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Acil direksiyon uyarı sistemi ile kaza önlenmesi: sürüş simülatörü yaklaşımı

Collision avoidance via emergency steering warning system: a driving simulator approach

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Acil Direksiyon Uyarı Sistemiyle Kaza Önlenmesi: Sürüş Simülatörü Yaklaşımı

Araştırma Makalesi / Research Article

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ÖZ

Bu çalışma, karayollarındaki aynı yönde ilerleyen araçların emniyetini iyileştirmek için bir Acil Direksiyon Uyarı Sisteminin (ADUS) uygulanabilirliğini analiz etmektedir. Önerilen sistem, aracın fiziksel sınırlarını ve sürücünün tepkisini göz önünde bulundurarak bir ses veya benzeri bir teşvik yardımıyla çarpışmayı önlemenin kararını vermeye yardımcı olmaktadır. Tipik simülasyon senaryoları MATLAB/Simulink ve IPG / CarMaker ortak simülasyon ortamlarında tasarlanmıştır. Önceden belirlenmiş senaryoda, öndeki taşıtlar sistemin yüklü olduğu taşıtın bulunduğu şeride karışık bir algoritma ile aniden geçer ve sonrasında sürücünün direksiyon ya da fren yaparak çarpışmayı önlemesi beklenir. ADUS sistemi, servis freni kullanılmasıyla kazanın kaçınılmaz olduğu tespit edildiğinde ve engelden kaçınmanın tek yolunun şerit değiştirmesi olduğu durumlarda sesli uyarı üretmektedir. Simülasyonlar, ADUS sistemi yüklü olan ve olmayan sürüş simülatörü kullanan bir grup katılımcı tarafından gerçekleştirilmiştir. ADUS sistemi katılımcıları bazı kritik trafik durumlarında avantajlı olabilecek daha erken ve yumuşak bir direksiyon manevrası yapmaya teşvik etmiştir. İstatistiksel sonuçlar, sesli uyaranın sürücülerin reaksiyon sürelerini önemli ölçüde azalttığını ve önerilen çarpışma uyarısı sistemi ile sürücülerin bir dizi kazayı önleyebileceğini göstermiştir.

Anahtar Kelimeler: MATLAB/Simulink, direksiyon uyarısı, otonom araçlar, taşıt kontrol sistemleri, sürücü destek sistemleri.

Collision Avoidance Via Emergency Steering Warning System: A Driving Simulator Approach

ABSTRACT

This study analyzes the viability of an Emergency Steering Warning System (ESWS) to improve the safety of vehicles on highways traveling in the same direction. The proposed system evaluates the vehicle's physical limits, driver's reaction and assists in making the most logical decision to avoid a crash using a sound or a similar stimulus. Typical driving simulator events were designed in MATLAB/Simulink and IPG/CarMaker co-simulation environment. In the predetermined scenario, the leading vehicles suddenly move into the host vehicle's lane and the driver is expected to avoid crash by either steering or braking. The ESWS system generates a sound stimulus when it is determined that the crash is unavoidable with the use of service brakes and the only way to avoid the obstacle is steering. The simulation events were performed by a group of participants using a driver simulator with and without the ESWS system. The proposed ESWS encouraged participants to do an earlier and smoother steering maneuver which can be advantageous in some certain critical traffic situations. The statistical results showed that the sound stimulus reduced the drivers' reaction time significantly and a number of accidents can be avoided by the suggested crash warning system.

Keywords: MATLAB/Simulink, steering warning, autonomous control systems, vehicle control systems, advanced driver assistance systems

1. INTRODUCTION

Various active safety systems have been developed for collision avoidance such as emergency brake assist, stability control systems and anti-collision systems [1]. The significance of the active safety systems arises in unexpected situations, since drivers usually have longer reaction time in unexpected situations [2]. Therefore, active safety systems have an important role for mitigation or avoidance of a possible collision by a warning or an autonomously triggered steering and braking action [3].

