博士論文

Effect of In-Vehicle Traffic Signals on Driving Behaviors

（車内交通信号が運転行動に与える効果）

楊 波

Contents

Abstract

Intersections are one of the most common components in modern transport systems, which can normally be classified as signalized and unsignalized intersections. How to improve traffic efficiency and driving safety at intersections is an essential issue to be solved. Traffic signals are considered to be one of the most important factors for maintaining traffic efficiency and safety at intersections. Emerging vehicular communication makes it easier to provide traffic signal information to drivers, and in-vehicle displays can be applied to provide these information inside vehicles. However, the effects of this method on driving behaviors are still unclear, and there is a concern that the application of in-vehicle traffic signals may result in driver distraction. This study, therefore, tried to investigate the influences of the proposed in-vehicle traffic signal system on driving behaviors, considering driver models and the penetration rate of the system at signalized and unsignalized intersections.

For the application of in-vehicle traffic signals in full deployment scenarios, the analysis of driving behaviors was mainly performed with driver models considering the influences of look ahead information. At signalized intersections, two modes of in-vehicle traffic signals were proposed to assist drivers: a “current” mode providing real-time information of the upcoming ground traffic lights, and a “predicted” mode offering look ahead information regarding ground traffic lights, taking into account the time to arrival at the upcoming intersection. Two kinds of in-vehicle displays were also compared for displaying these in-vehicle traffic signals: a normal 4.3-inch display and a head-up display. Driving simulator experiments were executed for eleven participants, and driving behaviors were evaluated for driving operations and eye-gaze behaviors. The results demonstrated that disruptive braking and accelerating operations were significantly reduced when look ahead information of traffic signals were provided and glance time was significant shorter for the head-up display than for the normal 4.3-inch display. It can be concluded that the predicted mode easily prompted drivers to better driving performances, and that the head-up display was reliable for providing in-vehicle traffic information.

For the application of in-vehicle traffic signals in full deployment scenarios at unsignalized intersections, two types of in-vehicle traffic signals were proposed to assist drivers, which were corresponded to two-way and all-way stop-controlled intersections. The gap acceptance theory and a first-come-first-served strategy were adopted to determine the passing priority for the two types of intersections, respectively. Driving

simulator experiments involving twenty-three participants were conducted, to investigate the driving behaviors elicited by the proposed system. Four experimental conditions were prepared with a combination of in-vehicle traffic signals and auditory warnings. The results indicated that in-vehicle traffic signals were associated with significant longer post-encroachment time and a significant shorter maximum brake stroke. In terms of eye-gaze behaviors, the percentage of gaze concentration to the road center area and the mean glance durations were deemed acceptable for the avoidance of visual distraction, when in-vehicle traffic signals were presented via a head-up display. Therefore, the analysis of driving behaviors indicated that the in-vehicle traffic signals could effectively provide driver assistance at unsignalized intersections. Moreover, it was considered that the availability of in-vehicle traffic signals at unsignalized intersections might be influenced without considering the waiting time of drivers. Hence, the analysis of waiting time on driver behaviors were performed for intersections which consist of one major and two minor roads. A gap acceptance theory considering waiting time was adopted in the implementation of in-vehicle traffic signals, to assist minor-road drivers in passing through unsignalized intersections by selecting appropriate major-road gaps. Driving simulator experiments involving twelve participants were performed on the minor and major roads, by applying the in-vehicle traffic signals with and without the consideration of waiting time, respectively. The results demonstrated that the maximum gas pedal strokes of minor-road vehicles were significantly reduced, indicating a smaller possibility of aggressive driving while the in-vehicle traffic signal considering waiting time was applied. Meanwhile, an improved steering stability could also be observed at intersections, as the maximum lateral accelerations of minor-road vehicles significantly decreased when the waiting time was considered.

Penetration rate is one of the essential issues that need to be considered for the application of in-vehicle traffic signals. For the application of in-vehicle traffic signals in partial deployment scenarios, the analysis of driving behaviors was mainly performed with driver models considering the influences of look ahead information, the car following behaviors at signalized intersections, and drivers' trust on the system at unsignalized intersections. To analyze the influences of penetration rate on the effects of in-vehicle traffic signals at signalized intersections, this study presented actual vehicle experiments involving twelve participants and two electric vehicles, considering three different deployment conditions of in-vehicle traffic signals: both the two vehicles unequipped, only the preceding vehicle equipped, and only the following vehicle equipped. Meanwhile, two scenarios were prepared since a vehicle would either stop at or pass through an intersection: a stop scenario in which vehicles would encounter a red traffic signal at the intersection, and a pass scenario that a green traffic signal would be presented to drivers when they arrived at the intersection. As the predicted mode which provided look ahead information of traffic signals had been proved to be effective in the previous driving simulator experiments, the applied in-vehicle traffic signals in the actual vehicle experiment adopted the predicted mode only. It was found that, for a vehicle equipped with in-vehicle traffic signals, the maximum braking deceleration would significantly decrease, compared to the condition when no in-vehicle traffic signal was provided. As for a vehicle without in-vehicle traffic signals, the maximum braking deceleration might also be significantly reduced if its preceding vehicle was in-vehicle traffic signals equipped. The results indicated that the application of in-vehicle traffic signals might significantly improve the driving performances even in a partial deployment environment. Meanwhile, simulations were performed for signalized intersections to evaluate the influences of penetration rate on the traffic flow. It was verified that the higher the penetration rate was, the more the travel time might be reduced. Finally, for analyzing the influences of penetration rate on driving behaviors at unsignalized intersections, a driver model considering drivers' trust was applied. Driving simulator experiments were performed to investigate drivers' initial trust on the system and the changes of trust while experiencing successful and failed usages of the system. Simulations and driving simulator experiments were then conducted to analyze the times of near miss accidents while applying the in-vehicle traffic signals in different penetration rates. It was found that the near miss accidents at intersections could be reduced even with a low penetration rate of the system, compared to the condition when no in-vehicle traffic signal system was applied.

It can be concluded from the results that the application of in-vehicle traffic signals will significantly improve driving safety and easily prompt driving performances at intersections, without inducing undesired driver distractions. Meanwhile, the applicability of this method in both full and partial deployment scenarios has also been demonstrated by experiments and simulations.

