participants, i.e., 21 novice drivers, 16 elderly drivers, and 21 commercial drivers. The average age of the participants was approximately 46 years old, and the average driving experience of participants was slightly more than 20 years. The demographic statistics of the participants are provided in Table 2.

4. Results

4.1. Results of the Sensitivity Analysis for Extreme Driving Behaviors with SSMs. In this study, we conducted a
sensitivity analysis for extreme driving behaviors to test whether SSMs could significantly distinguish between normal, conservative, and risky driving. Twenty SSMs were analyzed for extreme driving behaviors for 31 drivers. The SSMs were analyzed for the entire road section and the freeway section because the lane-changing in the urban road section was forced due to the direction of the designed travel route, in contrast to the discretionary lane changes in the freeway section. In this study, driving behaviors except lane-changing were evaluated over the entire road section, but lane-changing was evaluated only for the freeway section. Also, an ANOVA test and a post-hoc test (Tukey HSD) at the 95% significance level were performed to evaluate whether the SSMs could detect significant differences in extreme driving behaviors across the different conditions.

Differences were not statistically significant for five SSMs, i.e., lane deviation, DRAC, Min_Front_GD, Min_Lead_GD, and Min_Lag_TTC (Table 3). Lane deviation and DRAC, which evaluate driving behavior over the entire road section, did not exhibit significant differences. Few studies have compared lane deviations for different degrees of extreme driving behaviors. However, one previous study found that there was no significant difference in the mean of lane deviation before and after training [25]. In contrast to GD, TTC, and DRAC, the measure of minimum deceleration to avoid a collision has been known to be limited to reflect a conflict situation, and drivers may fail to adjust DRAC to avoid a conflict situation [47].

When a driver changes lanes on the freeway, the subject vehicle enters the target lane at a higher speed than the front vehicle in the current lane and the lead vehicle in the target lane. Min_Front_GD and Min_Lead_GD become shortened when changing lanes, and the driver changed lanes in a situation in which the driver maintained the distance between the surrounding vehicles necessary for changing lanes. Regardless of the driver’s extreme driving behaviors, Min_Front_GD and Min_Lead_GD were not significantly different. However, Min_Front_TTC and Min_Lead_TTC, which reflect the relative speed differences between vehicles, showed statistically significant differences because the entry speed in risky driving is higher than that in conservative driving. Min_Lag_GD showed a statistically significant difference because drivers changed lanes at a shorter gap distance in risky driving and a longer gap distance in conservative driving than in normal driving. In the scenario of this study, the lag vehicle in the target lane decelerated when the subject vehicle entered the target lane because the car-following model was applied to the movements of surrounding vehicles. Therefore, there was no statistically significant difference between the extreme driving behaviors of Min_Lag_TTC due to the decrease in the speed of the lag vehicle even though the distance between the subject vehicle and the lag vehicle in the target lane was shorter in risky driving.

### 4.2. Results of Improvement for Risky Driving Behaviors with SSMs

In this study, we classified 15 SSMs into six types of risky driving behaviors to improve the driver’s understanding of SSMs in an intervention of simulator-based
4.2.1. Comparison among Novice, Elderly, Commercial, and Typical Drivers. Before analyzing the effect of simulator-based training using SSMs on the improvement of driving behaviors, it was necessary to identify how risky the drivers participating in the simulator-based training were. This is because drivers who had safe driving behaviors were less likely to improve their driving behaviors, even though they were trained. In this study, 31 drivers who participated in the sensitivity analysis experiment were selected as typical drivers to compare with the three driver groups, i.e., novice, elderly, and commercial drivers. Because the 31 drivers were recruited randomly irrespective of gender, age, and driving experience, the risky driving behaviors of the three driver groups before the intervention were analyzed and compared based on the normal driving of typical drivers. The larger the values of Min_Lag_GD, Min_Front_TTC, and Min_Lead_TTC were, the safer the drivers’ driving behaviors drivers were. The smaller the values of the other SSMs were, the safer the driving behaviors of the drivers were (see Figure 3).

Novice drivers were found to be riskier than typical drivers except for Min_Lag_GD and Min_Lead_TTC (see Figure 3). Novice drivers have poor driving skills because of low driving experience [48]. Since novice drivers have difficulty in maintaining a safe distance from a leading vehicle because of their lack of driving experience, they were inclined to tailgate leading vehicles to a greater extent than typical drivers. Also, novice drivers had limited in-advance perception of dangerous situations, and therefore, it also was difficult for them to maintain a constant speed [43].