Most active safety systems focus on controlling the longitudinal behavior of the vehicle in order to avoid collision such as Forward Collision Warning (FCW) and Active City Stop (ACS). However, in some cases active longitudinal control may not be sufficient to avoid a collision [4]. If the relative speed between vehicles is more than 50 km/h, the distance required to avoid collision by a steering maneuver is less than the distance required to avoid collision by a braking maneuver [5]. Moreover, a single braking maneuver without steering was identified as the most frequently encountered first natural response for drivers, and a steering maneuver could be observed if a single braking maneuver is perceived as insufficient by drivers [6,7]. Therefore, first attempt of the drivers could be braking, and after then a combination of steering and braking even though a single steering maneuver could avoid a possible collision. The

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reason of this could be the lack of experience of the drivers for applying high lateral accelerations [8]. Driving simulators could provide significant information for design and development of active safety systems [8-10]. A steering warning system has been proposed in this study by considering whether a single braking maneuver is sufficient to avoid a possible collision.

In this study an Emergency Steering Warning System (ESWS) is proposed to reduce the drivers' response time and encourage drivers to avoid an obstacle by steering using a warning system with a sound stimulus if the relative speed between vehicles is above 50 km/h. The ESWS was designed to be activated if only a single braking maneuver is not enough to avoid a possible collision. If the ESWS is active it does not guarantee that the collision could be prevented via steering, however a steering maneuver is definitely necessary to avoid or mitigate a possible collision. The proposed ESWS was implemented to a driver simulator and a number of cases were designed. In the first case, the ESWS of the simulated vehicle was disabled so that participants used their own judgment for choosing steering or braking maneuvers. In the other case, the ESWS was activated so that participants were prompted by a sound stimulus to steer away where the collision is determined to be inevitable. The aim of this study is to investigate the viability of the proposed ESWS in a driving simulator by carefully examining the effects on drivers' response time, number of possible collisions avoided and reduction of the average maximum absolute yaw rate.

The literature survey showed that most of the studies performed on emergency crash warning systems to date focus mainly on the longitudinal aspects of the problem, and the studies on lane change warning systems considering the lateral vehicle dynamics is very scarce. The originality of the proposed method is that when a possible crash is detected, the system evaluates the safe braking and steerable distances; if the crash avoidance using steering is more favorable than the driver is stimulated by a warning signal. The objective of this study is to understand the effectiveness and possible consequences of the proposed ESWS system using driving simulator tests. In the following sections, the training phase and the simulator experiments will be explained, the participants' information and the simulation results will be shown and the effects of the ESWS on human response and accident avoidance will be discussed in detail.

2. METHOD

The experiments were performed by using a fixed-base driving simulator. Thirty drivers were participated in the experiments. In a simulator room, the simulation was performed by using a video projector, force feedback steering wheel including an accelerator and a brake pedal. The software environment is co-simulation where the driver training and simulator experiments were prepared by using IPG/CarMaker and MATLAB/Simulink together. The nonlinear tire model is embedded by default in the CarMaker software which is experimentally validated via various studies [11-15].

2.1. Training Phase

The road selected was double lane in one way. Host vehicle, which was driven by the participants was placed onto the left lane of the road by default. The width of each lane and longitudinal distance of the training path was designed as 3.5 meters and 10 km respectively to make enough exercises with a driving speed of 130 km/h. The coefficient friction of the road was set to be 1.0 as experienced on a dry asphalt. The overall mass of the host vehicle, height of the center of gravity, body roll moment of inertia, body yaw moment of inertia and body pitch moment of inertia are shown in Table 1. The maximum legal speed is 130 km/h in most countries in Europe. Therefore, the maximum legal speed was chosen as the speed of host vehicle in this study.

