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Research Article

Effects of In-Vehicle Navigation on Perceptual Responses and Driving Behaviours of Drivers at Tunnel Entrances: A Naturalistic Driving Study

Xinsha Fu [1], **Shijian He** [1], **Jintao Du** [1], **and Ting Ge** [2]

[1] *School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510640, China*
[2] *School of Civil Engineering, Suzhou University of Science and Technology, Suzhou 215011, China*

Correspondence should be addressed to Ting Ge; geting_usts@126.com

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The perceptual responses and driving behaviours of drivers at tunnel entrances vary, which could cause interference and accidents. This study investigated the effects of in-vehicle navigation on the perceptual responses and driving behaviours and whether these effects are actually valid for safety improvement. For this purpose, a series of naturalistic driving experiments was conducted and a comparative analysis was performed considering two different experiment conditions, control condition and in-vehicle navigation condition. Under each condition, the performances of twenty drivers at seven tunnels were evaluated. The area from 200 m outside the tunnel portal to 200 m inside the tunnel portal was averagely divided into four zones. In each zone, two types of perceptual responses (visual responses and psychological responses) and driving behaviours were analysed using six indicators: number of fixations, average duration of fixations, time interval between continuous R-waves, skin conductance response, speed difference in zones, and maximum deceleration. The results showed that in-vehicle navigation significantly affects the perceptual responses and driving behaviours of drivers, and these effects varied in different zones of the tunnel entrance. Furthermore, in-vehicle navigation was found to be valid for safety improvement because beneficial changes in four of the six indicators proved to be effective at appropriate zones. The remaining two indicators, average duration of fixations and maximum deceleration, were not valid, implying that the difficulty of driving information cognition and driving comfort could not be improved by in-vehicle navigation. Moreover, a negative correlation was discovered between the number of fixations and speed difference in zones. This study provides engineers a new knowledge by extending the quantifiable approaches to the analyses of the effectiveness of the effects of in-vehicle navigation.

1. Introduction

Tunnels are usually designed to provide a fast passage for vehicles when a terrain with large elevation difference needs to be overcome. As such, drivers experience an environmental transition from the general open environment to the semiclosed environment when approaching and passing the tunnel entrance section. This environmental transition disturbs the perceptual responses and driving behaviours of drivers, which could increase the possibility of traffic interference and accident occurrences [1, 2]. Previous studies have shown that accidents occur more frequently with higher severity at tunnel entrances than in other areas [3–5].

Recently, several studies analysed the relationship between drivers' perceptual responses and driving behaviours with the driving safety of tunnel entrances. In these studies, two types of perceptual responses could be derived: visual response and psychological response. Many visual issues of environmental transition have been investigated in driving simulation; for example, the fixation type was affirmed to be connected to terrain changes in environmental transition [6], steering operation during environmental transition was related to the fixation angle [7], and the number of fixations could reflect the grade of driving load during environmental transition [8–10]. Psychological responses, which were extracted from electrocardiography (ECG) and electrodermal activity (EDA) signals, could be used to evaluate the psychological adaptability of drivers [11–13]. Objectively, psychological responses could reflect the psychological stress experienced by drivers during the

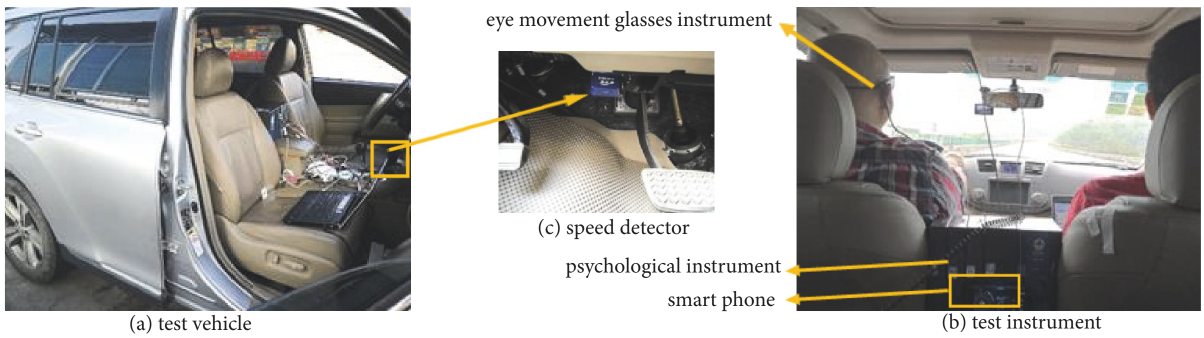

Figure 1: Vehicle and instruments used in naturalistic driving experiment. (a) Test vehicle, (b) test instruments, and (c) speed detector.

environmental transition [14–16]. Moreover, recent research indicates that the deceleration behaviour is an important factor of driving safety [17, 18]; safety problems can be expected if drivers are forced to decelerate too quickly [2, 19, 20].

To improve the driving safety at tunnel entrances, several studies have proposed many safety measures to manage the drivers' perceptual responses and driving behaviours. These safety measures referred to reducing the environmental transition issues by providing more guiding information for drivers. Conventionally, the safety measures include the following aspects: geometric alignment optimization of the tunnel entrance [17, 21, 22]; environment management, particularly tunnel illumination design [23, 24]; improvement of pavement conditions [25]; restriction of road signs and markings [5, 9]; and additional prewarning measures [26–29]. Nowadays, with the rapid development of the intelligent transportation system (ITS), vehicle-to-infrastructure (V2I) wireless communication technologies are being introduced to improve drivers' awareness [30]. In-vehicle navigation is an innovative driving safety measure that has been used widely [31–33]. It can provide driving information to drivers through images and sounds. Several studies have determined the relationship between in-vehicle navigation and driving safety.

Existing studies related to in-vehicle navigation mainly focus on the methodology of safety measures [34, 35]. For instance, Varhelyi et al. considered four types of warnings, namely, speed limit warning, curve road-line warning, forward collision warning, and blind spot warning, in their user-related evaluation study of in-vehicle navigation [36]. Many indicators of driving behaviour were used to verify the effect of in-vehicle navigation. For example, six indicators of lane-change behaviour were used to discuss the effects of in-vehicle navigation on driving safety at urban expressway diverge segments in driving simulation [18]. The effects of in-vehicle navigation on different road segments have also been evaluated for relevant driving behaviours, such as braking behaviour in merging areas [37], steering behaviour in curves [38], and following behaviour in main lanes [39]. However, studies exploring the effect of in-vehicle navigation on driving behaviour at tunnel entrances have rarely been conducted.

