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Accident Analysis and Prevention 40 (2008) 1164–1170

ACCIDENT ANALYSIS & PREVENTION

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The effects of in-vehicle tasks and time-gap selection while reclaiming control from adaptive cruise control (ACC) with bus simulator

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Received 11 October 2007; received in revised form 19 December 2007; accepted 24 December 2007

Abstract

This research aimed to find out the effects of in-vehicle distractions and time-gap settings with a fix-based bus driving simulator in a following scenario. Professional bus drivers were recruited to perform in-vehicle tasks while driving with adaptive cruise control (ACC) of changeable time-gap settings in freeway traffic. Thirty subjects were divided equally into three groups for different in-vehicle task modes (between subjects), including no task distraction, hands-free, and manual modes. Further, time-gap settings for the experimental ACC were: shorter than 1.0 s, 1.0–1.5 s, 1.5–2.0 s, and longer than 2.0 s (within subjects). Longitudinal (mean headway, forward collision rate, and response time) and lateral control (mean lateral lane position and its standard deviation) performance was assessed. In the results, longitudinal control performance was worsened by both shorter time-gaps and heavier in-vehicle tasks. But the interaction indicated that the harm by heavier in-vehicle distraction could be improved by longer time-gaps. As for the lateral control, it would only be negatively affected by shorter time-gap settings. This research indicates the effects of time-gaps and in-vehicle distraction, as well as the interaction. Proper time-gap selection under different in-vehicle distractions can help avoid accidents and keep safe.

Keywords: Adaptive cruise control (ACC); In-vehicle distraction; Time-gaps; Bus

1. Introduction

Advanced technologies for driving support and information provision are increasingly popular with in-vehicle system design. In the effects of these technologies, one issue that may reduce driving performance is distraction. Distraction may occur while an event eliciting the attention-shift away from driving tasks. Recently, there are many researches related to driver distraction upon driving performance, including the effects of cognitive, visual, auditory demanding and interactions (Blanco et al., 2006; Engström et al., 2005; Haigney et al., 2000; Harbluk and Noy, 2002; Harbluk et al., 2007; Horberry et al., 2006; Lamble et al., 1999; Noy et al., 2004; Recarte and Nunes, 2003). Although advanced automation technologies can help drivers obtain useful information by presenting routes, traffic jam, and warnings, driving safely with the system is much more important than driving efficiently. To process feedbacks produced by automation technologies that contain in-vehicle information systems (IVIS), adaptive cruise control (ACC), and collision warning system (CWS) are drivers' secondary in-vehicle tasks, even tertiary tasks. However, the modalities for primary driving task may conflict to doing additional works. In the past, human was considered as a single channel processor, but intelligent systems would adapt to human abilities to concurrently process information while different sensory modalities being used (Wickens and Hollands, 2000). Multiple resource allocation is possible but needs to be concerned with overloading, especially with conditions that are related to safety.

ACC is the system that can support the resource required for longitudinal control, such as visual (e.g. watch out for the lead vehicle) and manual task (e.g. control throttle and brake). People can drive with the selected time-gap and the system will keep a constant headway. Owing to the existence of ACC, drivers' behavior patterns change and drivers will pay more attention for other in-vehicle tasks. However, the attention for sub-tasks, such as cell phone conversation, is a kind of driving distraction and will increase mental load while driving with ACC (Ma and Kaber, 2005). Thus, it is important to find out the

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doi:10.1016/j.aap.2007.12.009

effects of different modalities of tasks with ACC. Further, the drivers' behavior may also be affected by different time-gaps, so time-gap setting is another factor that must be discussed. This research purposes to find out the effect and interaction between in-vehicle tasks and time-gaps with several performance measures.

