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Effects of time-gap settings of adaptive cruise control (ACC) on driving performance and subjective acceptance in a bus driving simulator

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ABSTRACT

A study was conducted to investigate the effects of time-gap settings and contents of secondary tasks on a fix-based bus driving simulator on drivers' performance while reclaiming control from ACC in a car-following scenario of emergency brake by the lead vehicle. Thirty professional bus drivers drove on the simulator with the scenario of highway traffic flow under 12 random time-gap settings: from 0.64 s to 2.40 s with the interval of 0.16 s. As for the effects of secondary tasks, subjects were evenly divided into three conditions: no secondary task interference, simple secondary task, and complex task. The results demonstrated that different safety demarcations of time-gaps on subjective acceptance and driving performance can be found out. The integrated demarcations separated time-gaps into divisions that represented different levels of danger. It revealed that the safer time-gaps for different situations were: longer than 1.60 s for none-secondary task distraction and longer than 2.08 s for being continuously distracted by secondary tasks. The demand for simple tasks is relatively high, so a larger time-gap is needed for the driver to remain safe. This research has implications for the time-gap selection of ACC and effects of secondary task distraction on buses. A next logical step will focus on determining time-gaps for lead vehicles on curves or slopes, when multiple vehicles are present ahead, and modeling driver behavior and performance with ACC for cars, buses, and other types of vehicles.

1. Introduction

Driving is a dynamic control process that at times can be overwhelming. Nowadays, automated driving assist systems have been developed and implemented to make that task less overwhelming. In general, automated driving assistance systems are expected to improve system and operator safety, efficiency, and comfort (Ward, 2000). One such driving automation system, adaptive cruise control (ACC), is now standard equipment for some upscale passenger cars (e.g., the BMW 500/700 series after 2003 and Audi A6 after 2005).

ACC is an enhancement of conventional cruise control systems, which sets a fixed driving speed regardless of traffic. With ACC, the driver is not only a controller, but a supervisor for some critical driving tasks. ACC can maintain a driver-selected "time-gap" between the front bumper of the subject's vehicle and the rear end of the lead vehicle by measuring that distance with radar or lidar and the speed of the subject's vehicle (SAE, 2003). Furthermore, in addition to controlling the engine and power train, ACC also provides some automatic operation of the brakes (SAE, 2003).

1.1. How ACC affects driving performance

ACC systems can have positive or negative effects on traffic flow and safety. For traffic flow, some drivers may choose longer time-gaps to reduce the number of mismatches in drivers' expectations of when and how the ACC decelerates (Zheng and McDonald, 2005), which will reduce highway capacity. However, overall, ACC leads to more gradual acceleration and deceleration of traffic streams, improving traffic flow.

Because an ACC system maintains a gap to the vehicle in front that is adjusted for the driving conditions, providing ACC systems should make driving safer. Therefore, the driver should have more resources available to attend to other tasks, such as looking at route signs and traffic signals, or potentially overloading in-vehicle tasks such as conversing on a cell phone and monitoring information systems. Further, while using ACC, previous research indicates that the maximum speed (Bjørkli and Jenssen, 2003; Törnros et al., 2002), mean speed and headway variance (Ward, 2000) are less, a safer condition. Moreover, the speed variance (Bjørkli and Jenssen, 2003; Suzuki and Nakatsuji, 2003; Törnros et al., 2002; Ward, 2000) and headway variance (Fancher et al., 1998) are also less, which reduces the likelihood of crashes. Also, when ACC is provided, drivers pay more attention to lateral control than when

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ACC is not provided (Ohno, 2001), which should reduce lane departures.

In contrast, drivers may glance “off-road” more frequently and longer when using ACC (Thompson et al., 2006), which decreases safety. Studies have found ACC brought about larger brake and acceleration forces (Bjørkli and Jenssen, 2003; Törnros et al., 2002), especially at higher speeds (Hoedemaeker and Brookhuis, 1998), potentially leading to a loss of control. Finally, ACC could also lead to shorter minimum time-gap (Hoedemaeker and Brookhuis, 1998; Törnros et al., 2002).