Nomenclatures

$d_K(t)$	Distance to the upcoming intersection of the vehicle K
$d_J(t)$	Distance to the upcoming intersection of the vehicle J
$G_K(t)$	Major road gap related with the vehicle K
$G_J(t)$	Major road gap related with the vehicle J
$G_N(t)$	Major road gap for the vehicle N
G_C	Critical gap
H	Heaviside step function
$L_K(t)$	In-vehicle traffic signal for the major-road vehicle K
$L_i(t)$	Instantaneous distance to the upcoming intersection at the time step t
$L_N(t)$	In-vehicle traffic signal for the minor-road vehicle N
P_I	Positions of intersections
P_V	Current position of the vehicle
P_S	Current phase of ground traffic lights
$P_U(t)$	Priority status of the major road vehicle
$P_V(t)$	Priority status of the minor road vehicle
$P_N(t)$	Functions for judging the major-road gap for the vehicle N
$P_K(t)$	Function for judging the entry of minor-road vehicle for the vehicle K

$R_N(t)$	Functions for judging the rank of the vehicle *N*
R_O	Operation range of the in-vehicle traffic signals
$R(t)$	Reminder function
R_{system}	Reliability of the system
T_{driver}	Drivers' trust on the system
T_G	Length of the green phase
$TTI_i(t)$	Time to intersection
T_L	Left time of the current phase
T_L^Y	Left time of the current yellow phase
t_{LA}	Look ahead time
T_p	Post-encroachment time
T_R	Length of the red phase
T_Y	Length of the yellow phase
$V(t+t_{LA})$	Expected speed at t_{LA} seconds later
$V_i(t)$	Current speed of the vehicle *i* at the time step *t*
$\dot{V}_{LA}(t)$	Acceleration with look ahead information at the time *t*
$v_K(t)$	Current velocity of the vehicle *K* at the time step *t*
$v_J(t)$	Current velocity of the vehicle *J* at the time step *t*

Abbreviations

ADAS	Advanced driver assistance system
ANOVA	Analysis of variance
DGPS	Differential global positioning system
DSRC	Dedicated short range communications
Eq	Equation
GPS	Global positioning system
Hz	Hertz
HMI	Human machine interface
HUD	Head up display
ITARDA	Data analysis center for traffic accident
IVTS	In-vehicle traffic signal
Km	Kilometer
Km/h	Kilometer per hour
LA	Look ahead
LIDAR	Light detection and ranging
m	Meter
MHz	Mega Hertz
min	Minimum
mod	Modulus after division
OBD	On-board diagnostics
PET	Post-encroachment time
PRT	Perception reaction time
RTK	Real time kinematic
s	Second
SD	Standard deviation
THW	Time headway
TTC	Time to collision
TTI	Time to intersection
V2X	Vehicle to X communication
V2I	Vehicle to infrastructure communication
V2V	Vehicle to vehicle communication

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Chapter 1

Introduction

Introduction

1.1. Background

Transport systems are expected to be safer, cleaner and more efficient by modern society. However, traffic congestions and numerous accidents still exist nowadays, which indicate that the traditional traffic systems may be unable to meet the rapid growth of transport demand. To solve this problem, researchers have spent great efforts in searching for emerging technologies that have the potentials to change the current traffic situations.

In the modern transport systems, intersections are one of the most common and fundamental components. According to a widely accepted definition, intersections are the places where multiple roads intersect, and will be used by vehicles approaching from different directions. Compared to other parts of traffic systems, intersections are comparatively limited spaces with much more difficult driving conditions. The needs of cooperating with other intersection users result in a possible increase in the traffic delay and collision risks. It was reported that in the United States, intersections were the places where traffic crashes happened the most frequently, and most of them were very fatal [1]. The report believed that approximately one fifth of all the reported crashes and one sixth of all the fatal crashes occurred at intersections every year [1]. As for the detailed numbers, around 1.2 million crashes, among which more than 5,000 were fatal crashes, were reported for the year of 2015 [2]. As to the intersection accidents in Japan, according to the data from Data Analysis Center for Traffic Accident (ITARDA), more than 30% of all the traffic death accidents occurred at intersections [3]. Therefore, intersections are one of the key points to solve traffic problems, and have attracted the interests of many researchers for more than decades.

For the typical classification of intersections, it is normally conducted based on the existence of ground traffic lights. Intersections which rely on ground traffic lights to regulate traffic flows are named signalized intersections. Oppositely, intersections without ground traffic lights are defined as unsignalized intersections. Intersections with a high traffic volume are usually signalized, however, it is still reported that most of the intersections all over the world are unsignalized, as the equipment of ground traffic lights requires a high infrastructure investment [4]. Moreover, for the unsignalized intersections, it can normally be classified as two-way stop-controlled intersections and all-way stop-controlled intersections. At the two-way stop-controlled intersections, vehicles from the two side branches will face a stop line, therefore, need to make a temporary stop before entering the intersections. For the all-way stop-controlled intersections, vehicles from all the sides will confront a stop line.

According to the data published by the ITARDA, the ratios of traffic deaths and injuries in 2010 by road shapes are shown in Fig. 1.1. It can be observed that more than half of the fatal traffic accidents happened at or around intersections, among which around 26% accidents occurred at unsignalized intersections. Meanwhile, it was also found that there might be a positive correlation between traffic congestions and traffic accidents [5]. Therefore, it is an essential task to provide effective assistances for drivers at intersections to improve driving performances.

1.2. Advanced driver assistance systems at intersections

Advanced driver assistance systems (ADAS) are considered as one of the most effective methods in assisting drivers at intersections [6]. The general aims of ADAS are to improve traffic safety, achieve better driving performances and reduce undesired traffic congestions. Many kinds of ADAS have been proposed to assist drivers to control vehicles better, including the systems which help vehicles maintain proper speeds and the systems which inform drivers about necessary traffic information. As the driver assistance systems are developed for supporting driving tasks, they might be classified according to the information process of drivers. The information process of a driver can be normally classified into perception, decision, and action phases, during which the human errors in perception phase are considered to be one of the most common errors in traffic accidents.

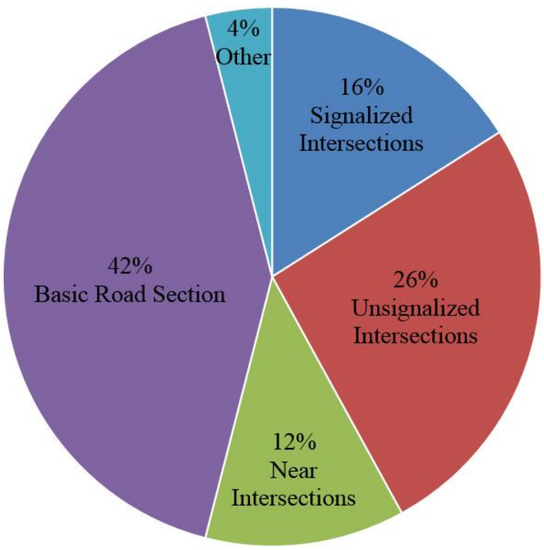

Fig. 1.1. Ratios of traffic deaths and injuries in 2010 by road shapes [3].

The perceptual errors can be caused by situations including a poor visibility of drivers as the hazard may be blocked. If the necessary perceptual information are delayed during driving, it will be difficult for drivers to properly process them in time. Some systems including collision warning systems, could offer cautions or alerts for avoiding the effects of these errors and helping drivers understand current driving situations.

With the popularity of in-vehicle displays, in-vehicle information systems are developed as one kind of ADAS to assist drivers by displaying traffic information inside vehicles. They are capable of providing various types of information to drivers, including navigation information, current traffic conditions and even hazard alerts. Numerous studies have demonstrated that in-vehicle information systems are helpful in improving traffic safety and efficiency [7-12]. According to the classification provided in a report, the in-vehicle information systems may be divided into informing and warning systems [13]. For the informing systems, they will only inform drivers some necessary driving information, including the positions and speeds of vehicles. On the other hand, the warning systems will not only collect traffic information around the vehicles but also support drivers in some dangerous situations. In some risky situations, the warning systems will judge the traffic situations and provide warnings to drivers in advance if needed, and the drivers will then make appropriate decisions based on the provided warnings and finally take actions.