1.1. Effects of in-vehicle task occurrence

While driving, potential in-vehicle distraction may be caused by concurrent visual, auditory, cognitive, and manual loads in using information systems, such as tuning the radio, having a conversation, or dialing the cellular phone. The interaction with in-vehicle systems is concerned with multiple resource theories by Wickens (2002), who proposed the existence of separate resources. A typical conflict matrix by Horrey and Wickens (2003) and Wickens (2002) also indicates that there will be greater interference between two tasks if they share resources. It is very helpful to compare the seriousness of sharing a resource under different perception stages, processing codes, or modalities. For driving task, it is a highly visual-demand task, but there are more and more in-vehicle distractions from other devices that require multimodality resources, such as telematics and on-board information systems. From the conflict matrix, the potential distraction by these devices has critical influence on primary driving task with additional loads, including the resource sharing of visual perception (e.g. searching, visual detection), auditory perception (e.g. auditory detection, positioning), cognitive (e.g. selection, computation, recognition, planning), and response (e.g. voice command, manual response) tasks. Effects by resource sharing can be roughly divided into three parts: performance (the core issue in this research), behavior, and risk compensation.

For effects on driving performance, secondary visual loads can lead to two main performance degradation: (1) delay in brake reaction time and decreasing time-to-collision (Lamble et al., 1999; Summala et al., 1998), and (2) increasing lane keeping variation and number of lane excess (Engström et al., 2005; Noy et al., 2004). Although Wickens (2002) indicated that secondary visual loads have more conflict than auditory and cognitive loads in visual-demand tasks (driving) because the visual modality is shared, auditory and cognitive loads also have impact on performance. Subjects may give it a higher priority to perform auditory tasks (Green, 2001). Audio-verbal acquisition tasks are innocuous and low in demand because of the high redundancy of the common verbal language (Recarte and Nunes, 2003). However, conversation, including auditory and cognitive demand, will increase response time (Lamble et al., 1999; Lee et al., 2001; Richard et al., 2002) and complex tasks result in critical degradations in increasing speed, headway variance, and number of lane deviations (Blanco et al., 2006).

To sum up, in-vehicle tasks may have negative effects on driving safety and should be regulated, even though IVIS help drivers to obtain diverse information for efficient driving.

1.2. Workload reduction by adaptive cruise control

It is anticipated that vehicle automation will also be developed to assist drivers to process more in-vehicle tasks. Adaptive cruise control is the system that promotes a new generation of vehicle automation. ACC can slow the vehicle down when an obstacle appears and restore target speed while the obstacle is removed (Stanton et al., 1997). The key parameter for ACC is the "time-gap", which means the time interval for traveling a distance to the forward vehicle, given the current vehicle speed (SAE, 2003). With ACC aided in high-speed driving, the longitudinal control is substituted, so theoretically, drivers have resource on lateral control or in-vehicle information processing. Exactly, many researches indicated reduction in the driver's workload, associated with operating ACC (Ma and Kaber, 2005; Stanton et al., 1997; Stanton and Young, 2005; Young and Stanton, 2004). That is to say, drivers with ACC not only do primary driving more easily, but also have spare capacity. Therefore, as the application of vehicle automation (ACC), drivers are more capable to process the helpful information by IVIS.

Although ACC brings workload reduction, it must, however, be stressed that the automation of ACC means the extent to which the driver is out of the vehicle control loop. Reduced levels of attention associated with lower levels of workload may negatively affect the human supervisory control ability in maintaining the awareness of system status (Stanton et al., 1997). The attention reduction is especially dangerous for the situation that ACC cannot handle. According to the standard of SAE J2399, ACC works well in smooth-flowing traffic excluding stop and go and emergency brakes (SAE, 2003). For emergent situations, drivers must re-enter the control loop to keep safe. The action is called "reclaim control" in this research. Therefore, to reclaim control from ACC at the right moment is necessary to avoid accidents and remain safe.

1.3. Objectives of the present research

As discussed above, the effects of in-vehicle tasks and ACC assist have to be considered concurrently. In this research, it is aimed to make clear how in-vehicle tasks affect driving safety with the support of ACC under different time-gaps. The mental resource saved by ACC was applied to conduct the in-vehicle tasks in order to build up the relationship to one another. Objective performance measures were used to evaluate effects by task distractions and time-gaps. Also, the interaction was interpreted how in-vehicle distraction affected the efficiency of time-gaps.