1.2. Research on time-gaps

Contemporary ACC systems are designed primarily for use in smooth flowing, light-to-heavy traffic at highway speeds, not stop and go traffic or emergency braking situations. Accordingly, when an unexpected condition occurs that may require emergency braking, the driver will need to intervene and react. Normally, how much time do drivers need to avoid accidents? At present, there is research on ACC operating characteristics for cars, but almost no research for buses. To provide context, Table 1 lists some recommended time-gap ranges for cars. Some characteristics are considered for these ranges, such as drivers' sex and age (Fancher et al., 1998), and roads (Törnros et al., 2002).

1.3. Importance

Buses differ in many ways from cars. The driver eye height for buses (280 cm) is greater than for cars (120 cm), allowing drivers to see farther down the road, which should lead to shorter desired time-gaps, but buses have much larger stopping distances (80 m from 100 km/h) than cars (40 m), which should increase desired time-gaps. Buses have a much lower horsepower to weight ratio (hp/lb) than cars (0.009–0.013 vs. 0.045–0.16), so they accelerate more slowly, making precise control of a time-gap more difficult. Furthermore, buses have a lower static stability factor (SSF) than passenger cars, with lower rollover resistance ratings (1–1.2 vs. 1.3–1.5), so swerving is less of an option than braking. Finally, because bus occupants are much more likely to be passengers rather than drivers and not in control of the vehicle, more sedate acceleration is desired. In summary, there are so many differences between the two vehicle types, the recommended ACC settings for buses may be different from cars and should be determined.

1.4. Objectives of this research

In this paper, three major issues relating to bus ACC systems were addressed: (1) what ACC time-gaps (between 0.64 s and 2.40 s) are preferred on expressway driving, (2) what time-gaps maximize safety, as assessed by statistics of the gap when braking begins, brake pedal movement time (from contact to 50% depression), the minimum gap during an encounter, and the number of crashes, and (3) how time-gaps are affected by the complexity of concurrent secondary tasks.

2. Method

2.1. Participants

Thirty professional bus drivers (all male, between 26 and 53 years of age; 15 city bus drivers and 15 expressway bus drivers) were paid NT$2000 ($60) for participating in this experiment. All participants had a valid professional bus driver's license for at least three years and no crashes recorded for their current employer. All were employed by motor transport companies and drove at least 40 h per week.

2.2. Apparatus

Data was collected in custom-made, fixed base, bus driving simulator at Chung Hua University, Taiwan. The intercity bus simulated was for 10 m (length) × 3 m (width) × 4 m (height).

The simulator used consisted of two subsystems. The sensing subsystem consisted of a bus cab with steering wheel, accelerator, brake, and dashboard with speedometers connected to the main computer (Intel Pentium IV 3.0G). Speed was shown on a head-up display (HUD) located in front of the driver, at 15° below line of sight of the driver who was 180 cm in height. The digits were 15 cm (height) × 12 cm (width). The eye to screen distance was 1.5 m. In simulators, drivers often underestimate their speed, and this HUD was intended to make that less likely (Godley et al., 2002; Törnros, 1998).

The interface between the simulator and the computer was a NI PCI-6034E analog card, and the software, Virtools Dev 3.0, generated the 3-D models (of cars, trees, roads, etc.), and controlled traffic flow and car motion. The graphics subsystem controlled the information flow between the main computer (server) and two client computers (Pentium IV 2.0G), each of which served as an image generator for side projectors. (The main computer controlled the central projector.) Communication between the server and client was controlled by Visual C++ code from the software development kit (SDK) of Virtools Dev 3.0. The total horizontal field of view (FOV) of the three projectors was 160°.

As typical for buses of this type, the simulated bus had an automatic transmission and was capable of 0.3 g maximum acceleration and −0.51 g maximum braking. The operating characteristics and user interface to the ACC conformed with SAE J2399 standard (SAE, 2003). The maximum deceleration provided by the system was 0.2 g. While the ACC system was active, the official ISO symbol (ISO 7000-2580) was shown on the windscreen in front of the driver. The symbol would disappear if the driver controlled the vehicle manually.