For the ADAS applied at signalized intersections, most of them were focused on providing information including the desired speed of vehicles and the dilemma zone information for drivers. In the United Kingdom, researchers were focused on the development of intelligent speed adaptation system to provide advices of desired speed to drivers [14]. Besides, a warning system was proposed based on infrastructure-based and OBDII-based vehicle sensors to avoid the red-light violation at signalized intersections [15]. As for the ADAS related with the avoidance of dilemma zone, it was pointed out that most of drivers were caught in a dilemma zone due to high approaching speeds and aggressive driving behaviors [16], [17]. To solve this problem, a dynamic dilemma-zone protection system was proposed based on microwave sensors to track the vehicles approaching signalized intersections [18]. Moreover, to improve the acceptance of ADAS at signalized intersections, a personalized optimization system was even proposed in which the driving characteristics were taken into consideration [19].

For the application of ADAS at unsignalized intersections, the improvement of driving safety is an urgent issue that requires attentions [20]. In previous studies, driver assistance systems for unsignalized intersections normally relied on the application of sensors and cameras to obtain information [21], [22]. A cooperative collision warning system was proposed to provide warning information to drivers, using ubiquitous sensor network [23]. For the usage of cameras, an automatic conflict detection method using image sequences was proposed, which could detect traffic collisions more accurately and effectively [24]. Moreover, a radio frequency identification based driver assistance system was developed, which might help drivers start to decelerate at an earlier distance to the intersection, and thus would possibly enhance the driving safety at unsignalized intersections [25].

The ADAS for unsignalized intersections can also be classified based on the characteristics of the intersections. Previous studies pointed out that one of the major problems at two-way stop-controlled intersections was that, many minor-road drivers had difficulties in judging adequate major-road gaps [26], [27]. Most of the crashes at two-way stop-controlled intersections were caused by driver errors, especially the failures of minor-road drivers in selecting a proper gap on the major road [28]. The American Association of State Highway and Transportation Officials therefore identified that the usage of new technologies for assisting drivers in judging gaps at two-way stop-controlled intersections was a key initiative to address the intersection crashes [29]. Several methods have been proposed to assist minor-road drivers to cross unisignalized intersections [30], [31]. Researchers from Minnesota Department of Transportation developed an infrastructure-based system to help minor-road drivers make better decisions at unsignalized intersections, by collecting the information of major-road vehicles with the application of multiple surveillance sensors along the major roads [32], [33]. Most of these proposed systems highly relies on the installation of sensors at intersections, which might require comparatively high costs of infrastructure investments. Cameras are another choice to detect necessary traffic information at intersections [34]. Since the cameras have a higher resolution than sensors, it is possible for the ADAS to distinguish whether the detected object is a vehicle or a pedestrian. Meanwhile, with the application of cameras, it is also possible to calculate the approximate distance to the object and the size of the object for making decisions in the ADAS. However, there are also some obvious limitations while using the cameras. When it is dark or the weather is bad, including a rainy day, thick fog, and snow, or in the conditions with strong external light, including the sunlight and the light of oncoming vehicles, the performances of cameras may heavily deteriorate.

1.3. Virtual traffic signal concept

Recently, the development of vehicular communications has attracted significant attentions all over the world. Compared to sensors and cameras, vehicular communications have several advantages, including the reduction in deployment costs, the minimization of time delays and the expansion of operating distances. In the United States, 5.9 GHz DSRC has already been used as a mean of communication, not only between the roadside infrastructure and vehicles but also among vehicles. For the communication between infrastructure and vehicles, it is named as vehicle-to-infrastructure communication (V2I). For the communication among vehicles, it is named as vehicle-to-vehicle communication (V2V).

With the application of in-vehicle information systems and vehicular communications, it becomes possible to virtually convey traffic signal information, which is traditionally displayed by ground traffic lights, to drivers inside vehicles. In Japan, a traffic signal prediction system can transfer the signal cycle information of upcoming intersections within 30 kilometers to vehicles at one time [35]. The signal cycle information are collected by the monitoring center from the ground traffic lights and then be transferred to vehicles through infrared beacons. Meanwhile, a project named ITS Connect was proposed based on V2I and V2V. The system would notice drivers the waiting time at signalized intersections, based on obtained signal cycle information in real time [36]. In the United States, Audi is working together with the government to provide countdown information of red signals to drivers at signalized intersections [37].

Traffic signal information is an essential information in maintaining traffic flow, by helping drivers make decisions about passing through or stopping at intersections. Statistical data from the National Highway Traffic Safety Administration indicated that the absence of traffic signal information significantly increased the risk of intersection collisions [38]. However, it was pointed out that the impairment in visual capability that might occur at any age, especially in the older population, would make it difficult to observe traffic signal information far away from intersections and, therefore, threaten driving safety [39]. It was also reported that the disturbance of visual acuity was likely to result in difficulties in reading traffic signals at distances which were deemed safe for making decisions [40]. Furthermore, drivers' fields of vision may be compromised by bad weather or blocked by obstacles, including the preceding vehicles. In these cases, an effective method to provide traffic signal information to drivers should be considered.

Based on the emerging V2V and V2I communication technologies, a concept of virtual traffic signals was proposed in which traffic signals were displayed inside a vehicle on the windshield, instead of via ground traffic lights [41], [42]. Previous studies suggest that virtual traffic signals may have great potential in improving traffic efficiency. According to a traffic simulation study, the application of virtual traffic signals may increase traffic flow rates in urban areas by more than 60% [43]. The virtual traffic signals were also associated with an 18% reduction in carbon dioxide emissions in another simulation study [44]. For the application of virtual traffic signals at signalized intersections, it was found that when the real-time state of ground traffic lights was projected on the windshield to drivers, the driving performances using virtual traffic signals did not significantly differ from the performances using conventional ground traffic lights [45]. However, the influences of virtual traffic signals on driver behaviors while offering different kinds of information, including the predicted traffic signal information at signalized intersections, still requires investigation. As for the application of virtual traffic signals at unsignalized intersections, few research was focused on the practicality of this approach at intersections without ground traffic lights. Moreover, the virtual traffic signal system is highly relied on vehicular communications to obtain information at intersections, while it is considered that the deployment of vehicular communications for all the vehicles may last for decades. Therefore, the influences of different penetration rates on the usage of virtual traffic signals should also be investigated. For the previous research on the influence of penetration rate on the application of virtual traffic signals, a simulation study with all-way stop-controlled intersections found a 14.3% increase in the capacity of intersections when only 40% of vehicles were equipped with virtual traffic signals [46]. The effects of different penetration rates on the reliability of the virtual traffic signal system was not considered.

In this study, the virtual traffic signals were referred to as in-vehicle traffic signals, to be distinguished from those used in the previous traffic simulations. For the application of in-vehicle traffic signals at signalized intersections, it was assumed that V2I communication was applied to transfer information between vehicles and ground traffic lights. For the application of in-vehicle traffic signals at unsignalized intersections, it was assumed to be relied on V2V communication to transfer information among vehicles. Meanwhile, the in-vehicle traffic signal system was a kind of driver assistance system and drivers would finally control the vehicles. The system would only consider the existence of vehicles. Other road users including cyclists, motorbikes and pedestrians would not be considered.