2. Method

2.1. Equipment

The equipments used in this study were (1) the fix-based bus driving simulator, (2) digital video, (3) software interfaces for information process, transformation, collection, and display, (4) hardware interfaces for simulator operation, (5) information display (touch panel), (6) auditory display, and (7) three video

Fig. 1. The bus driving simulator.

projectors displaying with 170° field of view. The close-up of the simulator was shown in Fig. 1.

This ACC system was conducted via the standard of SAE J2399 (2003). It was not allowed to be over-ruled and would automatically change the speed while the lead vehicle was detected (maximum $\pm 2\,m/s^2$ acceleration). In general, ACC would remain active and give assistance, but drivers should reclaim control from the system while emergent situation occurred. The scenario of the emergency would be described in Section 2.3.

2.2. Participants

Thirty professional bus drivers aged 26–52 years (mean = 43.67, S.D. = 5.59) took part individually in this study and were paid NT$2000 (around $60). All the drivers held active professional bus driver's license, and were employed in regular bus driving for 1.5–25 years (mean = 11.73, S.D. = 6.09). No subject had the experience of using ACC before.

2.3. Design, tasks, and procedure

A two-way design was conducted in this study, including factors of in-vehicle distraction (no task, simple hands-free task, and complex manual task; between subjects) and car following time-gaps (under 1 s, 1–1.5 s, 1.5–2 s, over 2 s; within subjects). Thirty participants were divided equally into three groups, and each drove in four conditions (one distraction with four time-gaps). For higher reliability, each condition would be repeated for three times and the average of the three was used for data analysis.

A simulated straight and flat highway route with three conventional lanes, one shoulder, and traffic flow was adopted. Participants needed to perform a following task, but changing lateral position and speeding (speed limit 100 km/h) were forbidden. The lead vehicle would remain in front of the subject vehicle and change speed from time to time. In each experimental condition, the lead vehicle would unexpectedly make emergency brake to 20 km/h ($8\,m/s^2$ deceleration). When the emergency brake occurred, ACC was insufficient for the urgency owing to the large deceleration, so drivers must reclaim control from ACC to avoid accidents. The duration of control reclaiming was the critical period for analysis in this research.

For the distraction factor, one control group and two distraction tasks were applied. In the simple (hands-free) task, visual, cognitive, verbal tasks were included, in which participants were required to look at the information display, add two double-digit numbers (e.g. 38 + 29), and give the answer verbally. The time interval of any two math questions was 3–5 s and each question would be passed over if it was not confirmed in 8 s. As to the complex (manual) task, participants had to confirm by button on the display (touch panel) after verbally answering besides completing the simple task. The display was placed at 42° right and 24° below the eyesight of a subject who was 170 cm in height.

In the beginning of the experiment, participants were introduced to the bus driving simulator and shown the functions and operational modes of ACC system. Then they took part in practice for about 10 min until they were familiar with the simulator operation and required tasks. After a short brake, four time-gap conditions with three replicates (12 trials, as described in the first paragraph of Section 2.3) were randomly applied to participants. Participants were instructed to behave as their normal driving and take comfort and safety as principles. While the first six trials passed through, a 10-min rest must be taken. Then the other six trials began. Each participant would approximately take 90 min to complete the whole experiment.

2.4. Performance measures

All driving performance measures were collected during the time interval that the driver began to reclaim control from ACC and ended while the lead vehicle finished the emergency brake and then re-accelerated. Five objective driving performance measures were recorded in each condition: mean headway, forward collision occurrence, response time, mean lateral position, and standard deviation of lateral position. These measures were collected at 10 Hz except the forward collision occurrence, which was the binary outcome. As mentioned in Section 2.3, the repeated data would be averaged, so four data sets could be yielded for each subject in one performance measure. Then because of the averaging, binary forward collision occurrence would be turned into the forward collision rate.