Table 1. Host Vehicle Parameters

Overall mass	1564	kg
Height of the center of gravity	0.5	m
Body roll moment of Inertia	485	kgm^2
Body yaw moment of Inertia	1850	kgm^2
Body pitch moment of Inertia	1640	kgm^2
Tire designation	RT 225 50 R17	[-]

During the training phase, participants were asked to perform a sudden braking to a complete stop while driving straight at a constant speed of 130 km/h. After they were adapted to braking, they were recommended to make lane change maneuvers during full braking to avoid collision to obstacles. Finally, they were recommended to make lane change maneuvers suddenly without braking at 130 km/h to avoid collision to vehicles. The training session lasted approximately for half an hour prior to the simulator experiments. It's known that direct experience is needed in addition to anticipatory information to benefit from a warning system in driver assistance technologies [16]. Therefore, drivers were informed and experienced about ESWS.

2.2. Simulator Experiments

In the experiments, 15 busses were placed onto the right lane of the road 150 meters apart. The distance between host vehicle and the closest bus was defined as 3 km at the beginning of simulation. The host vehicle was placed onto the left lane of road by default. When the simulation started, the busses accelerated by keeping same distance until they reached 40 km/h. Host vehicle was totally controlled by the participants as it is mentioned earlier. The participants were asked to accelerate until they reach 130 km/h constant speed on the left lane. The driving simulator is shown in Figure 1.

Figure 1. Driving Simulator

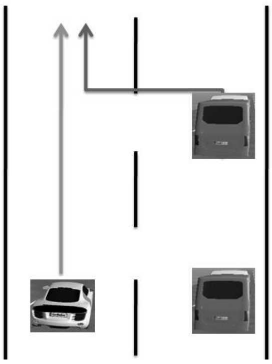

Figure 2. The cut in event of the busses.

In the first case, the ESWS of the vehicle was disabled however in the second case the ESWS was activated. The participants were adapted to the driving simulator after an intense training and therefore the results are free from learning effect. In both cases, the participants were advised to drive at a constant speed of 130 km/h which is the legal speed limit on highways in most countries unless they recognize an obstacle or a vehicle on their lane. One of the busses (selected randomly for each experiment) cut into the left lane with 5 m/s lateral velocity as it is illustrated in Figure 2. The distance between the preceding and host vehicle at the time the bus (preceding vehicle) started to change lane, has to be identified and must be the same value for all participants. ESWS sound is activated (second case) if a single braking maneuver is not sufficient to avoid a possible collision as it is illustrated in both Figure 3 and equations (1) & (2). For a warning instrument, a sound stimulus was selected. A modern car is equipped with many warning systems by sound, however in this study the host car was just equipped with ESWS. Therefore, it is not a problem for the driver to distinguish different sounds. The sound stimuli of ESWS was designed to be activated at the time the bus started to enter the lane of the host vehicle. For this reason, the distance at the time the bus started to enter the lane of host vehicle must be lower than the minimum distance required to avoid a possible collision via a braking maneuver. In order to identify the distance between the preceding and the host vehicle at the time the bus started to change lane, the minimum distance required to avoid a possible collision via a braking maneuver could be identified at first.

$$d_{brake} = \frac{1}{2a_{x(mean)}} v_{relative}{}^2 + \tau_{response} v_{vehicle} \quad (1)$$

As it is shown in equation (1), d_{brake} is the minimum longitudinal distance from the preceding vehicle to avoid collision (last time to brake in Figure 3) via a braking maneuver [17]. It depends on the average longitudinal deceleration $a_{x(mean)}$, relative speed between vehicles $v_{relative}$ and response time $\tau_{response}$. The weather conditions were not taken into account in this study. The average longitudinal deceleration on a dry asphalt $a_{x(mean)}$ was calculated as 7.8 m/s² depending on the full braking exercise performed in IPG/CarMaker software. Actually, it was the minimum time calculated for brake pedal to reach 100% position (brake pedal is pressed) from 0% position (brake pedal is not pressed) without considering response time. The relative speed between vehicles was defined as 90 km/h according to the given speed values of the preceding and host vehicle. The response time $\tau_{response}$ depends on the simulation delay $\tau_{simulation}$ and reaction time $\tau_{reaction}$ as shown in equation (2).