Table 1
Previous results about recommended time-gaps on ACC (for cars)

Measures	Number of subjects	Exposure duration (Per subject)	Environment	Max ACC decel. level	Recommended time-gaps	Source
Subjective preference	24	30 km	Driving simulator	–	1.50–2.49 s (motorway) 1.66–3.21 s (rural road)	Törnros et al. (2002)
Number of expectation mismatches	None	–	Computational simulation	3 m/s^2	2 s or more	Zheng and McDonald (2005)
Headway time margin	108	519 km	Equipped car	0.686 m/s^2	1.1 s (young) 1.5 s (middle-aged) 2.1 s (older)	Fancher et al. (1998)
Driver's preference	38	15 min	Driving simulator	–	No preference	Hoedemaeker and Brookhuis (1998)
Subjective selection	9	600 km	Equipped car	–	1.1–1.8 s	Reichart et al., (1996)

2.3. Tasks, experimental design, and procedure

A two-way (12 time-gaps, within-subjects; 3 secondary tasks, between-subjects) factorial design was used in this study. Time-gaps were from 0.64 s to 2.40 s in 0.16 s increment (0.64 s, 0.80 s, 0.96 s,...,2.24 s, 2.40 s), which were selected based on consideration of prior ACC studies involving passenger cars. Time-gaps were presented in random order. The primary task in this study was driving on a straight and level three-lane highway (3.5 m wide/lane) with a shoulder (1 m wide). Participants were asked to drive in the middle lane without overtaking, changing lanes, or exceeding the speed limit (100 km/h) while following the lead vehicle. Secondary tasks were separated into three levels: none, simple, and complex tasks. The secondary task was the addition of two numbers with two-digits each (less than 50), such as 18 + 36, shown in the LCD monitor at the right-hand side of the driver. The maximum response time was 8 s and the inter-trial interval was 3–5 s. A tone would occur as a cue just before the question appeared. In the simple secondary task, participants had to calculate the sum and answer verbally. For the complex task, participants needed to calculate, answer, and then to press the button on the LCD monitor (touch panel) to confirm. In other words, the complex task had one more step than the simple one, the confirmation.

This experiment was divided into 12 blocks, one for each different time-gap. Every block consisted of four trials, so there were 48 trials in all. Emergency braking of the lead vehicle would occur in one of the four trials in each block, where the lead vehicle would unexpectedly decelerate at 0.82 g from 100 km/h to 20 km/h (but only if the subject vehicle reached 100 km/h). After the lead vehicle reached the speed of 20 km/h, it would remain the speed for 5 s and reaccelerate to drive away. For the other three trials, the lead vehicle would only adjust the speed between 100 km/h and 80 km/h with the deceleration of 0.2 g, again, remaining at 80 km/h for five seconds before the lead vehicle reaccelerated and drove away. The unexpected emergency braking was beyond what the ACC could handle, so the driver had to reclaim control to avoid a crash. The trial on which emergency braking occurred varied from block to block, as shown in Fig. 1.

To begin, participants were briefed about the function of the simulator. Next, the primary driving and secondary tasks were explained and subjects were told they could quit whenever they felt dizzy or uncomfortable. Next, subjects practiced driving for 20–30 min. After that, subjects drove the 12 test blocks. At the end of the experiment, each subject completed a test in which they judged the distance to a lead vehicle (on the 2D projection, presented at 10 m, 20 m, and 40 m). At 100 km/h, these distances correspond to time-gaps of 0.36 s, 0.72 s, and 1.44 s. Since the experiment involved decisions about the distance or time to a lead vehicle, it was important to ensure their gap estimates were accurate. In total, the experiment lasted 80–100 min for each participant.