3. Results

Data analysis of driving performance in this experiment was separated into longitudinal and lateral control. The longitudinal control relates to ACC, including mean headway, forward collision rate, and response time. The lateral control was another issue for lane keeping, and the lateral lane position of subject vehicle and its variation were involved. Factorial ANOVA was used for analysis with the factors of time-gaps (four levels) and in-vehicle distraction (three levels). Least significant difference (LSD) multiple comparison method was employed for post-hoc tests of the between-subject factor and for the analysis of simple main effect if the interaction was significant.

Paired-t test was applied to compare means for the within-subject factor.

3.1. Driving performance analysis: longitudinal control

Mean headway, forward collision rate, and response time were sequentially analyzed which related to longitudinal control and safety.

3.1.1. Mean headway

A significant main effect on mean headway was found out for the time-gap ($F(3,81) = 1022.152$, $p < .001$) and in-vehicle tasks ($F(2,27) = 18.073$, $p < .001$). LSD post-hoc test showed that no in-vehicle task resulted in longer mean headway than the condition of simple task ($p < .001$) or complex task ($p < .001$). There was no significant difference between simple and complex tasks ($p = .105$). As to the effect of time-gap selection, paired-t test showed that any two of the four time-gap conditions were significantly different on mean headway ($t(29) > 14.959$, $p < .001$ for all).

The interaction between in-vehicle tasks and time-gaps was also significant ($F(6,81) = 7.835$, $p < .001$). The simple main effect of time-gap in Fig. 2 indicated that each level of time-gap was significantly different no matter driving with or without in-vehicle tasks, with simple and complex tasks ($p < .001$). In the case of the simple main effect of in-vehicle tasks, driving without in-vehicle tasks distraction could significantly cause longer mean headway under all time-gaps than driving with in-vehicle tasks ($p < .05$ for all), and there was no difference on mean headway between simple and complex in-vehicle tasks except the condition of 1.5–2 s time-gap ($p < .01$).

3.1.2. Forward collision rate

Both the effects of time-gaps and in-vehicle tasks were significant on the forward collision rate ($F(3,81) = 145.619$, $p < .001$; $F(2,27) = 22.013$, $p < .001$). By the LSD post-hoc test, significant difference could be found between no task and task conditions ($p < .001$) and the later ones brought about higher forward collision rate. But no difference was found between complex task and simple task conditions ($p = .07$). Paired-t test indicated that any two of the four time-gap conditions were significantly different on forward collision rate ($t(29) > 2.693$, $p < .001$ for all). More discussions must be done because of the significant interaction between time-gaps and in-vehicle tasks ($F(6,81) = 9.072$, $p < .001$).

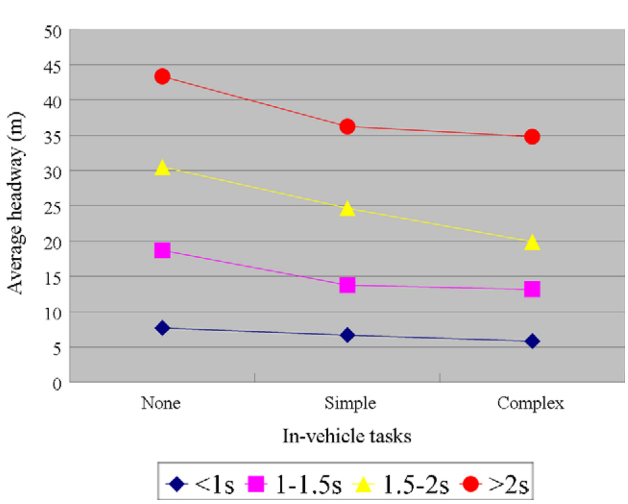

Fig. 2. Mean headway of in-vehicle tasks by time-gaps.