1.4. Evaluations of advanced driver assistance systems

It was pointed out that the effectiveness of ADAS depends highly on the interaction between drivers and ADAS [47]. Understanding the information presented by ADAS as well as the performances while using the ADAS, affect the final effects of the system [13]. The interactions between drivers and ADAS normally can be evaluated by analyzing driving behaviors [48]. Evaluations of driver behaviors are of crucial importance in designing and testing intelligent transport systems [49]. In a previous study, driver behaviors were examined to determine whether long-term experience with an intelligent speed adaptation system could prompt a change in speed related cognitions or not [50]. Moreover, an automatic platooning of trucks and its influences on driver behaviors related with emergency-avoidance braking were investigated, and a bio-signal analysis was presented to assess mental stress in automatic driving [51], [52]. Meanwhile, for newly proposed visual-based driver assistance systems, including the in-vehicle traffic signals, driver distractions are of great importance in the evaluation of the systems [53-55]. An examination of 474 traffic accidents revealed that all the accidents were associated with errors that arose as a consequence of distraction [56]. Indeed, one of the essential functions of driver assistance systems is to minimize driver distraction. This is especially challenging in the design of driver assistance systems that display information via a visual modality, as this may increase visual distraction [57]. Driver distraction is an important safety concern [58]. The extent of visual distraction induced by visual-based driver assistance systems can be studied by analyzing eye-gaze behaviors [59]. Recent studies have demonstrated that nonintrusive eye-gaze tracking technologies can produce accurate measurements of eye-gaze behaviors, and such nonintrusive technology has already been used to analyze eye-gaze behaviors while participants interacted with navigation systems [61], [62].

The evaluations of ADAS, including the in-vehicle traffic signal system, might be performed based on their influences on transport systems, including driving safety and traffic flow. For the analysis of driving safety, it is one of the most important issues in the evaluations of ADAS, as the ADAS are mainly developed to compensate the human driver errors. Some indexes calculated based on the driving operations, including post-encroachment time (PET), are popular in the safety analysis [63], [64]. PET is defined as the elapsed time between the departure of a leading vehicle and the arrival of an oncoming vehicle at the same location. A low value of PET indicates a high possibility of conflict. Meanwhile, it was mentioned that the mental workload caused by using ADAS should also be viewed a safety issue [65]. It is, therefore, an important task to verify whether a system can be used safely without inducing too much workload or not. For the investigation of traffic flow, the most common measures that have been used are speed, travel time, and acceleration operations [13]. It was believed that increased traffic flow and speed indicated an improved traffic performance [13]. Meanwhile, speed variations, number of accelerations and braking could also be the indicators for analyzing whether the traffic flow was smooth or not [13]. Moreover, driving style was another essential factor that might affect traffic flow. It was pointed out that the numbers of decelerations and accelerations could be used for evaluating the influences of ADAS on the traffic flow [13]. With the assistance of ADAS, drivers may be better prepared for the upcoming traffic condition, and perform smoother accelerations that will decrease the energy consumption [66], [67]. In addition, for the application of ADAS, different penetration rates of ADAS is another important task to be investigated. It was reported that the penetration rate of ADAS might have congestion assistance functions, which could influence congestion positively [13]. A previous study also pointed out that increased penetration rate of ACC equipped vehicles might lead to increased road capacity [68].

1.5. Objective and structure

This dissertation primarily focuses on investigating the effects of in-vehicle traffic signals on driving behaviors when the system was applied to assist drivers in crossing signalized and unsignalized intersections. The analysis of the influences of the system was mainly performed based on driver models considering look ahead information and the penetration rate of the system. The main objectives of this dissertation are highlighted as follows:

(1) To investigate the effects of in-vehicle traffic signals on driving behaviors, based on driver models considering the influences of look ahead information, and confirm that the application of in-vehicle traffic signals can produce positive effects, including the improvement of driving performances and the reduction of driver workload, without having negative effects, including driver distraction and the impairment of driving safety;

(2) To analyze the driving behaviors while applying the in-vehicle traffic signals in partial deployment conditions based on driver models considering look ahead information, car following behaviors and drivers' trust on the system, and indicate that the in-vehicle traffic signals can still have certain positive influences on the traffic system, even at the stage when the penetration rate changes from 0% to 100%.

In Chapter 1, the background of this research, including the existing traffic problems at intersections and previous methods for assisting drivers at signalized and unsignalized intersections were introduced. Meanwhile, a brief introduction of the in-vehicle traffic signal system was provided.

Chapter 2 introduced the driver models while using the in-vehicle traffic signals at signalized and unsignalized intersections in different penetration rates of the system. For the driver model in a full deployment scenario, the analysis was performed based on the influences of look-ahead information on the driver behaviors. For the driver model in a partial deployment scenario, the investigation was performed based on the effects of look-ahead information while considering car following behaviors at signalized intersections and drivers' trust on the system at unsignalized intersections.

As presented in Chapter 3, the implementations of in-vehicle traffic signals at signalized and unsignalized intersections were presented. For the in-vehicle traffic signal system at signalized intersections, two modes of in-vehicles traffic signals, a "current" mode and a "predicted" mode, were proposed to assist drivers based on V2I communication. For the unsignalized intersections, an in-vehicle traffic signal system was proposed to assist drivers at two-way and all-way stop-controlled intersections, given the application of V2V communication.

Chapter 4 were focused on providing the details of experiments performed in full deployment scenario at signalized and unsignalized intersections. For the experiment of full deployment scenario at signalized intersections, driving simulator experiments were performed to analyze how two different modes, a "current" mode and a "predicted" mode, of in-vehicle traffic signals influenced driver behaviors. For the experiment of full deployment scenario at unsignalized intersections, two driving simulator experiments were performed with constant critical gap and critical gap considering waiting time, respectively, to analyze the influences of the system on driving safety.

Chapter 5 provided the details of experiments and simulations for investigating driving behaviors while considering the penetration rate of the system. Actual vehicle experiments were performed at signalized intersections to analyze the influences of an in-vehicle traffic signal equipped vehicle on the driving performances of its following unequipped vehicle. Moreover, simulations were performed with different penetration rates at signalized intersections to investigate the influences on travel time. Furthermore, two driving simulator experiments and traffic simulations were conducted at unsignalized intersections, to analyze drivers' initial trust and the changes of trust while using the system in partial deployment scenarios, and the effects of in-vehicle traffic signals on driving behaviors were also investigated for different penetration rates.

In Chapter 6, the influences of in-vehicle traffic signals on driver behaviors were discussed, from the views of driving safety, traffic flow and driver distraction. The matters that need attention while applying the system were also presented.

Chapter 7 concluded the details and significances of this research.