To investigate the effects of in-vehicle navigation on driving safety at tunnel entrances, two main limitations need to be addressed. Firstly, the effects of in-vehicle navigation on driving safety have rarely been verified through the analysis of drivers' perceptual responses, which can directly reflect the effects of environmental transition on drivers [40–42]. Considering the special status of tunnel entrances, not only general factors such as driving behaviours, but also the perceptual responses of drivers should be considered in analysing the effects of in-vehicle navigation. Secondly, the effectiveness of in-vehicle navigation measures has rarely been verified. Consequently, there are no clear and critical standards to guide the design of in-vehicle navigation. Due to the lack of the corresponding design and evaluation standards for the tunnel entrance, driving safety problems at tunnel entrances have still not been adequately resolved [43]. Moreover, almost all current researches are conducted under driving simulation conditions. Testing in driving simulations may not endanger the real safety of drivers [44]. With this cognition, drivers in the driving simulation may not reflect the same perceptual responses and behaviours as in naturalistic driving conditions [45, 46]. Therefore, drivers' perceptual responses and driving behaviours based on naturalistic driving experiments should be combined in the analysis of the effectiveness of in-vehicle navigation.

The objective of this study, therefore, is to examine how in-vehicle navigation affects drivers' perceptual responses and driving behaviours, and whether these effects are really valid for improving driving safety at tunnel entrances. Because driving simulation and real-world data are different, a naturalistic driving test was conducted. This study is a preliminary analysis of using naturalistic parameters to observe drivers' perceptual responses and driving behaviours at tunnel entrances. Continuous perceptual responses and driving behaviours were collected using relevant instruments including eye movement glasses, psychological detector, and speed detector. A comparative analysis was conducted between control conditions and in-vehicle navigation conditions. The experiments involved the perceptual responses and driving behaviours of twenty drivers under two conditions in 7 tunnels along the No. G55 mountainous freeway in Guangdong Province, China.

2. Methods

2.1. Apparatus. Figure 1 shows the apparatus used in the experiment. As shown in Figure 1(a), the test vehicle

Table 1: Information of test tunnels.

Number	Name	Length [m]	Portal structure	Radius of horizontal alignment [m]	Slope [%]
1	Gaoding Tunnel (left)	933	End wall	1300	0.38
2	Fengkeng Tunnel (left)	762	Bamboo-truncating	3720	1.72
3	Wenkeng Tunnel (left)	867	Bamboo-truncating	-	-0.64
4	Shimen Tunnel (left)	781	Bamboo-truncating	3440	-2.36
5	Shimen Tunnel (right)	768	Bamboo-truncating	2550	2.28
6	Wenkeng Tunnel (right)	920	Bamboo-truncating	3800	0.71
7	Fengkeng Tunnel (right)	795	Stepped wall	3450	-1.53

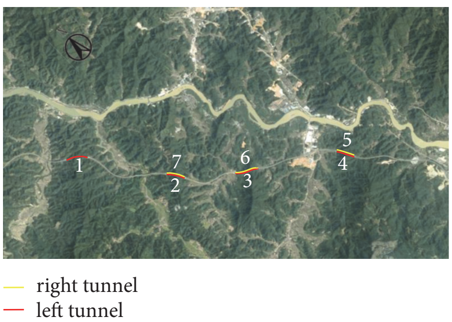

Figure 2: Selected test tunnels along the No. G55 expressway, Guangdong, China.

(Highlander, Toyota, Guangzhou, China) had a normal mechanical status. Two types of portable acquisition equipment were employed for recording the perceptual responses (Figure 1(b)). One was an eye movement glasses instrument (ETG-2.6, SensoMotoric Instruments GmbH Warthestrasse, Teltow, Germany) with the following device parameters: the range of tracking visual angle was 80° in the horizontal and 60° in the vertical direction, the tracking resolution was lower than 0.1°, the imaging resolution was 960×720 pixels, and the sampling frequency was 60 Hz. The other was a psychological instrument (BIOPAC MP160, BIOPAC Systems Inc., Goleta, USA) that can record ECG and EDA signals. The device parameters of the psychological detector are as follows: the sampling frequency was 2000 Hz; the ECG signal was amplified 1000 times; the EDA signal was amplified at 5 μsm (microsiemens) per volt; the measured positions of EDA were the index and ring fingers.

Similar to a recent study [20], a speed detector (see Figure 1(c)) was inserted in the on-board diagnostics (OBD) interface for obtaining information on the vehicle status from the controller area network (CAN) of the vehicle. The sampling frequencies of speed and deceleration were 2 Hz. A smartphone was used to broadcast in-vehicle navigation warnings and to receive network data.

2.2. Driving Environment. In this study, the naturalistic driving experiments were carried out on the No. G55 freeway from Sanshui to Huaiji in Guangdong Province, China. Figure 2 shows the locations of the tunnels selected in the study. Seven tunnels along an 80.5 km road section were considered. These tunnels had similar length and entrance conditions, and the main technical indicators of the test road section are listed in Table 1. The design speed of the test road section was 100 km/h, and the lane layout was in the form of two-way six lanes with 3.75 m width per lane.

To ensure that the experiments were carried out under the same condition of traffic flow, the time distribution of the traffic volume in the test road section was investigated prior to experimental planning. According to the investigation results, the daily test durations were finally determined to range from 7:00 am to 11:00 am. During this period, the traffic volume per lane was in the range of 320–460 vehicles per hour, and the time headway was more than 6 s. Moreover, abnormal states, such as car passing, car following, and device breakdown, were recorded during the test. In order to eliminate the interference of these abnormal states with the research results, the data of these states were removed from the following analysis.

2.3. Participants. To minimise the interference of variables with the results, uniformity of the samples was taken into account in the selection process of the participants. Variables, such as the ages, driving habits, driving experience and proficiency, and psychological stress resistance of the drivers, were considered. At the same time, the influence of variables on the safety and security of the naturalistic driving tests in the freeway was also taken into account. The participants included twenty drivers (16 males and 4 females). Participants were recruited via social media, via email, and in person in our university campus and management company of test road. Written consent was obtained from the participants, and the study conforms to ethical guidelines. The mean age of the participants was 32.7 years with a standard deviation of 3.2 years; the mean value of driving years was 6.5 years, with a standard deviation of 3.5 years; the mean value of expressway driving was 5800 km, with a standard deviation of 3250 km. Each participant had a legal driving license with grade C1 of China. None of the participants had any driving experience in the test road before this experiment; that is, they were unfamiliar with the road conditions of the test road.