2.4. Data collection and analysis

Only part of each test session was of interest, namely from when the lead vehicle began emergency braking until the lead vehicle reaccelerated and left. The gap to the lead vehicle, vehicle speed, and the position of acceleration and brake pedal were all collected at 10 Hz. Four statistics during the interval were computed, (1) the gap when braking began (where they were when braking began), (2) brake pedal movement time (time from brake pedal contact until 50% pedal travel-how quickly they responded), (3) minimum gap (how close they were to the lead vehicle at any time), and (4) the number of crashes (how many negative outcomes occurred). Also, driver's subjective acceptance (1 = not acceptable; 0 = acceptable) for each time-gap setting was collected after each braking event.

ANOVA was computed for three statistics, the gap when braking began, brake pedal movement time, and minimum gap, to examine main effects and interactions. The non-parametric Cochran Q test was used to analyze the subjective acceptance and the number of crashes. Then, the two-stage clustering (Punj and Stewart, 1983) was applied to discriminate subsets for 12 time-gap settings, and the LSD test was used to find out the difference among three secondary tasks.

Ward's hierarchical grouping method (Ward, 1963) was used to form mutually exclusive subsets (by specified characteristics) for the first stage. The procedure was to unite n observations to $n-1$ clusters repeatedly until only one group remained. At each round, the distance between cluster centers could be found. The longer the distance was, the more distinct clusters would be. After that, time-gaps could be classified by K-means clustering (second stage), whose purpose was to maximize the within-cluster homogeneity and between-cluster separation with four main steps (Cox, 2005). In this experiment, for two-stage clustering, 12 time-gaps might be taken as "observations" that should be classified, and 30 participants would be treated as "characteristics" for observations.

3. Results

3.1. What time-gaps did subjects accept?

There were significant differences on subjective acceptance for time-gaps (Cochran's $Q = 220.281$, $p < 0.001$). The numbers were

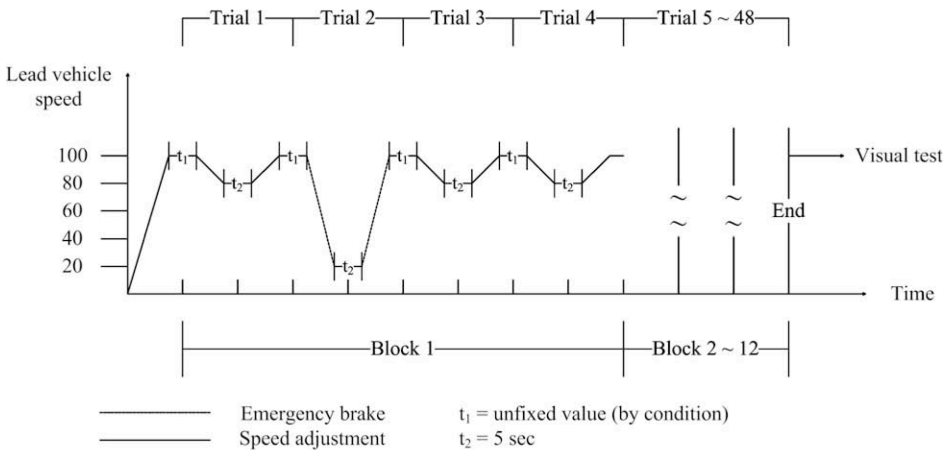

Fig. 1. The test trials illustration.

shown in Fig. 2 and two subsets (time-gaps below 1.44 s and above 1.60 s) were recommended by the clustering procedure, which meant that time-gaps greater than 1.60 s were relatively more acceptable than time-gaps below 1.44 s. When the time-gap was increased from 1.44 s to 1.60 s, the proportion of acceptance rose to about 50%, that is, almost half of participating bus drivers could accept 1.60 s as the current time-gap. If longer time-gaps were selected, more than half of subjects could accept them. How drivers' subjective acceptance would affect their risk avoidance strategies and behavior was analyzed in the following sections.