$$\tau_{response} = \tau_{reaction} + \tau_{simulation} \quad (2)$$

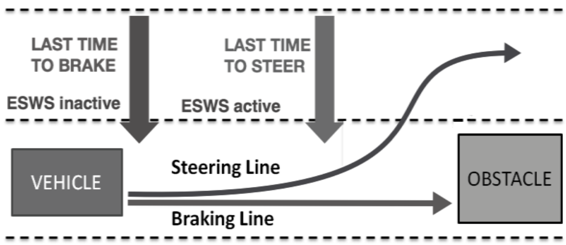

Figure 3. The activation principle of ESWS according to the last time to brake.

At first, the reaction time was selected as 160 ms which is in line with the studies as the mean reaction time of humans to a sound stimulus is 160ms [18-20]. Moreover, the average simulation delay was calculated as 250 ms according to MATLAB/Simulink and IPG/CarMaker software. A summation of the average simulation delay and mean reaction time gives 410 ms for the average response time depending on equation (2). The minimum longitudinal distance between the preceding and host vehicle was calculated as 50.31 meters to avoid collision via braking according to equation (1). This value stands for the last time to brake as shown in Figure 3. Therefore, the distance between vehicles at the time the bus started to change lane must be lower than 50.31 meters to activate the sound stimuli of ESWS at that time. As shown in Table 2, by considering the maximum range of the long range radar (LRR) as 120 meters, the distance between vehicles at the time the bus started to change lane was proposed as 43.7 meters for the activation of ESWS, which is lower than 50.31 meters. As mentioned before, the collision could not be prevented via braking if the distance between vehicles at the time the bus started to a lane change maneuver is higher than 50.31 meters.

Table 2. The parameters to calculate the proposed distance between vehicles at the time the bus started to change lane

Average proposed driver response time	410	ms
Relative speed between vehicles (the preceding and host vehicle)	25	m/s
Calculated minimum distance required to avoid a possible collision avoidance via braking	50.31	m
Desired distance between vehicles at the time the bus started to change lane	43.7	m

In this study, the proposed distance and speeds of the preceding and host vehicle were constant before the activation of ESWS. On the other hand, all of them could be variable in the real traffic situations. Therefore, by considering mean deceleration value and response time, the activation of ESWS was coded as an embedded function in MATLAB/Simulink. This function depends on the relative speed and distance between vehicles which could be read from LRR as continuous variables in real-time in MATLAB/Simulink. Therefore, ESWS was also working with different speed values of the preceding and host vehicle in this study. On the other hand, to compare average maximum absolute yaw rate and average shortest distance for all participants, the proposed distance and speeds of the preceding and host vehicle were selected as constant values.

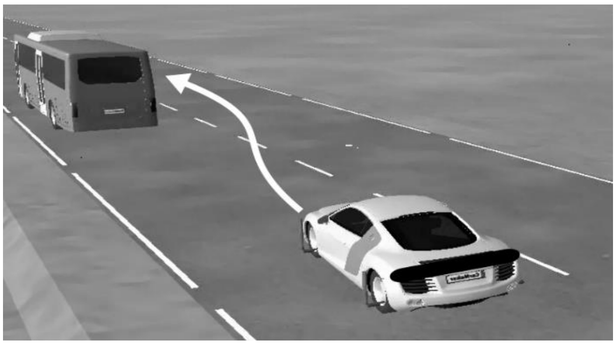

Figure 4. The necessity of an emergency steering maneuver for collision avoidance.

In both first and second cases after the bus cut into the left lane, the participants were free to steer and brake according to their experiences as it is illustrated in Figure 4. In the second case, the conditions were the same as first case except ESWS. Moreover, in the second case the frequency and loudness of the sound stimulus of ESWS was desired as 450 Hz and respectively 74 dB.