2.4. Experimental Procedure. The experiment was designed as a comparison test under two different conditions: control condition and in-vehicle navigation condition. The in-vehicle navigation condition was defined as driving condition with in-vehicle navigation warning. The control condition was defined as normal driving condition without in-vehicle navigation.

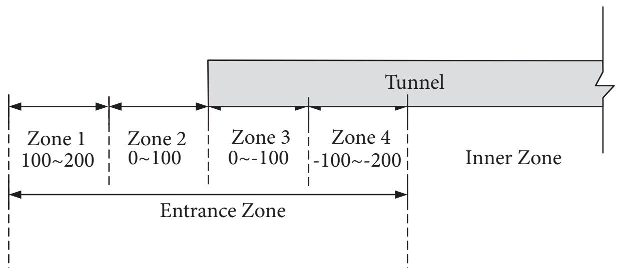

Figure 3: Division of zones at the tunnel entrance.

The in-vehicle navigation condition was set up through a voice warning message system. At the position of one kilometre before the tunnel portal, the smartphone started to broadcast the voice warning message, which stated: "there is a tunnel ahead, please pay attention to the safety of driving". The duration of each message was 3 s, the interval of messages was 5 s, and the message was repeated five times for each tunnel under the in-vehicle navigation condition. Information of the warning message mentioned above was preliminarily written into a smartphone application.

Each participant was asked to drive through the test road for two rounds. In the first round, the in-vehicle navigation condition was set up at tunnels No. 1, No. 3, No. 5, and No. 7, and the control condition was set up at tunnels No. 2, No. 4, and No. 6. In the second round, the in-vehicle navigation condition was set up at tunnels No. 2, No. 4, and No. 6, and the control condition was set up at tunnels No. 1, No. 3, No. 5, and No. 7. In this manner, the testing parameters of each tunnel under the control and in-vehicle navigation conditions could be obtained.

Before the start of each individual test, the driver was reminded to drive normally but was not notified of the condition setting of the test. During each individual driving test, an equipment operator and a recorder were installed in the test car, in addition to the driver.

2.5. Zone Division of Tunnel Entrances. Similar to recent studies [3–5, 21], the tunnel entrance was divided into four zones, as shown in Figure 3. Zone 1 was defined as the area from 200 m to 100 m in front of the tunnel portal; Zone 2 was defined as the area from 100 m to 0 m in front of the tunnel portal; Zone 3 was defined as the area from 0 m to 100 m after the tunnel portal; Zone 4 was defined as the area from 100 m to 200 m after the tunnel portal. The observation indicators were analysed to identify variations in perceptual responses and driving behaviours at different zones of the tunnel entrance with and without in-vehicle navigation. The observation indicators of this study are described below.

2.6. Observation Indicators. It is generally believed that the multifactorial study is more comprehensive. Therefore, six indicators were selected for analysis in this study: the number of fixations, average duration of fixations, time interval between continuous R-waves (R-R interval) and skin conductance response (SCR), speed difference in zones, and maximum deceleration. The number of fixations and average duration of fixations represent visual responses, R-R interval and SCR represent psychological responses, and speed difference in zones and maximum deceleration represent driving behaviours.

(1) Number of fixations is the total number of fixations of a driver in a specific zone. When the driver maintains a certain position or area of vision for a certain period of time, this behaviour is called a gaze. In this study, a gaze of longer than 50 ms is defined as a fixation.

(2) Average duration of fixations is the average duration of the total fixations in a specific zone. The duration of fixation refers to the length of time from the beginning to the end of a fixation.

(3) R-R interval is the time interval between continuous R-waves of heartbeat, which is extracted from ECG signals. ECG signals are records of electrical changes associated with cardiac heart activity, which is controlled by sympathetic and parasympathetic activities in the autonomic nervous system.

(4) Skin conductance response (SCR) is an indicator extracted from EDA signals. It indicates psychological arousal caused by stimulus.

(5) Speed difference in zones is the speed difference between the end cross section and the starting cross section in one zone. The end cross section of the previous zone is also the starting cross section of the next zone; for example, the end cross section of Zone 1 is also the starting cross section of Zone 2.

(6) Maximum deceleration is the maximum deceleration throughout the tunnel entrance.

3. Results and Discussion

To achieve the research aim of gaining further understanding of the effectiveness of in-vehicle navigation at tunnel entrances, we analysed the visual responses, psychological responses, and driving behaviours of drivers through naturalistic driving experiments. After eliminating invalid data attributable to equipment errors and abnormal traffic states, 272 groups of eye movement data, 264 groups of ECG data, 252 groups of EDA data, and 274 groups of speed and deceleration data were used for analysis.

3.1. Characteristic of Visual Responses

(1) Number of Fixations. The number of fixations is a signal indicator of interaction between drivers and the driving environment. The amount of information points obtained by the driver from the driving environment is directly proportional to the number of fixations collected in the driving task. However, there is no relationship between the number of fixations and the depth of information points [10].

Figure 4 shows the results of the number of fixations in each zone of the tunnel entrance. Bars indicate the mean value of the number of fixations from twenty drivers, and the error bars denote 90% confidence levels. Blue bars denote fixations obtained under the control condition, and red bars denote those obtained under the in-vehicle navigation condition. The distribution of the number of fixations under the control condition was found to follow the order Zone 2 > Zone 3 >

Table 2: Statistical results of the number of fixations.

	Control		In-vehicle navigation		[c]P
	[a]mean	[b]sd	mean	sd	
Zone 1	8.35	2.90	9.62	1.62	<0.001
Zone 2	11.45	2.62	11.80	3.31	<0.01
Zone 3	10.15	2.35	9.91	2.81	0.30
Zone 4	8.28	1.91	8.10	2.10	0.06

[a]Mean value of fixations. [b]Standard deviation of fixations. [c]P-value of F-test.