Chapter 2

Methodology

Methodology

The in-vehicle traffic signal system relies on vehicular communications to obtain traffic information at intersections. However, the deployment of vehicular communications may last for decades. Therefore, it is necessary to consider driver models in different penetration rates. For the driver model in a full deployment scenario, the analysis was mainly performed based on the influences of look-ahead information on driver behaviors. For the driver model in a partial deployment scenario, the investigation was performed based on the influences of look-ahead information, car following behaviors and drivers' trust on the system.

As shown in Fig. 2.1, ego and other drivers normally control vehicles based on the observations from the environment, including traffic signal information and the states of surrounding vehicles. If in-vehicle traffic signals are applied, the look ahead information of the environment can be provided for drivers. For the application of in-vehicle traffic signal system, drivers' trust on the system and the penetration rate of the system are two essential issues to be considered. In full deployment scenarios, the penetration rate can be regarded as one. As for drivers' trust on the system, it was also regarded as one in full deployment scenarios for the following reasons: the in-vehicle traffic signal system is a kind of driver assistance system and drivers will finally control the vehicles; in full deployment scenarios, the in-vehicle traffic signals can provide correct information for drivers and will not affect driving safety; the trust issue is, therefore, not the main target of the investigations for full deployment scenarios. In full deployment scenarios of in-

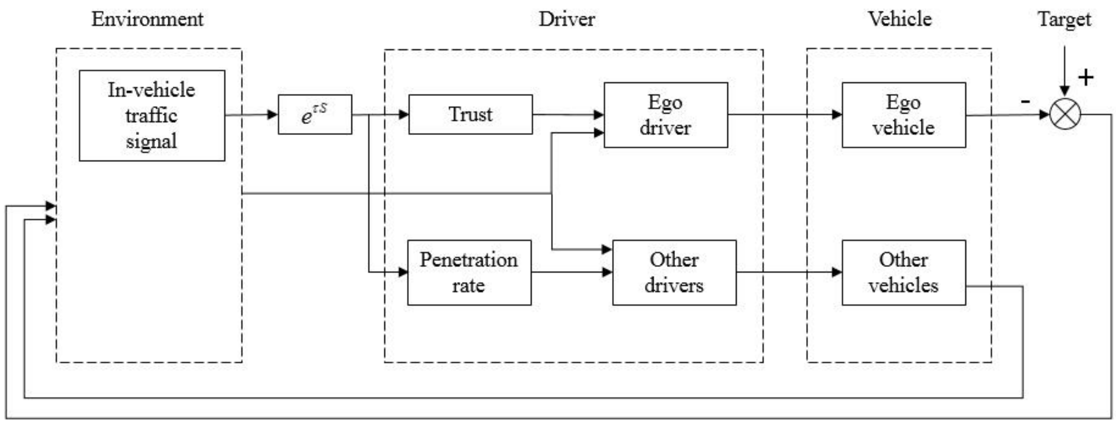

Fig. 2.1. Driver model which considers look ahead information provided by in-vehicle traffic signals, the penetration rate of the system and drivers' trust on the system.

vehicle traffic signals at signalized intersections, the driving behaviors of all the vehicles will be mainly influenced by the current traffic signal information provided by ground traffic lights, the look ahead information displayed by in-vehicle traffic signals and the behaviors of surrounding vehicles. For the full deployment conditions at unsignalized intersections, there is no ground traffic light to provide current traffic signal information. The look ahead information will be provided by the in-vehicle traffic signals. Therefore, the driving behaviors of all the vehicles will be affected by the look ahead information and the behaviors of surrounding vehicles.

For partial deployment scenarios, the penetration rate can be a value ranging from zero to one. At signalized intersections, the trust parameter can be regarded as one for the following reasons: the driving safety can be ensured as the traffic is controlled by ground traffic lights and the in-vehicle traffic signals, which are based on V2I communications, can provide correct information at signalized intersections even in partial deployment scenarios; the trust issue is, therefore, not the main target of the investigations for partial deployment scenarios at signalized intersections. When no in-vehicle traffic signal is displayed for the ego vehicle, the behaviors of ego driver will be directly affected by the current traffic signal information offered by ground traffic lights and the behaviors of surrounding vehicles. As the behaviors of surrounding vehicles will be affected by the in-vehicle traffic signals if the penetration rate is not zero, the look ahead information may still affect the driver behaviors of ego vehicle indirectly. When the ego vehicle is equipped with in-vehicle traffic signals at signalized intersections, the behaviors of ego vehicle and other vehicles equipped with in-vehicle traffic signals will be influenced by the current traffic signal information provided by ground traffic lights, the look ahead information displayed by in-vehicle traffic signals and the behaviors of surrounding vehicles. The behaviors of vehicles unequipped with in-vehicle traffic signals will be directly affected by the traffic signal information of ground traffic lights and the behaviors of surrounding vehicles, and, therefore, will be indirectly affected by the look ahead information. For partial deployment scenarios at unsignalized intersections, the effects of in-vehicle traffic signals and driving safety will be highly relied on drivers' trust on the system. The trust parameter should be a value between zero and one, and a drivers' trust model is needed. The trust issue will be mainly considered for ego driver, and the penetration issue will be mainly considered for other vehicles.

2.1. Driver model with full deployment of in-vehicle traffic signals

The driver model while facing traffic signal information can be considered as a rule based driver model. It is formed by drivers themselves based on previous experience and rules, and can represent the understandings of drivers on the driving conditions. The rule based driver model can be expressed as follows,

$$\text{Opeartion} = func\left(\text{rule, observation}\right) \tag{2.1}$$

According to drivers' previous experience, when it is a red signal at intersections, they need to stop the vehicle at the stop line. Therefore, drivers will choose to decelerate when they observe that the traffic signal has turned red. On the other hand, when it is a green signal, there is no need to stop the vehicle. Thus, drivers will try to cross the intersection as soon as possible without stop, if the current signal is in green phase.

At a signalized intersection, when there is no in-vehicle traffic signal, the observations of traffic signals can only be obtained from the ground traffic lights. With the usage of in-vehicle traffic signals, the traffic signal information can be obtained from both the ground traffic lights and the in-vehicle traffic signals. Importantly, the information provided by the in-vehicle traffic signal system is the predicted traffic signal which will be displayed for drivers when they arrive at the intersection. The predicted traffic signal is a kind of look-ahead information, which can help drivers have a correct expectation for the upcoming traffic conditions. In full deployment scenarios, all the vehicles are equipped with in-vehicle traffic signals, therefore, will be influenced by the look ahead information. For an ego vehicle, the driver will receive the current traffic signal information from ground traffic lights, and the look ahead information from in-vehicle traffic signals. The states of other vehicles will also influence the driver behaviors of the ego vehicle. For the state of other vehicle, it will be affected by the current traffic signal information from ground traffic lights, the look ahead information from in-vehicle traffic signals, and the driving operations of the ego vehicle. At unsignalized intersections, drivers need to observe the traffic conditions to judge whether it is safe or not to cross when there is no in-vehicle traffic signal. With the application of in-vehicle traffic signals at unsignalized intersections in full deployment scenarios, all the vehicles will receive the look ahead information of the traffic conditions. The driving behaviors will then be affected by the look ahead information and the behaviors of surrounding vehicles.