2.3. Decision Making

The activation principle of ESWS not only depends on the last time to brake as shown in Figure 2, but also depends on the other parameters as shown in Figure 5. The first condition for the activation of ESWS is passing the last time to brake as mentioned before. In addition to this, the relative speed between vehicles must be above 50 km/h for the activation of ESWS, since it could be still possible to avoid collision via steering after passing the last time to brake for that speed [5,17]

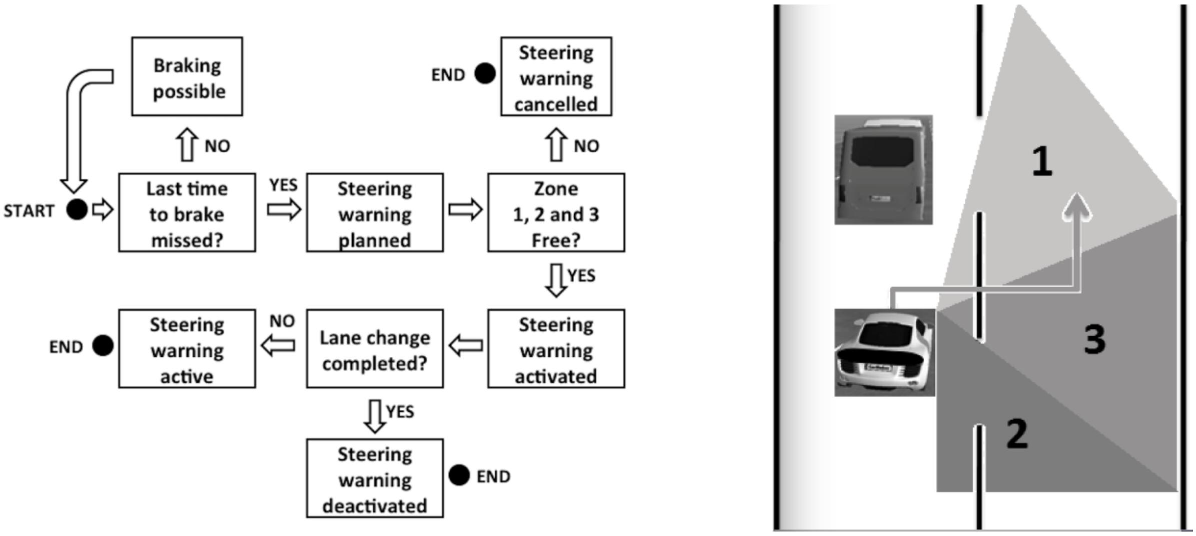

Figure 5. Decision making for the activation of ESW

In order to fulfill this condition, Blind Spot Detection system (BSD) and related corresponding systems could be used simultaneously [21]. At first glance, it could be decided that it is still possible for a lane change if zone 1 is not free. On the other hand, if the speed of the vehicle travelling in zone 1 is lower than the preceding bus, the devastation of the collision could be even more. Therefore, the safest condition is to perform a steering maneuver if all zones are free. If there are more than two lanes on road, the driver may choose an appropriate direction which is free to steer via the assist of BSD. In a real unstructured setting the ESWS may include a steering vibration instead of a sound stimuli as haptic warnings lead to a faster driver reaction in steering [22].

2.4. Information About Participants

30 people participated in this simulation as mentioned before. The distribution of the distance driven by the participants per year could be seen in Figure 6. The average distance driven by the participants per year was calculated as 5771 km.

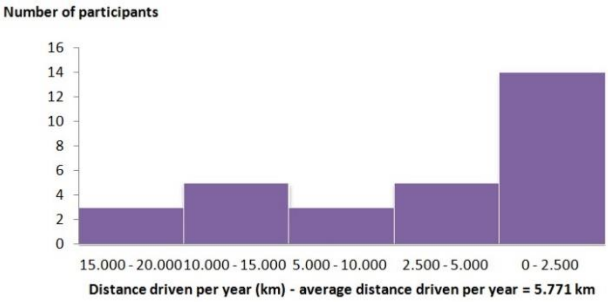

Figure 6. Distance driven by participants per year.