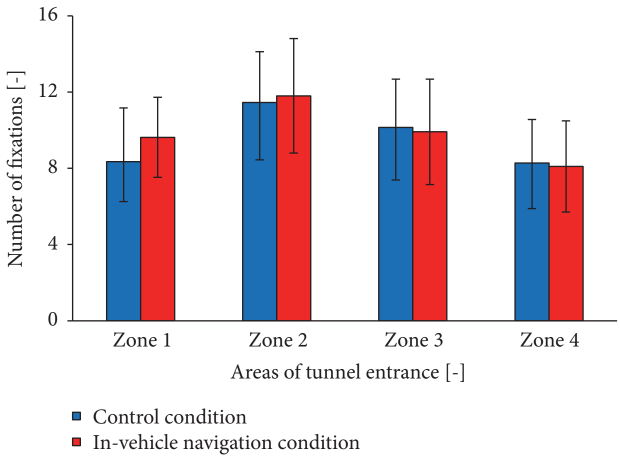

Figure 4: Comparison of the number of fixations between the control and in-vehicle navigation conditions.

Zone 1 > Zone 4. This indicates that drivers need more driving information in Zone 2 and Zone 3 rather than in other zones. This result may explain the achievements of recent research [3, 10] in which accident risk was found to be higher in the range of 50 m before tunnel portal to 50 m after the tunnel portal than that in other ranges.

Under control condition, the largest average value of the number of fixations was found in Zone 2. This implies that drivers require driving information the most for Zone 2 for interaction. It demonstrates that drivers are willing to seek more driving information within the range of 100 m from outside of tunnel portals. This may verify the inference of previous research [10, 45] that drivers desire more driving information to ensure driving safety during environmental transition. According to the distribution of the number of fixations, Zone 2 should be treated as the most important area of driving information interaction. In other words, only if a driving safety measure could improve driving information interaction in Zone 2, this measure could be treated as an effective measure based on the number of fixations.

Variability in the number of fixations was observed with the implementation of the in-vehicle navigation system. As shown in Figure 4, compared to the result of control condition, the number of fixations under the in-vehicle navigation condition increased in Zone 1 and Zone 2 and decreased in Zone 3 and Zone 4. Table 2 summarises the average values of the number of fixations under the two conditions and the statistical results of analyses of variance (ANOVA). Significant differences were found between the control condition and in-vehicle navigation condition in Zone 1 ($p<0.001$) and Zone 2 ($p<0.01$), but there was no significant difference in Zone 3 ($p=0.30$) and Zone 4 ($p=0.06$). This means that in-vehicle navigation could clearly enable drivers to pay more attention to driving information interaction before entering the tunnel. In this manner, interference of the driving environment, which threatens driving safety, could be discovered more easily. In particular, this beneficial change attributable to in-vehicle navigation was applicable to Zone 2, which is the most important area of driving information interaction at the tunnel entrance. This validates the effectiveness of in-vehicle navigation in improving driving information interaction. The driving information interaction decreased in areas inside the tunnel but this change was not significant.

Moreover, the distribution of the number of fixations under the control condition was the same as that under the in-vehicle navigation condition. The distribution regulation was Zone 2>Zone 3>Zone 1>Zone 4. This implies that the distribution of the number of fixations is a macroscopic regulation that may be basically controlled by the general driving environment.

(2) Average Duration of Fixations. The average duration of fixations reflects the depth of the driver's fixation and could effectively represent the difficulty of driving information cognition experienced by the driver during environmental transition at the tunnel entrance. For a driver, the longer the average duration of fixation, the more difficult the cognition of information from the driving environment [46].

Figure 5 shows the results of the average duration of fixations in each zone of the tunnel entrance. The error bars denote 90% confidence levels. The solid and broken lines represent fixations obtained under the control and in-vehicle navigation conditions, respectively. Under the control condition, the largest average duration of fixations was found in Zone 4. This implies that Zone 4 was the most difficult area for driving information cognition. This may be attributed to the driving environment in Zone 4, which is narrower and darker than those of Zone 1, Zone 2, and Zone 3. Under this driving environment, in order to keep the position of vehicle in lane, drivers were always constrained to maintain their fixations on the road face straight ahead.

When in-vehicle navigation was added in the driving task, the average duration of fixations decreased in each zone, as shown in Figure 5. Table 3 shows the values of decrease and

Table 3: Statistical results of the average duration of fixations.

	Control		In-vehicle navigation		P
	mean [ms]	sd [ms]	mean [ms]	sd [ms]	
Zone 1	290.62	99.32	230.16	84.38	0.03
Zone 2	204.96	78.19	196.67	93.02	0.02
Zone 3	271.36	103.82	248.19	110.00	0.25
Zone 4	330.88	125.18	311.87	118.92	0.27

Table 4: Statistical results of the R-R interval.

	Control		In-vehicle navigation		[a]t	[b]Cohen's d
	mean [s]	sd [s]	mean [s]	sd [s]		
Zone 1	0.78	0.10	0.82	0.10	2.81	0.40
Zone 2	0.73	0.09	0.80	0.09	6.57	0.78
Zone 3	0.70	0.07	0.73	0.08	4.27	0.40
Zone 4	0.72	0.09	0.75	0.10	2.32	0.32

[a]T-test value. [b]Effect size Cohen's d.

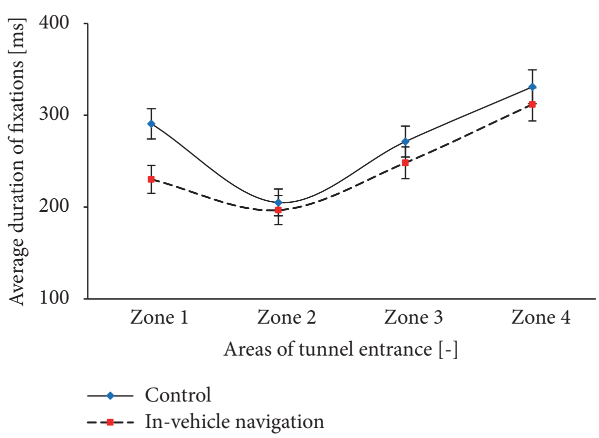

Figure 5: Comparisons of the average duration of fixations between the control condition and in-vehicle navigation condition.

ANOVA results of the average duration of fixations in each zone under two conditions. The ANOVA results revealed significant differences of the average duration of fixations in Zone 1 (p=0.03) and Zone 2 (p=0.02) between the control condition and the in-vehicle navigation condition, but there were no significant differences in Zone 3 and Zone 4. This indicates that the difficulty of driving information cognition before the tunnel portal was significantly decreased by in-vehicle navigation, but not after the tunnel portal. Thus, based on the ANOVA results of the average duration of fixations, only Zone 1 and Zone 2 can be considered applicable areas for in-vehicle navigation.