The influences of look ahead information on driver behaviors may be explained as follows,

$$\dot{V}_{LA}\left(t\right) = \frac{V\left(t + t_{LA}\right) - V\left(t\right)}{t_{LA}} \tag{2.2}$$

where subscript *LA* means look ahead; t_{LA} is the look ahead time; $\dot{V}_{LA}\left(t\right)$ is the acceleration with look ahead information at the time *t*; $V\left(t+t_{LA}\right)$ is the expected speed at t_{LA} seconds later; and $V\left(t\right)$ is the speed at the time *t*.

The eq. (2.2) indicates that drivers can predict the speed t_{LA} seconds later with the look ahead information provided by the in-vehicle traffic signals, which may influence the accelerate or brake operations of drivers. When there is no in-vehicle traffic signal, drivers can only predict the speed after the change of ground traffic light. For drivers with the assistance of the system, they can even predict the speed before the ground traffic light changes.

Meanwhile, the influences of in-vehicle traffic signals may also be analyzed from the view of information process. The Highway Safety Manual reported that a driver generally responds faster to expected events than to unexpected events [69]. It is considered that the driving performances related with reaction or decision may therefore be improved, when the predicted traffic information is provided by the in-vehicle traffic signals. Perception response time (PRT) is a reaction-related index, which is defined as the time gap between the onset of a traffic event and the onset of the driver's response to the event. The PRT contains time including the mental processing time and the action time of the driver. The mental processing time is the duration in which the driver assesses the traffic condition and decides proper actions to take. It can be further divided into the sensation time, the perception time, the situation awareness time, and the decision time [70], [71]. For the application of in-vehicle traffic signals at intersections, the system may collect the traffic information easier, faster and more correct than drivers based on the usage of vehicular communications. Before sending information to drivers, the in-vehicle traffic signal system has already completed the sensation, perception and situation recognition process in the background. Moreover, as the in-vehicle traffic signals will provide predicted information to drivers before arriving at the intersections, the drivers may start to make a decision before the onset of an event, including the change of ground traffic light. Therefore, the system can perform the situation recognition much faster than drivers, and consequently help reduce the total time required by a driver in response to an event.

2.2. Driver model with partial deployment of in-vehicle traffic signals

The in-vehicle traffic signal system mainly relies on vehicular communications to obtain information at intersections, while the full deployment of vehicular communications may cost decades. Therefore, it is possible that both the in-vehicle traffic signals equipped and unequipped vehicles exist at the intersections, and it is necessary to consider the driver model with partial deployment of in-vehicle traffic signals. For the driver model while applying the in-vehicle traffic signal system in a partial deployment scenario, car following behaviors were taken into consideration for analyzing the effects at signalized intersections, while the state of drivers' trust was mainly considered for unsignalized intersections.

2.2.1. Driver model considering car following behavior

The in-vehicle traffic signal system at signalized intersections is supposed to provide predicted traffic signal information for drivers. The necessary information for the prediction of traffic signal include the speed and the distance to intersection of the vehicle, and the traffic signal cycle of the ground traffic light. Therefore, the in-vehicle traffic signals at signalized intersections can be decided with the information transferred between the ground traffic light and the vehicle itself, based on V2I communications. It is considered that the penetration rate of the system may not directly influence the usage of the system for a single vehicle. However, if a system equipped vehicle is in a traffic flow, it may have some influences on the driving operations of other vehicles around it.

When other vehicles are in a row with the system equipped vehicle and move on a same road after the vehicle, the influences of in-vehicle traffic signals on other vehicles may be explained with the car following behaviors. As a ground traffic light is normally set up for a road with high traffic flow, the car following behaviors can usually be observed at signalized intersections.

As shown in Fig. 2.2, two vehicles A and B are approaching to a signalized intersection. As the vehicle B is following the vehicle A, a car following model is required for analyzing the behaviors of vehicle B. The basic philosophy of car following model is from the Newtonian mechanics, where the acceleration of a vehicle can be regarded as the

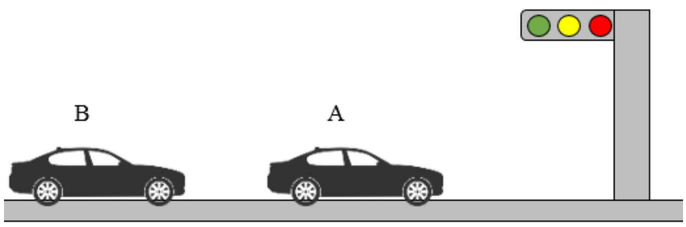

Fig. 2.2. Vehicles approaching to a signalized intersection.

response to the stimulus it receives. Hence, the basic philosophy of car following theories can be summarized by the following equation, which was proposed in [72],

$$\text{Response} = \text{Sensitivity} * \text{Stimuli} \tag{2.3}$$

where response refers to the acceleration of the following vehicle, stimuli means the interaction with the preceding vehicle, including the changes in the speed and the acceleration of the preceding vehicle.

To numerically simulate the motions of vehicles, the following equations can be applied for calculating the real time positions and speeds of the vehicles.

$$\begin{aligned} & x_k(t+\Delta t) = x_k(t) + v_k(t)\times\Delta t + \frac{a_k(t)\times\Delta t^2}{2} \\ & v_k(t+\Delta t) = v_k(t) + a_k(t)\times\Delta t \\ & t = \Delta t \times (iteration - 1) \end{aligned} \tag{2.4}$$

where $x_k(t)$, $v_k(t)$, and $a_k(t)$ are the position, speed and acceleration of the vehicle *K* at the time *t*, Δt is the time interval between the calculations. It can be observed from the eq. (2.4) that the acceleration is required for continuously calculating the speed and position of a vehicle.

For the acceleration of a vehicle equipped with the in-vehicle traffic signals, it can be decided with the expected speed based on the predicted traffic signals. For the acceleration of a vehicle without the in-vehicle traffic signals, the car following model revised from the reference [72] can be applied. The stimulus is considered to be composed of the speed of the following vehicle, the relative speeds and the distance headway between the preceding and following vehicles. Therefore, it is a function that can be represented as follows,

$$a_n^t = f_{sti}(v_n, \Delta x_n, \Delta v_n) \tag{2.5}$$

where a_n^t is the acceleration of the following vehicle, v_n is the speed of the following vehicle, Δv_n is the relative speeds between the preceding and the following vehicles. Δx_n is the distance headway.

For a vehicle equipped with in-vehicle traffic signals, its driving operations, including the acceleration and brake operations, may be influenced by the predicted traffic signal information. The changes in the driving operations of a system equipped vehicle will affect the relative speed and distance headway with its following vehicle, which may finally influence the acceleration and brake operations of the following vehicle.

2.2.2. Driver model considering drivers' trust

The analysis on the application of in-vehicle traffic signal system at unsignalized intersections will be performed based on the relationship between drivers' trust on the system and the reliability of the system. As shown in Fig. 2.3, drivers' trust on the system and the reliability of the system itself are considered to have great influences on the effectiveness of the system.

For the relationship between drivers' trust on the system and the reliability of the system, it can be classified as: distrust, trust and over trust. For the first relationship, distrust, it can be described as follows,

$$T_{driver} < R_{system} \tag{2.6}$$

where T_{driver} represents drivers' trust on the system, and R_{system} is the reliability of the system.