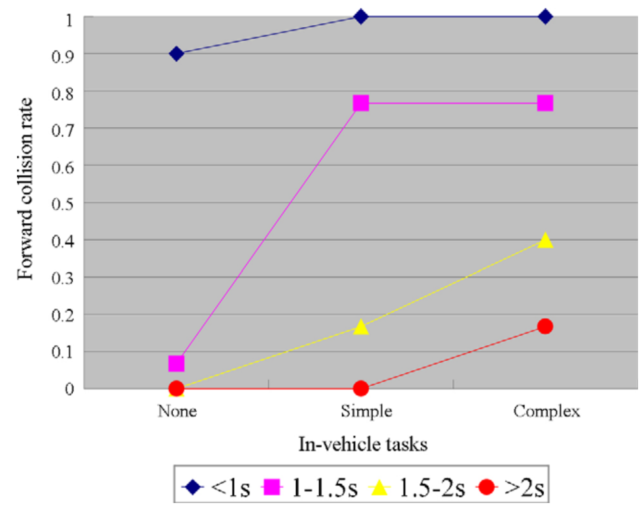

Fig. 3. Forward collision rate of in-vehicle tasks by time-gaps.

Simple main effects of time-gaps (Fig. 3) by LSD test showed that while driving without in-vehicle tasks, forward collision rate with the shortest time-gap (<1 s) was significantly higher than longer ones (>1 s, $p < .001$). However, by simple and complex tasks, the collision rate with time-gap of 1–1.5 s raised, so that the time-gap shorter than 1.5 s caused significantly higher forward collision rate than that longer than 1.5 s ($p < .001$).

Furthermore, the simple main effect of in-vehicle tasks revealed that if the time-gaps shorter than 1.5 s were used, driving without in-vehicle tasks could have lower collision rate than that with tasks ($p < .025$ for <1 s group; $p < .001$ for 1–1.5 s group). However, while increasing the time-gap to be longer than 1.5 s, there was no difference between no-task and simple task groups. That is to say, longer time-gap could reduce the forward collision rate effectively even though engaging in hands-free in-vehicle tasks. As to the complex task, the collision rate was still significantly higher than the other two conditions ($p = .001$ for 1.5–2 s group; $p < .05$ for >2 s group).

3.1.3. Response time

The measure represented the time interval from the beginning of the forward emergency brake to the time that the driver started to brake. Factors of time-gap and in-vehicle tasks would both have significant effects on drivers' response time ($F(3,81) = 7.69$, $p < .001$; $F(2,27) = 15.055$, $p < .001$). Slower response (longer response time) occurred with longer time-gaps and in-vehicle tasks. The interaction effect was not significant ($F(6,81) = 1.16$, $p = .336$). In Table 1, LSD multiple comparison for in-vehicle tasks showed that the response time without task was shorter ($p = .001$ for simple tasks; $p < .001$ for complex tasks). Also, the response times of four time-gap groups were also shown in Table 1, and signifi-

Table 1
Response time for forward emergency brakes

In-vehicle distractions	Response time (s)
None	0.901
Simple (hands-free)	1.314
Complex (manual)	1.523
Time-gaps (s)	**Response time (s)**
Under 1.0	1.116
1.0–1.5	1.168
1.5–2.0	1.328
Over 2.0	1.372

cant difference was found between 1–1.5 s and 1.5–2 s groups ($t(29) = 2.718$, $p < .01$). Therefore, two subsets could be precisely divided, in which the longer two groups caused longer response time.

3.2. Driving performance analysis: lateral control

Lateral control measures included the mean lateral lane position and the standard deviation of lateral lane position. Deviated lateral lane position might induce risk that the subject vehicle might diverge from its own lane.

3.2.1. Mean lateral lane position

The effect of time-gap was significant on mean lateral lane position ($F(3,81) = 5.87$, $p = .001$), but there was no significant difference for in-vehicle tasks ($F(2,27) = .371$, $p = .694$), neither with significant interaction between time-gaps and in-vehicle tasks ($F(6,81) = .841$, $p = .542$). Drivers were able to maintain their vehicles at the same lateral position even if engaging in different modes of in-vehicle tasks. Paired-*t* test for main effect indicated that greater time-gaps produced less deviation (closer to the lane centre) than inferior ones. While driving with time-gap over 2 s, drivers would drive more closely to the lane centre than 1.5–2 s ($t(29) = 3.113$, $p < .01$), 1–1.5 s ($t(29) = 1.818$, $p < .05$), and <1 s groups ($t(29) = 4.186$, $p < .001$). There was no difference between 1.5–2 s and 1–1.5 s groups ($t(29) = .252$, $p = .402$), but the mean lateral position under these two settings was more close to the lane centre than <1 s group ($t(29) = 1.919$, $p < .05$ for 1–1.5 s group; $t(29) = 2.508$, $p < .01$ for 1.5–2 s group). Therefore, three subsets for this criterion could be found, including <2 s, 1–2 s (1–1.5 s and 1.5–2 s), and <1 s settings.