Unfortunately, Zone 4 was the most difficult area of driving information cognition requiring changes the most. This implies that in-vehicle navigation may not be very effective in improving the driving information cognition as its positive effect was unclear on the most difficult area of driving information cognition.

3.2. Characteristics of Psychological Responses

(1) R-R Interval. R-R interval reflects the mental workload experienced by the driver during driving task. The larger the R-R interval, the greater the mental workload perceived by the driver [29].

Table 4 lists the statistical results of R-R interval in each zone of the tunnel entrance. Under the control condition, the variation of the mean value of R-R interval in adjacent zones followed the order Zone 3<Zone 4<Zone 2<Zone 1. This result indicates that the mental workload inside the tunnel was obviously higher than that outside the tunnel. This phenomenon may be attributed to the difference between the semiclosed driving environment inside the tunnel and the open driving environment outside the tunnel; semiclosed environments are more likely to induce a sense of depression and make drivers anxious [13]. The minimum value of R-R interval was found in Zone 3 under both conditions; in other words, drivers perceived the largest mental workload in Zone 3.

Compared to the control condition, the mean value of R-R interval increased in each zone under the in-vehicle navigation condition, but the order of variation in adjacent zones remained the same. This may confirm that the in-vehicle navigation alleviated the mental workload perceived by the driver during the environmental transition. Further, T-test and Cohen's effect were used to identify effective areas of the in-vehicle navigation. The results of statistical analysis of R-R interval are shown in Table 4. In general, no large effect was found, but minor effects were found in Zone 1, Zone 3, and Zone 4, and medium effect was found in Zone 2. This means that the in-vehicle navigation had the effect of reducing the mental workload of drivers at the tunnel entrance, but the effect was not obvious.

(2) Skin Conductance Response. The environmental transition at the tunnel entrance can be regarded as a stimulus to the driver, and the SCR can directly reflect the drivers'

Table 5: Statistical results of SCR between the control condition and in-vehicle navigation condition.

	Control			In-vehicle navigation			t	Cohen's d
	num	[a]m-a [μsm]	sd [μsm]	num	m-a [μsm]	sd [μsm]		
Zone 1	32.00	0.45	0.10	55.00	0.43	0.12	0.61	0.18
Zone 2	39.00	0.54	0.15	24.00	0.44	0.11	2.41	0.76
Zone 3	46.00	0.85	0.13	27.00	0.53	0.14	9.54	2.37
Zone 4	15.00	0.47	0.11	14.00	0.46	0.13	0.07	0.08

[a]Mean value of the amplitude of SCR.

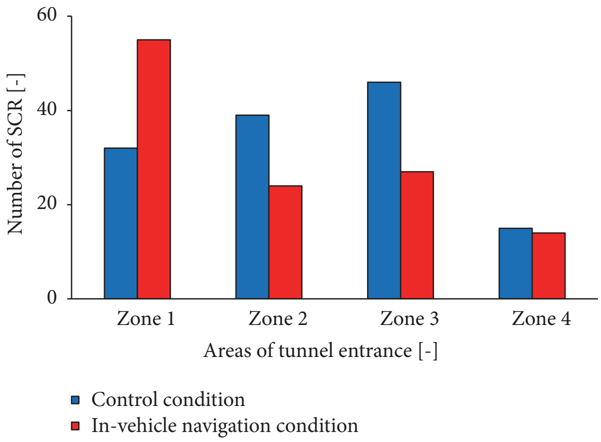

Figure 6: Comparisons of SCR between the control condition and in-vehicle navigation condition.

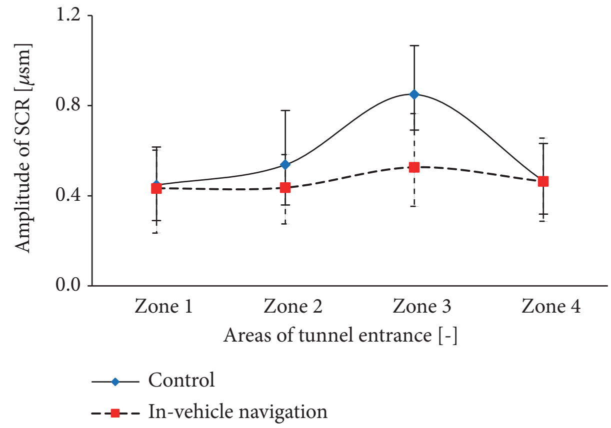

Figure 7: Comparisons of the amplitude of SCR between the control condition and in-vehicle navigation condition.

psychological arousal caused by the stimulus. The greater the SCR, the sharper the drivers' psychological arousal and the more the risk posed to driving safety [16].

Figure 6 shows the distribution of SCR under the two conditions. Colour conventions are the same as Figure 5. Compared to the control condition, the position of SCR under the in-vehicle navigation condition was transferred from zones inside the tunnel portals to those outside the tunnel portals. Table 5 shows specific changes of the position distribution of SCR. The number of SCR increased from 32 under the control condition to 55 under the in-vehicle navigation condition in Zone 1, decreased from 39 to 24 in Zone 2, decreased from 46 to 27 in Zone 3, and basically remained the same in Zone 4. This means that in-vehicle navigation helped drivers adapt to the environmental transition earlier than the control condition. Moreover, the total number of SCR decreased from 132 under the control condition to 120 under the in-vehicle navigation condition. This indicates that in-vehicle navigation could decrease the driving workload such that some drivers showed no significant psychological arousal during the environmental transition.

Figure 7 shows variations in the amplitude of SCR in different zones. The error bars denote 90% confidence levels. The largest SCR was found in Zone 3 under the control condition, which represents the most sensitive area of drivers' psychological arousal. After implementing in-vehicle navigation, the amplitude of SCR was generally reduced in each zone. Table 5 presents the results of the T-test and Cohen's effect. Specifically, a large effect was found in Zone 3 (Cohen's d=2.37), and a medium effect was found in Zone 2. This implies that in-vehicle navigation could effectively reduce the SCR of drivers, especially in Zone 3. Considering that Zone 3 is the most sensitive area of drivers' psychological arousal, as mentioned above, the effect of in-vehicle navigation on improving drivers' psychological arousal was applicable to the appropriate zone.