Probability functions for decisions can often be determined using logistic regression with two parameters, one of which represents the spread of the distribution and the second that described where the yes/no transaction occurs. For Eq. (1), the percent concordant was 85% and the *p*-value for the Hosmer and Lemeshow test was 0.949. Eq. (1) presents the function for the subjective acceptance and the probability a time-gap is unacceptable. An equation from acceptance for any time-gap can be estimated, not just those tested

$$Pr\ (\text{Current time-gap is unacceptable}) = \frac{e^{9.041-5.222x}}{1+e^{9.041-5.222x}},$$
$$\text{where } x = \text{time-gaps } (0.64\text{ s to } 2.40\text{ s}) \tag{1}$$

From this model, time-gaps below 1.44 s and above 1.60 s would cause the probability that current time-gap is unacceptable to be greater than 0.82 and lower than 0.67.

3.2. Driver performance

The statistics of gap when braking began, brake pedal movement time, minimum gap, and number of crashes were analyzed in this section with ANOVA (Cochran's Q test) and clustering. As shown in Table 2, all statistics were significantly affected by time-gaps. Only the interaction for the minimum gap was significant. For the situations without interaction, Ward's method indicated there were two time-gaps subsets, with K-means clustering showing the border was between 1.44 s and 1.60 s (Fig. 2a, c, and e). As to the result in Fig. 2b, the line had a steadily continuous increase with the difference of 4 m between each time-gap. It was not obvious where the border was.

The simple main effects of the two factors were analyzed through two-stage clustering (for time-gaps) and LSD method (for secondary tasks). As shown in Fig. 2d, without secondary tasks (the solid line in Fig. 2d), the border was also not obvious. The slope was stable. However, for simple and complex secondary tasks (the broken line in Fig. 2d), the border could be 2.08 s, which corresponded to an increase in the minimum gap by 7.40 m (three quarters of bus length). When being distracted by secondary tasks, longer time-gaps were recommended.

The LSD test indicated that the gap when braking began with no secondary task was significantly longer than with the simple and complex tasks. When comparing with no secondary task, simple and complex secondary tasks slowed down drivers' responses and shortened the gap when braking began by 4.14 m and 6.57 m respectively. Further, the simple main effects of secondary tasks on minimum gap showed that the significance between with/without secondary task conditions occurred as long as time-gaps were between 1.12 s and 1.92 s. Compared with no secondary task, minimum gaps with simple and complex secondary tasks were shorter by 5.25 m and 7.14 m.

To take the analysis of crashes one step further, logistic regression was used to model the relationship between crash probability and time-gaps Eq. (2). The percent concordant was 83% and the *p*-value for the Hosmer and Lemeshow test was 0.164