Elderly drivers were found to be riskier than typical drivers in the cases of deceleration, AN, and yaw rate. In contrast, other measures of elderly drivers were similar to or safer than that of typical drivers (see Figure 3). These results were consistent with the results that elderly drivers do not perceive the brake pedal pressure in the driving simulator as accurately as young drivers [43].

Commercial drivers were found to be riskier than typical drivers except for lane change and four SSMs related to tailgating (see Figure 3). This suggests that commercial drivers tend to be more risky drivers than typical drivers to save time, but maintaining a safe distance from a leading vehicle is essential for drivers of heavy trucks and buses [42].

4.2.2. Comparison of before and after Intervention by Driver Group. The SSMs used as evaluation measures were statistically tested at the 95% significance level with paired t-tests to determine whether drivers’ behaviors improved before and after the training in simulator-based training (see Table 4). In the case of novice drivers, Min_Lag_GD and Min_Front_TTC in lane-changing situations showed that the improvement before and after the training was not statistically significant. With the exception of AS, acceleration, deceleration, and AN, elderly drivers did not show statistically significant improvements after the training. In the case of commercial drivers, there were statistically significant differences for all measures except for Min_Front_TTC in lane-changing situations. The improvement in driving behaviors after the training was the greatest in commercial drivers and the least in elderly drivers.

In the case of novice drivers, the improvements in speeding, rapid acceleration and deceleration, and tailgating
Figure 3: Comparison of surrogate safety measures by driver group: (a) AS (speeding); (b) SU (reckless changing speeds); (c) SV (reckless changing speeds); (d) acceleration (rapid acc. and dec.); (e) deceleration (rapid acc. and dec.); (f) AN (rapid acc. and dec.); (g) yaw rate (erratic steering control); (h) lane change (erratic steering control); (i) GD (tailgating); (j) PSD (tailgating); (k) TTC (tailgating); (l) MTTC (tailgating); (m) Min_Lag_GD (erratic lane-changing); (n) Min_Front_TTC (erratic lane-changing); (o) Min_Lead_TTC (erratic lane-changing).
were significant, but no significant improvements were observed in erratic lane-changing (see Table 4). Through the simulator-based training, most novice drivers improved their ability to maintain a safe distance from the leading vehicle. However, they did not show improvement in keeping a safe distance from adjacent vehicles in lane-changing situations. Therefore, although novice drivers improved following the simulator training in the car-following situation, additional training should be provided for maintaining a safe distance between vehicles when changing lanes.

Elderly drivers showed improvement in speeding, rapid acceleration, and deceleration (see Table 4). Since elderly drivers tend to be more defensive than other driver groups, they showed the least improvement in risky driving behaviors of the three driver groups. Compared to the younger drivers, elderly drivers were less aware of the brake pedal pressure in a driving simulator during deceleration. They showed a tendency to decrease speed rapidly in the driving simulator before the intervention. After the intervention, the deceleration behavior of elderly drivers was improved because the instructors requested that they begin their deceleration earlier to prevent erratic deceleration. However, there is a limit to the conclusions that the simulator-based training improved the erratic decelerating behavior of elderly drivers since their erratic deceleration behavior may have resulted from their use of the driving simulator.

After the intervention, the driving behaviors of commercial drivers were improved in all 15 SSMs. The improvements in speeding, rapid acceleration, rapid deceleration, and tailgating were more significant than the other risky driving behaviors (see Table 4). Since the commercial drivers had shown more risky driving behaviors than other groups of drivers, their driving behaviors were improved to a greater extent by the simulator-based training than driving behaviors of drivers for other groups. These results showed that the simulator-based training program is effective in reducing risky driving behaviors of various driver groups by providing feedback on how risky their driving behaviors are.

5. Conclusions

This study implemented SSMs in a simulator-based training program to evaluate the crash potential with surrounding vehicles. The movements of surrounding vehicles need to be realistic to consider the interactions with surrounding vehicles in driver education. Traffic flow models developed from data collected on real roads were implemented for the movements of surrounding vehicles (car-following, lane-changing, and gap-acceptance at intersection). Twenty SSMs were implemented in the driving simulator. The preliminary experiment that was conducted with 31 participants verified that 15 SSMs could be used to capture risky driving behaviors. The 15 selected SSMs were used as the measure for current simulator-based training in the Republic of Korea to evaluate the driving behaviors of novice, elderly, and commercial drivers.