Comparing the SCR results under both conditions, we found that the beneficial effects of in-vehicle navigation could be proven through two observations. Firstly, the sensitive area of drivers' psychological arousal could be migrated from inside the tunnel to outside. Secondly, the amplitude of SCR, which reflects the ability of drivers to cope with the stimulus caused by the environmental transition, could be improved. In other words, in-vehicle navigation could help drivers avoid driving errors related to sharp psychological arousal.

3.3. Characteristics of Driving Behaviours

(1) Speed Difference in Zones. Speed difference in zones describes the speed coordination of zones. Speed differences in zones were collected from the naturalistic experiments for both conditions. Figure 8 shows distribution of speed difference in individual zone under control condition and in-vehicle navigation condition.

To further analyse the variation of speed difference in zones, we used ANOVA to determine significant difference

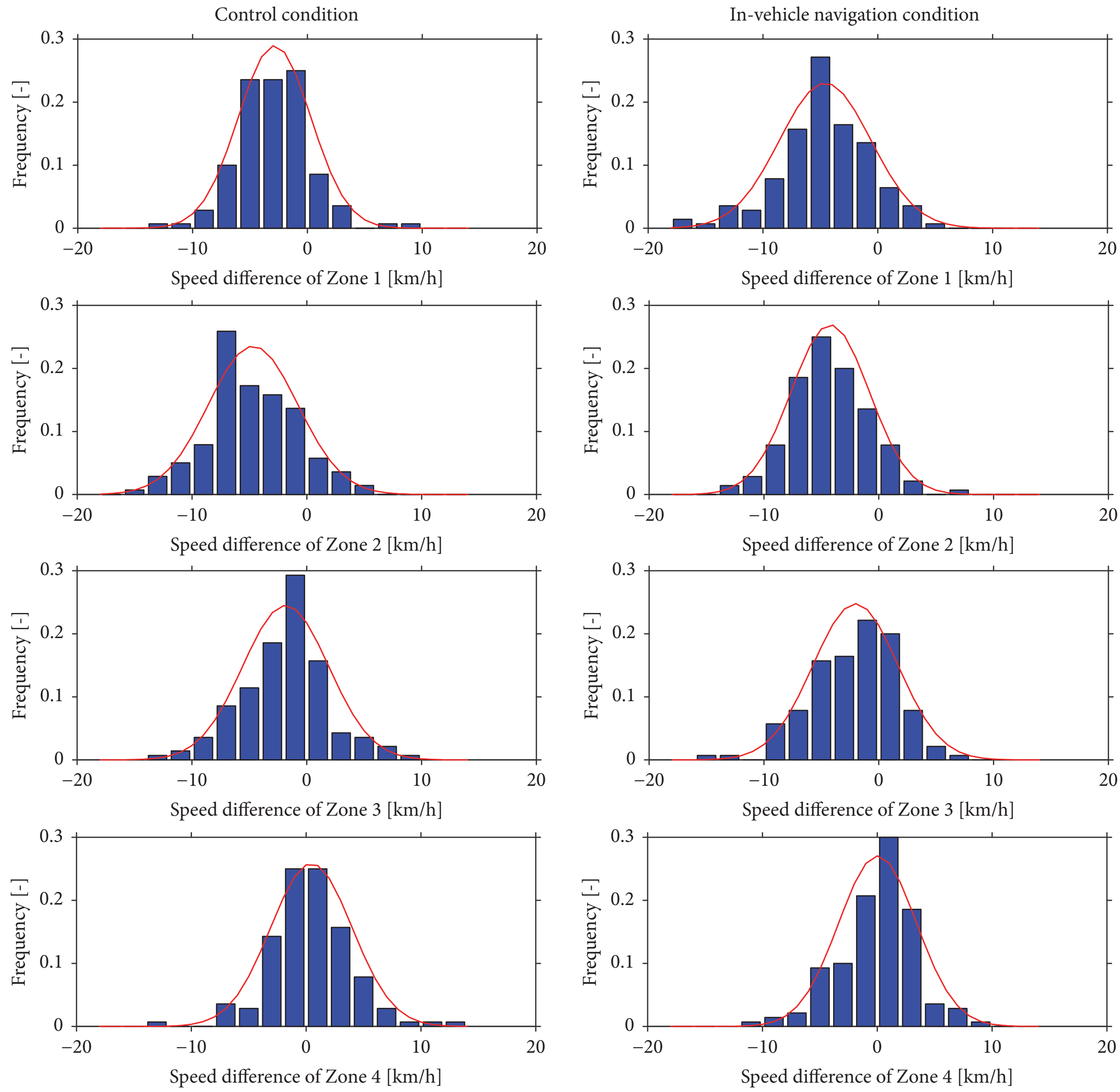

Figure 8: Distribution of speed difference under two conditions.

Table 6: Statistical results of the speed difference in zones.

	Control		In-vehicle navigation		p
	mean [km/h]	sd [km/h]	mean [km/h]	sd [km/h]	
Zone 1	-2.86	3.17	-4.58	3.98	0.004
Zone 2	-4.81	4.13	-4.32	3.41	0.02
Zone 3	-1.84	3.74	-2.03	3.70	0.36
Zone 4	0.45	3.54	0.03	3.39	0.22

between the control and in-vehicle navigation conditions, and the results are shown in Table 6.

The result shows that in-vehicle navigation generally reduced the speed difference, and the influences of in-vehicle navigation on the speed difference differed among the four zones. On the one hand, in-vehicle navigation significantly influenced the speed difference in Zone 1 (p=0.004) and Zone 2 (p=0.02). Particularly in Zone 2, the speed difference was reduced from -4.81 km/h (control condition) to -4.32 km/h (in-vehicle navigation condition). This reduction of speed difference in Zone 2, which is closest to the tunnel portal, is beneficial for driving safety. One the other hand, no significant influences were found in Zone 3 (p=0.36) and Zone 4 (p=0.22). This result may be due to two reasons. One

Table 7: Statistical results of the maximum deceleration.