Distrust might be induced for several reasons: the malfunction of the system and driver's insufficient understanding of the system, including the functions of the system and the way to use the system. Several possible methods, including the improvement of

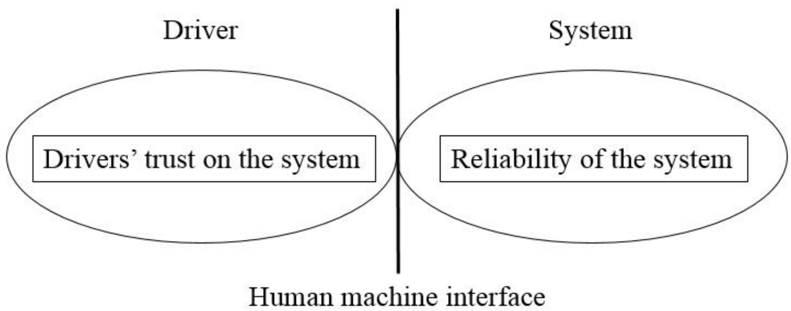

Fig. 2.3. Drivers' trust on the system and the reliability of the system will influence the effectiveness of the system.

system reliability, and the deepening of understandings of the system by offering driver education, might be applied to solve the distrust problem.

For the second relationship, trust, it can be described as follows,

$$T_{driver} = R_{system} \tag{2.7}$$

The relationship of trust is the expected relationship between drivers' trust on the system and the reliability of the system, which indicates that driver's understanding of the system is appropriate.

For the third relationship, over trust, it can be described as follows,

$$T_{driver} > R_{system} \tag{2.8}$$

Over trust might be induced for several reasons: drivers' insufficient understanding of the system, including the limitations of the system, and the decrease of alertness level. Several possible methods, including the improvement of system reliability, the deepening of understandings of the system by driver education, and the call up of drivers' attention with human machine interface, might be applied to solve the over trust problem.

As for the reliability of the system, according to the guidelines of communication based driving assistance systems announced by the Ministry of Land, Infrastructure and Transport, the possible factors that may influence the usage of the communication based driving assistance systems include GPS error and the existence of vehicles unequipped with communication devices [73]. The in-vehicle traffic signal system is proposed based on vehicular communications, therefore, the reliability of the system mainly depends on the GPS accuracy and the penetration rate of the system. For the influence of GPS information, it is considered that the GPS accuracy may be greatly improved by applying RTK-GPS or using data fusion. The penetration rate of the system is then considered as the key point to be investigated.

For the application of in-vehicle traffic signals at unsignalized intersections, the system is mainly proposed to assist drivers to cross intersections, by displaying traffic signals inside vehicles. The necessary information for the calculation of traffic signals at unsignalized intersections include the speeds and the distances to intersection of the vehicles approaching the intersection. Therefore, the in-vehicle traffic signals at unsignalized intersections are decided with the information exchanged among vehicles, based on V2V communications. If some of the vehicles on the road are without vehicular communication devices, they may be invisible for the system equipped vehicles. And the system may judge the traffic conditions at intersections without considering these system unequipped vehicles.

As there is no ground traffic light to control the traffic flow at unsignalized intersections, the stop and go decisions may heavily rely on the in-vehicle traffic signals for the system equipped vehicles. The driving safety may, therefore, be influenced if the penetration rate is not 100%, compared to that of signalized intersections. A driving condition at a two-way stop-controlled intersection is taken as an example. At the intersection, a minor-road vehicle is waiting at the stop line to find a safe gap to cross and it is equipped with the in-vehicle traffic signal system. As the penetration rate is below 100%, a green signal may be displayed to the minor-road vehicle, while an in-vehicle traffic signal unequipped vehicle is approaching from the major-road and is quite near the intersection, making the intersection entry unsafe for the minor-road vehicle.

However, it should not be easily concluded that the in-vehicle traffic signals cannot be used at intersections without ground traffic lights when the penetration rate is not 100%. As the in-vehicle traffic signals are proposed as a system to provide assistances to drivers, it is the drivers who will finally take actions and control the vehicles. When a green signal is displayed to the minor-road drivers, the drivers need to make a decision that whether to enter the intersection or not. The availability of in-vehicle traffic signal system at unsignalized intersections in a partial deployment environment is highly related with the judgment of drivers.

If a driver understands that the penetration rate of in-vehicle traffic signals is not 100% and is not over trust while using the system, it is expected that the driver will check the traffic condition carefully at intersections, and will reject to enter the intersection if it is observed that a conflict may happen, even when the in-vehicle traffic signal is green. A previous study introduced that no driver would accept a gap that was smaller than 2 seconds [74]. On the other hand, it is difficult for all the drivers to keep alert while driving. There is a possibility that some drivers may become over trust on the proposed in-vehicle traffic signals after successfully using the system for several times.

To analyze the influences of penetration rate on the application of in-vehicle traffic signals, it is necessary to consider the state of drivers' trust. However, for the previous research on drivers' trust, there are still a lot of contents remain unclear, and the accumulation of research resources is not enough at present, as a huge amount of data are required for the investigation of trust [75-77]. In this study, a driver model would be proposed which took into consideration the penetration rate of in-vehicle traffic signals and the state of drivers' trust at unsignalized intersection. The driver model might not accurately reflect the state of drivers' trust, but should be able to reflect the characteristics and the changing trend of trust.

For the modelling of drivers' trust, as shown in Fig. 2.4, it was proposed based on decision making process. Decision making is considered as a process of identifying a decision, gathering information, making a decision, taking actions, and reviewing the decision. When a newly proposed assistance system is provided to a driver, the driver will have an initial trust t_0 on the system. The initial trust will be greatly influenced by drivers' understanding of the system. If an appropriate driver education is performed for the driver before using the system, the driver will have an appropriate initial trust.

Then the driver will take actions a_1^h based on the initial trust t_0 on the system and the surrounding condition s_1, including the traffic conditions at the intersection. The performances p_1 will be decided by the driver actions a_1^h and the surrounding condition s_1. Finally, the trust of the driver on the system t_1 will be updated based on the initial trust t_0 and the performances p_1.

Moreover, the initial trust of drivers may vary depending on the penetration rate of the system. If the penetration rate is low, which means that it may be easy for the system to make a wrong prediction, therefore, the initial trust may become low. If the penetration rate becomes higher, which means that it will become less possible for the system to make a wrong prediction, therefore, the initial trust may become higher. Meanwhile, it is considered that the increase of initial trust may be loose when the penetration rate is low. If the penetration rate is high, the initial trust may increase rapidly.

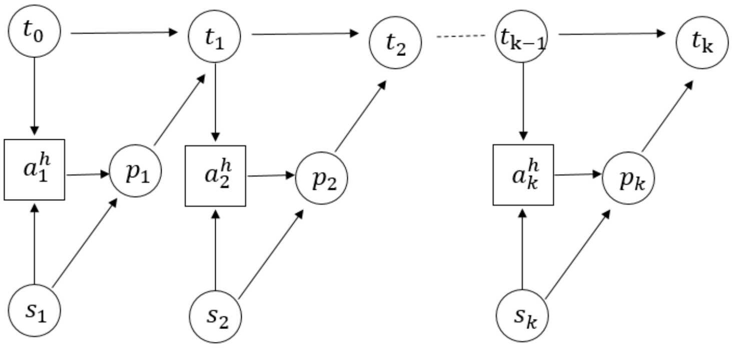

Fig. 2.4. Drivers' trust based on decision making process, where *t* means drivers' trust, *a* presents the action of drivers, *s* means the surroundings, including the penetration rate, and *p* means the performances.