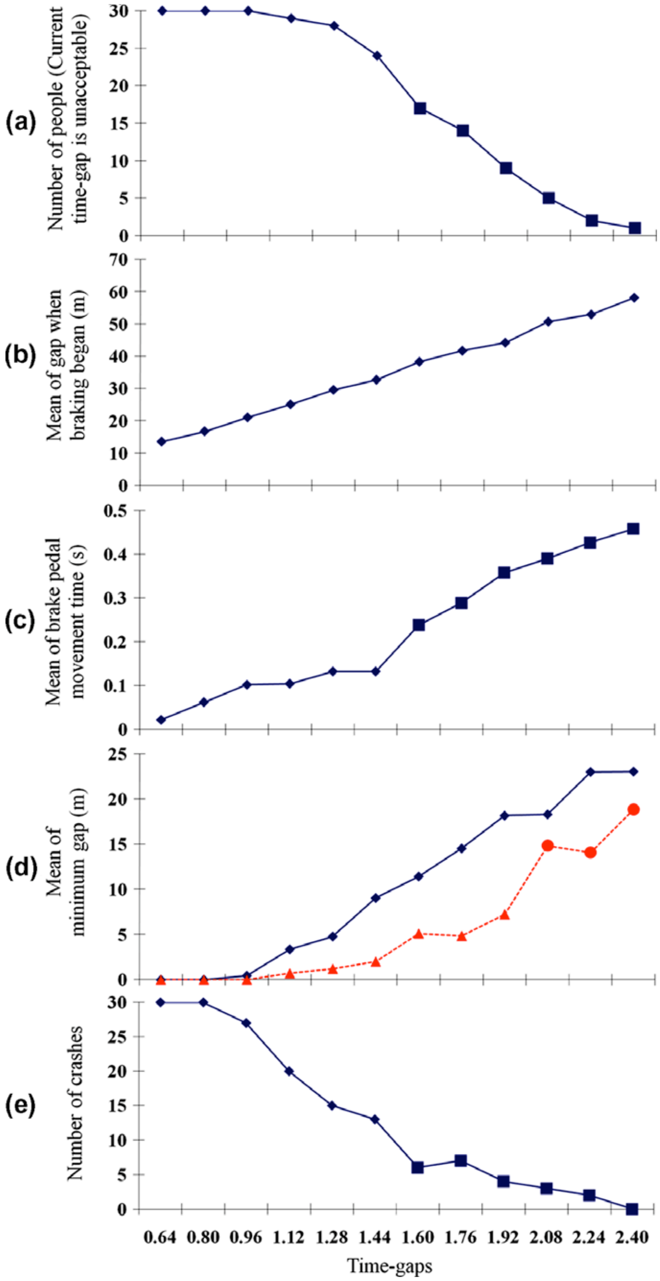

Fig. 2. Effect of time-gap on (a) subjective acceptance (b) gap when braking began, (c) brake pedal movement time, (d) minimum gap, and (e) number of crashes.

$$Pr\,(\text{Crashes}) = \frac{e^{5.745-4.126x}}{1+e^{5.745-4.126x}},$$
$$\text{where } x = \text{time-gaps } (0.64\text{ s to } 2.40\text{ s}) \tag{2}$$

In this model, time-gaps below 1.44 s and above 1.60 s would cause the crash mean to be greater than 0.45 and lower than 0.3.

3.3. Visual test for simulation environment

Distances (gaps) estimated for 10 m, 20 m, and 40 m were 9.5 m, 19.9 m, and 37.5 m, respectively, with a mean standard deviation of 0.8, 1.3, and 2.2 (8.4%, 6.7%, 6.0% of mean), so estimates of distance in the driving simulator were both accurate and precise, supporting the use of the driving simulator.

Table 2
ANOVA results for driver performance variables and Cochran's Q test result for number of crashes

Statistics	Source	*F*	*d.f.*	*p*
Gap when braking began	Time-gaps (T)	316.611	11	<0.001*
	T × S	1.076	22	0.372
	Error (T)		297	
	Secondary tasks (S)	12.352	2	<0.001*
	Error (S)		27	
Brake pedal movement time	Time-gaps (T)	27.344	11	<0.001*
	T × S	0.697	22	0.842
	Error (T)		297	
	Secondary tasks (S)	0.112	2	0.895
	Error (S)		27	
Minimum gap	Time-gaps (T)	76.423	11	<0.001*
	T × S	3.874	22	<0.001*
	Error (T)		297	
	Secondary tasks (S)	10.206	2	0.001*
	Error (S)		27	
Statistics	Source	*Cochran's Q*		*p*
The number of crashes	Time-gaps (T)	198.634		<0.001*

Note: *statistical significant.

4. Discussion

4.1. Time-gaps

For most measures, the demarcation between riskier and safer conditions was for time-gaps between 1.44 s and 1.60 s, so time-gaps above 1.60 s are recommended for buses for all secondary task conditions. However, the result is not consistent with some previous research for cars (in Table 1). Hoedemaeker and Brookhuis (1998) indicated that drivers had no significant preference for time-gaps based on rating scale mental effort (RSME). Time-gaps in Zheng and McDonald's research, 2005 were recommended to be more than 2 s. The difference could be due to that (1) subjects were professional bus drivers and the environment was a bus driving simulation in this research, and (2) time-gaps in this research were from 0.64 s to 2.40 s, which covered wider time-gap ranges than previous ones.