	Control		In-vehicle navigation		p
	mean [m/s^2]	sd [m/s^2]	mean [m/s^2]	sd [m/s^2]	
Zone 1	-0.61	0.22	-0.73	0.34	0.007
Zone 2	-0.76	0.32	-0.68	0.26	0.09
Zone 3	-0.74	0.38	-0.63	0.33	0.14
Zone 4	-0.54	0.16	-0.53	0.17	0.11

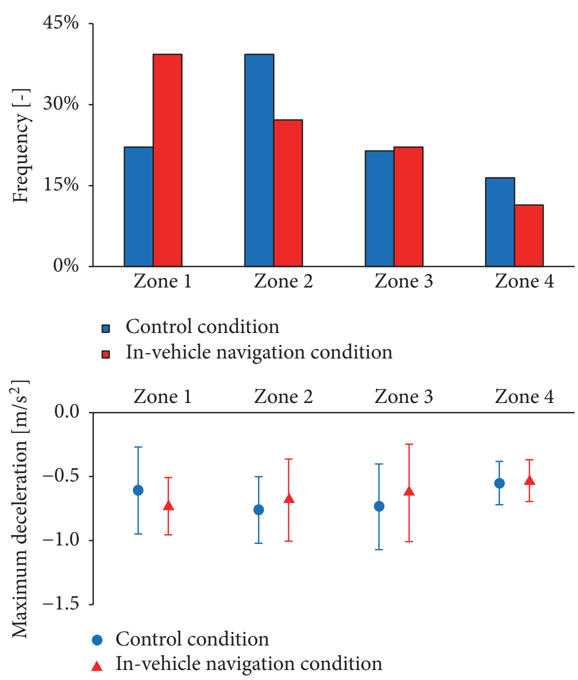

Figure 9: Maximum deceleration of drivers under two conditions.

is that the speed was already decreased to a safety level before entering the tunnel. The other is that the speed behaviour is mainly influenced by the environmental characteristics after entering the tunnel.

(2) Maximum Deceleration. The maximum deceleration is the most important factor representing the driving behaviour of deceleration, which can describe the driving comfort while approaching the tunnel entrance. The distributions of the maximum deceleration under different conditions were analysed, and the value difference of the maximum deceleration between control condition and in-vehicle navigation condition was tested with 90% confidence level (Figure 9).

Figure 9 shows that the proportions of maximum deceleration varied in each zone under different conditions, particularly Zone 1 and Zone 2. Under the control condition, 22% of the maximum deceleration occurred in Zone 1 and 39% occurred in Zone 2. The proportions changed to 39% in Zone 1 and 27% in Zone 2 under the in-vehicle navigation condition. In other words, an obvious distribution migration of the maximum deceleration occurred from Zone 2 to Zone 1 with the implementation of in-vehicle navigation.

To determine whether the maximum deceleration has significant difference between the control condition and in-vehicle navigation condition, ANOVA was performed, and the results are shown in Table 7.

According to Table 7, in-vehicle navigation increased the mean value of the maximum deceleration. This implies that in-vehicle navigation could improve driving comfort. The highest mean value of maximum deceleration was higher under the in-vehicle navigation condition (Zone 2, -0.73 m/s^2) than under the control condition (Zone 2, -0.76 m/s^2).

A significant influence of in-vehicle navigation was found in Zone 1 (P=0.007). In Zone 1, the maximum deceleration of in-vehicle navigation condition was statistically lower than that of the control condition, implying that the deceleration behaviour is more pronounced under the in-vehicle navigation condition than under the control condition. The deceleration behaviour was obviously increased in Zone 1 under the in-vehicle navigation condition. However, the effects of in-vehicle navigation on the maximum deceleration were not significant in Zone 2, Zone 3, and Zone 4, implying that the influence of in-vehicle navigation may be zone limited.

3.4. Evaluation of the Effectiveness of In-Vehicle Navigation. To evaluate the effectiveness of in-vehicle navigation at the tunnel entrance, we first defined two zones, namely, the key zone and the effective zone, to facilitate the following discussion. The key zone is defined as the zone in which perceptual responses and driving behaviours need to be improved the most under the control condition. The effective zone is defined as the zone in which in-vehicle navigation could induce significant changes. Then, we discuss the effectiveness of in-vehicle navigation according to the agreement of the key zone and the effective zone. We consider in-vehicle navigation to be actually helpful for improving drivers' perceptual responses and driving behaviours only if the effective zone covered the key zone. In such cases, the effectiveness of in-vehicle navigation in driving safety improvement could be considered as valid.

Table 8 shows the evaluation results of the effectiveness of in-vehicle navigation. Four indicators reflected valid effects of in-vehicle navigation, and the remaining two showed invalid effects. Specifically, in terms of the number of fixations, the effect zones (Zone 1 and Zone 2) covered the key zone (Zone 2); in terms of the R-R interval, the effective zones (all the four zones) covered the key zone (Zone 3); in terms of the SCR, the effective zones (Zone 2 and Zone 3) covered the key zone (Zone 3); in terms of the speed difference of zone, the effective zones (Zone 1 and Zone 2) covered the key zone (Zone 2).

Table 8: Evaluation results of the effectiveness of in-vehicle navigation.

Types	Indicators	Implication	Key Zone	Effective Zone	Effectiveness of in-vehicle navigation
Visual responses	The number of fixations	Driving information interaction	Zone 2	Zone 1, Zone 2	Valid
	The average duration of fixations	The difficulty of driving information cognition	Zone 4	Zone 1, Zone 2	Invalid
Psychological responses	R-R interval	Mental workload	Zone 3	All Zones	Valid
	SCR	Psychological arousal	Zone 3	Zone 2, Zone 3	Valid
Driving behaviours	Speed difference of zone	Speed coordination	Zone 2	Zone 1, Zone 2	Valid
	Maximum deceleration	Driving comfort	Zone 2	Zone 1	Invalid

This implies that the effects of in-vehicle navigation actually contribute towards improving driving safety at tunnel entrances. These helpful effects were manifested in improving the driving information interaction, mental workload, psychological arousal, and speed coordination. However, the in-vehicle navigation could not improve the difficulty of driving information cognition and driving comfort, as the effective zones of the two corresponding indicators (average duration of fixations and maximum deceleration) did not cover their key zones.

Zone 2 was identified as the key zone of driving behaviours. This means that drivers were more likely to reduce the speed nearer to the tunnel portal. Moreover, Zone 3 was identified as the key zone of psychological responses. This result may explain recent findings [10, 13, 45, 46] that the driving workload increased sharply when approaching the tunnel portal, and it achieved the largest level in the range of 50 m inside the tunnel portal.

Furthermore, the effective zones of R-R interval contained all the four zones. This means that in-vehicle navigation could alleviate mental workload throughout the driving process. As mentioned in previous studies, the reduction of mental workload was crucially beneficial for the improvement of driving safety [8, 13–16]. The reduction of mental workload is a major contribution of in-vehicle navigation towards improving driving safety at tunnel entrances.