After all experiments were completed, the data were processed to determine:

- average response time
- average time to collision (TTC) at the end of the response time
- average maximum absolute yaw rate
- average shortest distance between vehicles at the end of the response time

as it is illustrated in Table 3. The average response time decreased by 71 milliseconds in the second case in which ESWS was active. This reduction in the response time provided an additional 1.77 meters distance to the participants for a better response such that the average maximum yaw rate decreased by 0.133 rad/s in the second case. Therefore, the total number of collisions decreased by 4 in the second case. The distribution columns of the response time of the participants could be seen in Figure 7. The peak value of the number of the participants during ESWS OFF and ESWS OFF is 0.6 - 0.5 seconds and 0.5 - 0.4 seconds respectively. The number of the participants during ESWS ON is always higher than ESWS OFF between 0.5 and 0.2 seconds of the response time. However, the number of participants during ESWS OFF is always higher than ESWS ON between 0.8 and 0.5 seconds of the response time. The response time decreased for the 22 participants and increased for the 8 participants in case ESWS was activated. Therefore, 73% of the participants benefited from the proposed ESWS. The standard deviation of the average response time is 129 ms and 102 ms during ESWS ON and OFF conditions respectively. According to confidence analysis, p value in the change of the average response times was calculated as 0.002 which is smaller than 0.05 to satisfy 95% confidence. The distance between vehicles at the time the bus (preceding vehicle) started to lane change was desired as 43.7 meters (which

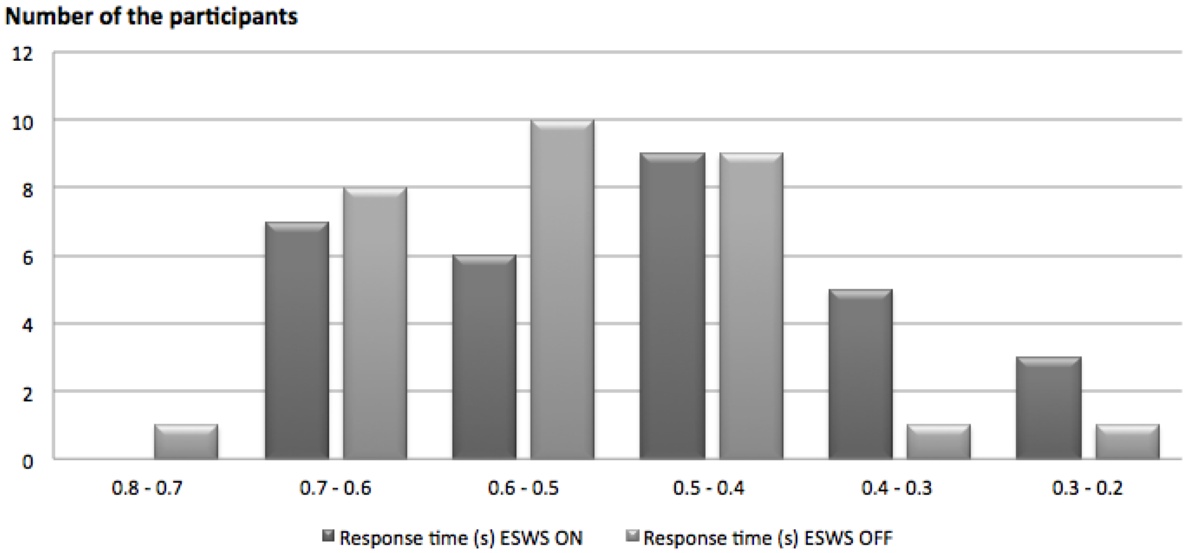

Figure 7. The distribution of the response time of the participants

3. RESULTS AND DISCUSSION

All of the simulator experiments (with/without ESWS) including the training phase were performed by using the same 30 participants. It took approximately 45 minutes for one of the participants to complete all of the experiments.

is lower than 50.31 meters) to activate ESWS as soon as possible during the cut-in event, as shown in Table 3 and 4. On the other hand, number of collisions because of a rear-end crash (the crash between the front side of host vehicle and the rear side of the bus) increased by 6 in the second case. These same 6 participants had an accident because of the departure from road in the first case and they had an accident because of a rear-end crash in the second case.