The experimental result showed that time-gaps above 1.60 s were more acceptable, and more likely to prevent collisions, but the border would increase to 2.08 s if drivers were distracted by secondary tasks. There was a huge time-gap difference (0.48 s, 13.2 m) between these two situations, which could be taken as the time for drivers to decouple from the secondary task. Fortunately, the negative effect of secondary tasks could be eliminated by longer time-gaps, as was the finding of previous research (Lin et al., 2008). It was also indicated that the driver would keep shorter minimum gaps when driving with ACC (Hoedemaeker and Brookhuis, 1998; Törnros et al., 2002), but time-gaps greater than 2.08 s were desired when distracted by a secondary task. In this research, to reclaim control was a highly visual-manual demanding task in which the driver observes the lead vehicle and perceives if the emergency braking occurred. The visual, auditory, and cognitive loads would lead to longer reaction time (Lee et al., 2001; Richard et al., 2002). That is why the designed secondary tasks had such a significant effect.

Comparing with other studies about the effect of secondary tasks, one needs to quantify the demands of these tasks. Yee et al. rated the visual (V), auditory (A), cognitive (C), and psychomotor (P) demands of 68 subtasks performed while driving. Ratings were from the US Army IMPRINT modeling tool (0-to-7 scale, with 7 being the most demanding) (Yee et al., 2007). For all four scales, subtasks could be rated according to their contents. For instance, the visual demand of the secondary task in this research (looking at the LCD monitor and read the numbers) belonged to the definition of "Visual read (symbol)," so the VACP demand could be rated with the score of 5.9 (see Yee et al. (2007)). By the same way, the total demands for simple and complex task in this study could be determined, which were 14.9 and 21.1, with VACP values of (5.9, 1.0, 7.0, 1.0) and (9.9, 1.0, 7.0, 3.2), respectively. Also, the demands of other in-vehicle subtasks (e.g. dial phone, eat food, hold a cigar, etc.) can be quantified using these ratings.

The consequences of a delayed response could be improved by selecting time-gaps of 2.08 s or longer, as larger gaps give the driver more time to assess the situation and take evasive action. Stanton et al. also suggested that ACC should provide drivers with enough time to reclaim control from the automated system (Stanton et al., 1997). Long time-gaps, however, could lead to delayed driver responses because the bus drivers thought the current time-gap was not so urgent that they could react later (Lin et al., 2008). Although the delayed response would not lead to danger because of the long time-gap, it could also bring about discomfort resulting rapid braking or steering.

In most cases interactions were not statistically significant, except the minimum gap. This phenomenon might be due to the design of experiment and number of subjects in each experimental condition. There were only 10 participants for each condition (30 participants evenly distributed into three secondary task conditions). Increasing the number of participants or replicates in this experiment could lead to interactions that are statistically significant.

4.2. Limitations

This research does have some limitations. The traffic density of the simulator is about 1080 vehicles per hour per lane with the speed of 110 km/h, which corresponds to Level of Service A on a freeway, the conditions under which ACC is most likely to be used. When the traffic density is greater, the speed will be lower and the required time-gap will change as well. Also, this experiment did not involve any task other than driving on a straight road and maneuvers other than braking. When driving on curves, depending on the radius and speed, some ACC systems lose and then re-acquire lead vehicles or may interpret vehicles in other lanes as being lead vehicles, especially if both the target and subject vehicles are close to the same lane boundary. This can cause the ACC system to slow the vehicle suddenly and severely. The extent to which this occurs varies with headway, traffic, and curvature, and not necessarily in a consistent manner with increasing headway. Furthermore, preferred ACC settings should be different when maneuvering (changing lanes, cut-ins) as maneuvers often lead to the sudden appearance of a lead vehicle at a short range, which leads to braking.

5. Conclusions

The safety implications of various ACC time-gap settings were examined using five driving performance statistics. For all five, the recommended time-gaps for "car following" on an expressway at 100 km/h with light traffic (Level of Service A) were: (1) longer than 1.60 s for no secondary task distraction and (2) longer than 2.08 s for being continuously distracted by secondary tasks, such as monitoring in-vehicle information systems or speech interaction. Even though drivers often misestimate distances and speeds in simulators, the judgment task indicates the distance estimates were precise and accurate. A next logical step will focus on determining time-gaps for lead vehicles on curves or slopes, when multiple vehicles are present ahead, and modeling driver behavior and performance with ACC. This should be done for cars, buses, and other types of vehicles as well.

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