After the intervention of the simulator-based training, the risky driving behaviors of novice drivers, elderly drivers, and commercial drivers were reduced in different ways. In the case of novice drivers, additional on-road training was required to reduce risky driving behaviors in lane-changing situations. For elderly drivers, the speeding and rapid acceleration behaviors were improved. However, other risky driving behaviors were not statistically reduced because elderly drivers already drive vehicles safely so that there was nothing to improve significantly except for speeding, rapid acceleration, and deceleration. The training using the driving simulator reduced the risky driving behaviors of commercial drivers. The reason that simulator-

### Table 4: Summary of statistics for surrogate safety measures in before and after intervention.

<table>
<thead>
<tr>
<th>Types of risky driving behaviors</th>
<th>SSMs</th>
<th>Novice (n = 21)</th>
<th>Elderly (n = 16)</th>
<th>Commercial (n = 21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>μ before</td>
<td>μ after</td>
<td>t-stat (p-value)</td>
</tr>
<tr>
<td>Speeding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reckless changing speeds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU</td>
<td>AS 3.54</td>
<td>1.48</td>
<td>5.41 (0.00)</td>
<td>0.71</td>
</tr>
<tr>
<td>SV</td>
<td>AS 15.03</td>
<td>12.97</td>
<td>4.10 (0.00)</td>
<td>13.51</td>
</tr>
<tr>
<td>Rapid acceleration and deceleration</td>
<td>Acceleration</td>
<td>0.24</td>
<td>0.15</td>
<td>6.94 (0.00)</td>
</tr>
<tr>
<td></td>
<td>Deceleration</td>
<td>0.17</td>
<td>0.11</td>
<td>6.07 (0.00)</td>
</tr>
<tr>
<td></td>
<td>AN 2.97</td>
<td>2.27</td>
<td>6.20 (0.00)</td>
<td>2.80</td>
</tr>
<tr>
<td>Erratic steering control</td>
<td>Yaw rate</td>
<td>0.14</td>
<td>0.12</td>
<td>2.85 (0.01)</td>
</tr>
<tr>
<td></td>
<td>Lane change</td>
<td>39.38</td>
<td>36.43</td>
<td>1.89 (0.07)</td>
</tr>
<tr>
<td>Tailgating</td>
<td>PSD 0.19</td>
<td>0.10</td>
<td>4.42 (0.00)</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>TTC 0.21</td>
<td>0.17</td>
<td>2.51 (0.02)</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>MTTC 0.24</td>
<td>0.15</td>
<td>4.39 (0.00)</td>
<td>0.17</td>
</tr>
<tr>
<td>Erratic lane-changing</td>
<td>Min_Lag_GD</td>
<td>27.75</td>
<td>49.99</td>
<td>−0.88 (0.39)</td>
</tr>
<tr>
<td></td>
<td>Min_Front_TTC</td>
<td>76.71</td>
<td>91.01</td>
<td>−0.30 (0.77)</td>
</tr>
<tr>
<td></td>
<td>Min_Lead_TTC</td>
<td>17.09</td>
<td>41.00</td>
<td>−2.66 (0.02)</td>
</tr>
</tbody>
</table>
based training was most effective for reducing the risky driving behaviors for commercial drivers was that their behaviors were risky compared to the behaviors of other groups of drivers.

The results of this study showed that SSMs could be used both for road safety and traffic management strategies and for the evaluation of individual drivers’ driving behaviors in driver education. However, there were two limitations in this study that should be addressed in future research. First, the possibility that adaptation to manipulating a driving simulator after the intervention has a positive effect on reducing risky driving behaviors cannot be ruled out. This study did not compare drivers trained in simulator-based training using SSMs with drivers trained in the previous simulator-based training. In this study, there are improvements in various driving behaviors by giving the drivers feedback using SSMs, but it is possible that intervention without SSMs also could contribute to reducing risky driving behaviors. Therefore, future research should determine the extent to which the intervention based on feedback using SSMs contributes to reducing risky driving behavior compared to existing simulator-based training. Second, it is unclear whether simulator-based training using SSMs will result in the reduction of risky driving behaviors in actual driving. This study only analyzed instantaneous training effects in simulator driving. Future research should examine how simulator-based training using SSMs reduces risky driving behaviors in actual driving. Therefore, it is necessary to study whether the trends of SSMs are the same by comparing drivers in the existing simulator-based training with those in the simulator-based training proposed in this study by comparing actual driving data with data from the driving simulator.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by the Institute of Construction and Environmental Engineering and the Institute of Engineering Research at Seoul National University. The authors wish to express their gratitude for their support.

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