3.2.2. Standard deviation of lateral lane position

In the performance analysis with the standard deviation of lateral lane position as the dependent variable, the stability of lane keeping could be assessed. The result indicated that the main effect of time-gaps was significant ($F(3,81) = 3.002$, $p < .05$), but the effect of in-vehicle tasks and the interaction between time-gaps and in-vehicle tasks were not significant. By the paired-*t* test, three time-gaps under 2 s belonged to the same subset and the difference between 1.5–2 s and >2 s group was significant ($t(29) = 1.898$, $p < .05$) in the S.D. of lateral lane position. To select time-gap that was longer than 2 s could lead to less variation of lateral control.

4. Discussions

The technology of ACC is proposed to assist drivers and lighten their load, especially in high-speed driving. Although the implication of ACC is helpful, short pre-selected time-gap, however, may incur dangerous situations. Besides, the distraction from in-vehicle devices has negative effects. In this research, a bus driving simulator was applied to find out the impact and interaction that different time-gaps and in-vehicle tasks had on drivers' performance.

4.1. Longitudinal control

Mean headway, a typical measure for driving safety, is discussed in this section. As shown in experimental results, mean headway was affected by time-gap settings, as well as by in-vehicle tasks. Previous researches about IVIS indicated that shorter time-to-collision would occur if engaging in visual, cognitive, and verbal secondary loads (Blanco et al., 2006; Lamble et al., 1999). However, if the time-gap was shorter than 1 s, the effect of in-vehicle tasks would be eliminated (Fig. 2). That is to say, the effect of time-gaps has dominated over the in-vehicle tasks on the mean headway when the time-gap is short. Even though no distracter was adopted, the time-gap under 1 s made the mean headway unchangeable. The fact was that the time-gaps would affect the mean headway during control reclaiming; especially the time-gap under 1 s was selected.

In the first half year of 2007, the traffic-accidental statistics by National Police Agency, Ministry of Interior (MOI) of Taiwan, indicated that 36.94% of accidents were caused by drivers' distraction, short-headway keeping, and speeding on the freeway (MOI, 2007). In this study, the effects of distraction (in-vehicle tasks), headway, and speed keeping (time-gap selection) were found out as well in the measure of forward collision rate. In the real world, the collision measure is unlikely to obtain due to the peril, yet, it is none the less important to assess the safety. Forward collision rate was investigated that some conditions of in-vehicle tasks and time-gaps would have negative results, but they could conform to compensation, from other points of view. For instance, negative outcomes of more complicated or resource-consumed in-vehicle tasks could be amended by longer time-gap selection. From the result of this experiment, higher forward collision rate occurred when setting time-gap shorter than 1 s without in-vehicle tasks. If drivers engaged in in-vehicle tasks (simple or complex), the forward collision rate of one longer time-gap group, 1–1.5 s, became higher as well. With time-gaps of 1–1.5 s, drivers would face higher forward collision rate if they were doing hands-free tasks. As waging manual tasks, time-gap between 1.5 s and 2 s might lead to the forward collision rate of 0.4, which did not equals to zero by the viewpoint of statistics. Consequently, the distraction that would bring about danger by different modes of in-vehicle task could be improved by different time-gaps. The results indicated that time-gaps longer than 1 s, 1.5 s, 2 s were better to maintain low forward collision rate of zero while driving without in-vehicle task, with hands-free tasks, and manual ones. From the viewpoint of application, in-vehicle tasks can bring advantages as well as additional loads, which may result in harmfulness. With the assist of ACC with longer time-gaps, these loads can be eased off.