In addition, the effective zones of visual responses and driving behaviours were limited in Zone 1 and Zone 2 (Table 8). This indicates that in-vehicle navigation is more likely to change the drivers' visual performance and driving behaviours outside the tunnel portals than inside. This could be attributed to two reasons. Firstly, the visual response inside the tunnel portals was basically restricted by weak light conditions. Secondly, the driving behaviour inside of the tunnel is stabilised by the dark environment. In view of the coincidence of the effective zone and key zone of visual responses and driving behaviours, there may be a hidden relationship between visual responses and driving behaviours.

3.5. Correlation Analysis of Visual Response and Driving Behaviour. Table 8 shows that the key zone and the effective zone of the number of fixations are the same as those of the speed difference of zone. Therefore, we could naturally suppose the existence of a hidden relationship between the number of fixations and the speed difference of zone. The hidden relationship between the number of fixations and the speed difference of zone was analysed based on the data of these two indicators in the effective zones (Zone 1 and Zone 2) using the correlation coefficient method (Figure 10).

The result shows a negative correlation between the number of fixations and the speed difference in zones. In-vehicle navigation strengthened this negative correlation, specifically in two aspects:

Firstly, in-vehicle navigation increased the grade of the correlation between these two indicators. The largest correlation coefficient of the in-vehicle navigation condition (Zone 1, r=-0.875) was higher than that of the control condition (Zone 2, r=-0.826).

Secondly, in-vehicle navigation expanded the scope of the correlation between these two indicators. Under the in-vehicle navigation condition, the negative correlation was significant in both Zone 1 (r=-0.875) and Zone 2 (r=-0.510). Under the control condition, the significant negative correlation was found only in Zone 2 (r=-0.826), and not in Zone 1 (r=-0.386). This indicates that the negative correlation is strengthened and maintained by in-vehicle navigation.

Overall, we can infer that the fundamental reason for the change in driving behaviour due to in-vehicle navigation is that in-vehicle navigation changed the visual response. The better the visual response, the safer the driving behaviour.

4. Conclusions

This study addressed the effects of in-vehicle navigation on drivers' perceptual responses and driving behaviours and determined the validity of these effects on driving

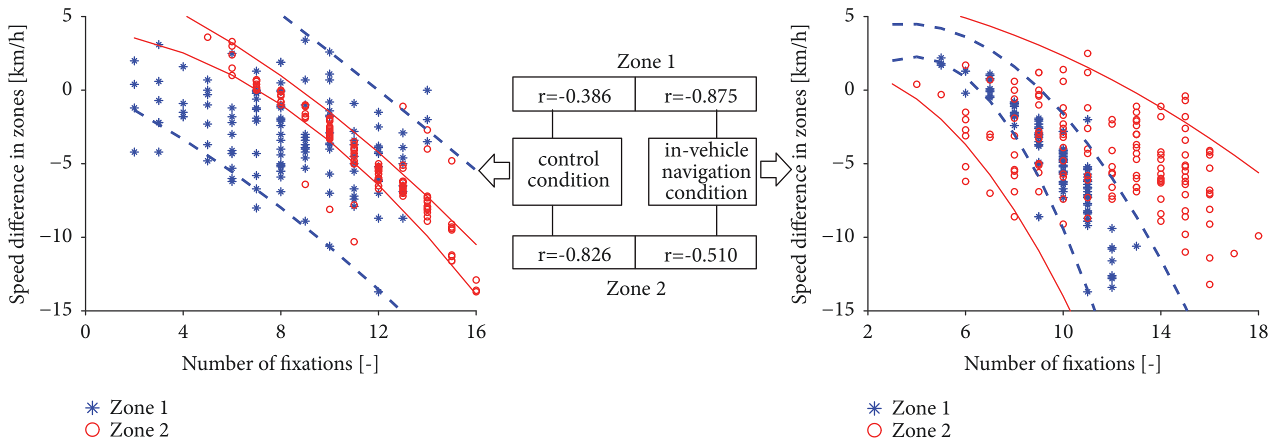

Figure 10: Correlation of visual response and driving behaviour under two conditions.

safety improvement. The perceptual responses and driving behaviours of drivers were analysed through naturalistic driving experiments. The following conclusions could be drawn.

(1) In-vehicle navigation could significantly affect drivers' perceptual responses and driving behaviours at tunnel entrances. According to analyses of the effective zone considering six indicators, the effects of in-vehicle navigation on drivers' perceptual responses and driving behaviours are more likely concentrated in zones outside the tunnel portal. Only psychological responses (R-R intervals and SCR) were partly affected by in-vehicle navigation inside the tunnel portal. This may be because in-vehicle navigation could not deeply change the drivers' perceptual responses and driving behaviours inside the tunnel portal, where they may be mainly controlled by the general driving environment.

(2) In general, in-vehicle navigation should be considered as an effective driving safety measure, because the corresponding beneficial changes were mostly valid. The effective zones of four indicators, namely, the number of fixations, R-R intervals, SCR, and speed difference of zone, covered their key zones. This means that the in-vehicle navigation can improve driver performances (driving information interaction, mental workload, psychological arousal, and speed coordination) in the requisite zones. This result validates the beneficial effects of in-vehicle navigation towards improving driving safety.

(3) The effectiveness of in-vehicle navigation in driving safety improvement was not always comprehensive. The effective zones of the average duration of fixations and that of maximum deceleration did not cover their relevant key zones. This means that in-vehicle navigation could not improve the difficulty of driving information cognition and driving comfort.

(4) A negative correlation was discovered between the number of fixations and speed difference in zones, and this correlation became more significant in Zone 1 with in-vehicle navigation. This result implies that safety measures on optimizing visual responses of drivers may be helpful for improving driving behaviours at tunnel entrances.

Although the findings in this study are promising, deeper studies are planned. Further research studies considering various road safety measures combined with in-vehicle navigation and various traffic characteristics should be performed to strengthen these findings. Specifically, the studies should be extended to different categories of road safety measures and the characteristics of traffic volume should be taken into account. Nevertheless, the findings improve our knowledge by extending the quantifiable approaches to the analyses of the effectiveness of the effects of in-vehicle navigation. In particular, the drivers' perceptual responses, which have rarely been investigated before, are used to verify the effects of in-vehicle navigation. Moreover, the correlation between drivers' perceptual responses and driving behaviours is explored.

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 they have no conflicts of interest.

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