Table 3. The simulation results

PARAMETERS	ESWS ON	ESWS OFF	DIFF.
Average measured response time	474 ms *(129 ms st.dev)*	545 ms *(102 ms st.dev)*	-71 ms
Average TTC at the end of the response time	1277 ms	1206 ms	+71 ms
Average maximum absolute yaw rate	0.458 rad/s	0.571 rad/s	-0.113 rad/s
Average shortest distance between vehicles at the end of the response time	31.92 m	30.15 m	+1.77m
Average longitudinal distance travelled during the response time	11.77 m	13.55 m	-1.77m
Distance between vehicles at the time the bus started to change lane	43.7 m	43.7 m	-
Total number of collisions	21	25	-4
Number of collisions because of a rear-end crash	11	5	+6
Number of collisions because of the departure from road	10	20	-10

Results show that the decrease of the average response time by 0.071 seconds, provided participants an additional 1.775 meters to do a smoother steering or braking maneuver when ESWS was active. The confidence analysis provides more than 95% confidence for the response times. The increase of TTC also resulted in the decrease of the total number of collisions by 4, when ESWS was active. The number of rear-end collisions seems to be increased by 6 when the ESWS was active. However, these 6 participants all had an accident because of the departure from road in the first case and because of a rear-end crash in the second case. Therefore, the increase in rear-end collisions in the second case came from the departure collisions in the first case. The statistical results showed that some of the participants who experienced collision as a result of lane departure when the ESWS was OFF, experienced rear-end collision with the busses when the ESWS was activated. It should be examined whether the rear-end collision or departure from road is preferable. It could depend on the vehicle type in front (such as a truck, bus or car) to prefer a read-end collision rather than departure from road. This is a case to be discussed during implementation of the system if possible and it is not in the scope of this study. Moreover, a collision mitigation system via braking is always suggestible with or without ESWS. The total number of collisions also depends on the distance between vehicles at the time the bus (preceding vehicle) started to change lane. If the distance is longer, the collision probability is less. The decrease in the total number of collision does not depend on learning effect because the participants tried ESWS on/off cases after a tough training. On the other hand, ESWS does not guarantee to avoid a collision. The aim of ESWS is the reduction of the response time to avoid a collision such as the most important aim of the warning systems. There are also many cases distracting the concentration of drivers while driving like having a conversation, talking on mobile and watching outside while driving. Therefore, warning systems have an important role for the driving safety by reducing the response time [3].

4. CONCLUSIONS

As a result, the proposed ESWS assisted to reduce the average response time and total number of collisions successfully in this study. The implementation of the system may include a haptic warning rather than a sound stimulus. On the other hand, ESWS was not sufficient to avoid most of the collisions since the proposed system is only a warning system which does not intervene the driver's actions. In order to avoid collisions, an emergency autonomous steering system could be designed by considering the response time according to the stability limits of the vehicle [3]. However, if driver is allowed to intervene this automatic steering maneuver, most of the drivers could possibly block this intervention according to a corresponding research [23]. Therefore, the autonomy level of the corresponding system must be determined in order to cooperate with the driver successfully. The simulations were performed on a fixed-base driving simulator which does not provide deceleration and acceleration feelings to the driver. Implementation of moving-base simulators are suggested for future studies so that combined braking and steering events can be replicated with high fidelity. In the performed simulations, the ABS was active to enable steering maneuvers during braking, however ESP was not used for simplicity. The response of the drivers against the proposed steering warning system with an active ESP needs further attention.

5. ABBREVIATIONS

ESWS	Emergency Steering Warning
FCW	Forward Collision Warning
ACS	Active City Stop
LRR	Long Range Radar
BSD	Blind Spot Detection

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