Higher possibility of accidents occurs because of late response. It is intuitive to understand that in-vehicle distraction is harmful to response time, as well as the result in this research. By the effect of visual, auditory, and cognitive loads, response time would be increased (Lamble et al., 1999; Lee et al., 2001; Richard et al., 2002; Summala et al., 1998). In this experiment, further, it was found that manual load would deteriorate the situation of late response and sometimes more visual resource was needed because drivers must make sure the position of manual devices. It was consistent with Wickens's theory (Wickens, 2002) that the late response was related to the resource sharing (visual and cognitive loads). However, it is noteworthy that longer time-gaps also caused later response. The time difference between two divided subsets (time-gap <1.5 s and >1.5 s) was about 0.2 s. It implied that time-gaps longer than 1.5 s were not so urgent for bus drivers, so they could react later but still avoid dangers.

4.2. Lateral control

The main function of ACC is to strengthen the safety in front of the vehicle. It cannot precisely know the effect for vehicle lateral control. Ohno's (2001) experiment indicated that drivers with the assist of ACC did lateral controls better than manual driving. This research showed that negative effects might come of shorter time-gaps. Beside the lateral lane position, its variation (standard deviation) was also larger if time-gaps were too short. Time-gaps longer than 2 s could just make drivers to remain most closed to the lane centre. While keeping shorter time-gaps, drivers paid more attention to the front to react in time, so the resource for lateral control would be shared out and the vehicle would diverge from the lane centre (to the right side). The reason of the right divergence should be related to the location of the cockpit that the driver's field of view was biased to the left. It was easier to estimate the deviation from the left side.

It is important to note that there was an inconsistent result between this research and previous studies, the effect of in-vehicle tasks on lateral control. Previous researches indicated that the lane keeping variation and lane excess number increased if drivers were burdened with visual and conversational loads (Blanco et al., 2006; Engström et al., 2005; Noy et al., 2004). But the lateral control would not be affected by in-vehicle distracters, but by time-gaps in this research. The principal cause may have something to do with the participants. The focused objects in this research are professional bus drivers who had never used ACC before, so the effect by time-gap was large. As to in-vehicle distraction, the effect could be weaker for these skilled and well-trained bus drivers.

4.3. Summary and conclusions

Results of this experiment can be posed and summarized which provide some important issues about driving performance and safety.

(1) Professional bus driver is a critical group to assess the ACC equipped on buses. Some different and new results are found against previous researches for common drivers and cars.
(2) Longitudinal control had intensive relationship to time-gap settings and in-vehicle tasks. For some unsafe situations, compensation occurred that serious in-vehicle distraction could be improved by longer time-gap settings. Complex tasks led to critical degradation in longitudinal driving performance even though long time-gaps were selected.
(3) Later response was observed in the situation of longer time-gaps (>1.5 s) and in-vehicle distraction. But accidents could still be avoided because the time-gap was long enough.
(4) Decreased time-gap settings were reflected in lateral control performance, resulting in lane deviation or lane excess. More control resources were applied to take notice of the short headway keeping.

As ACC and IVIS have become more and more popular, their effects on driving safety, efficiency, and convenience should be considered. IVIS are beneficial for efficiency, but probably bring additional loads to the driver. From the finding of this research, negative effects by these loads can be mitigated by longer time-gaps. The driver can interact with the hands-free (manual) IVIS and drive safely with the time-gap over 1.5 s (2.0 s). The cooperation of ACC and IVIS contributes to the safety as well as to the efficiency. For the future study, more assist systems will be considered, like CWS, and some real IVIS, such as navigation systems, will also be realized to analyze the effect and performance.

Acknowledgements

We thank the National Science Council (NSC) of Taiwan for funding (no. NSC93-2218-E-216-013-). This study was also supported by the Department of Transportation Technology and Logistic Management, Chung Hua University, to provide bus driving simulator platform.

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