To calculate drivers' trust while driving, both the initial trust and the change of trust are needed. For the change of the trust, it is considered that drivers' trust on the system may increase if they successfully cross the intersection while using the system. If the successful experience continues, the increase of trust may continue. On the other hand, drivers' trust on the system may decrease if they fail to cross the intersection while using the system. If the failed experience continues, the decrease of trust may also continue. Finally, the increase of trust while success may be less than the decrease of trust while failed according to the consideration that it is easy to lose trust, but hard to regain it.

For the definition of success, it is considered that if the drivers successfully pass through intersections and the values of PET are larger than 3 seconds, then it can be defined as a successful crossing [64]. On the other hand, for the definition of failure, it is considered that if the drivers pass through intersections while the values of PET are smaller than 3 seconds, or the drivers give up crossing intersections with a sudden brake and let other vehicles cross first, then it can be defined as a failure. Finally, driving behaviors may also be influenced by drivers' trust on the system. It is considered that the drivers may not check the right and left carefully while passing through the intersections if they become over trust on the system. Therefore, the driver model at unsignalized intersection would contain not only drivers' trust model, including the initial trust of drivers before using the system, and the changing model of trust while using the system, but also the driver behavior model while using the in-vehicle traffic signal system, including eye-gaze behaviors and driving operations. To determine the parameters of the trust models, a driving simulator experiment would be performed to obtain the necessary data on the initial trust, the change of drivers' trust, and related driving behaviors. Afterwards, simulations will be performed based on the obtained results of the experiments.

Chapter 3

Implementation of in-vehicle traffic signals

Implementation of in-vehicle traffic signals

3.1. In-vehicle traffic signals for signalized intersections

Two modes of in-vehicle traffic signals were proposed to assist drivers at signalized intersections, of which one is defined as current mode and the other is named predicted mode.

3.1.1. Current mode

In the current mode, when a vehicle has entered the operation range of the in-vehicle traffic signals, the real time information of the ground traffic light of the upcoming intersection is displayed directly to drivers by in-vehicle displays. For the vehicles which are without the operation range, no in-vehicle traffic signal will be displayed.

The current mode can be helpful for drivers when the ground traffic lights are out of the vision. It is possible that the ground traffic light may be difficult to be observed when the visibility of drivers is obstructed by a large-sized vehicle ahead. The necessary information needed by the current mode of in-vehicle traffic signals are listed in the table 3.1.

Table 3.1. Necessary information used by the current mode.

Symbol	Detail
P_I	Position of the intersection
P_V	Current position of the vehicle
P_S	Current phase of ground traffic lights

As shown in Fig. 3.1, the vehicle *A* has entered the range of the in-vehicle traffic signals. The ground traffic light that controls the lane of the vehicle *A* is in the red phase. Therefore, a red in-vehicle traffic signal is displayed to the vehicle *A*.

For the vehicles *C* or *D*, it can be observed from Fig. 3.1 that no signal is displayed to them. The vehicle *D* has not entered the operation range of the in-vehicle traffic signals, and the vehicle *C* has already passed the intersection and has not entered the operation range of in-vehicle traffic signals for the next intersection. As for the range of in-vehicle traffic signals, it is defined considering the speed limit and the quality of vehicular communication at intersections.

3.1.2. Predicted mode

For the predicted mode of the in-vehicle traffic signals, a predicted ground traffic light information of the upcoming intersection can be provided to the drivers if they have entered the operation range. Based on the predicted information offered by the in-vehicle traffic signals, drivers can get to know what kind of traffic signal they will confront if they approach to the upcoming intersection with the current speed. It is necessary to be mentioned that there is no yellow signal in the predicted mode of in-vehicle traffic signals. A yellow signal will be treated as a red signal in the predicted mode, to avoid the dilemma zone. Therefore, only green and red signals will be available in this mode.

The predicted mode normally required several information as listed in the table 3.2: the position of the upcoming intersection, the current position of the vehicle, the current phase of the ground traffic light that controls the lane of the vehicle, the current speed of the vehicle, the left time of the current phase, the length of the red phase, the length of the green phase and the length of the yellow phase of the upcoming ground traffic light.

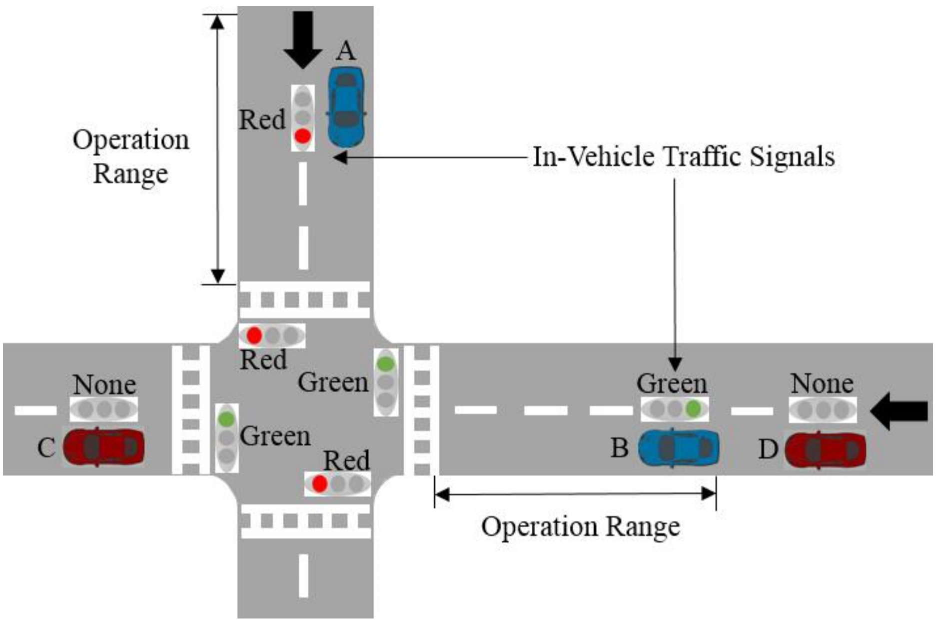

Fig. 3.1. Current mode of in-vehicle traffic signals. “None” means no in-vehicle traffic signal is displayed. “Green” indicates that a green signal is displayed and “Red” represents a red signal.

Table 3.2. Necessary information used by the predicted mode.

Symbol	Detail
P_i	Position of the intersection
P_v	Current position of the vehicle
P_s	Current phase of ground traffic lights
V	Current speed of the vehicle
T_L	Left time of the current phase
T_R	Length of the red phase
T_G	Length of the green phase
T_Y	Length of the yellow phase

For a vehicle *i*, the instantaneous distance to the upcoming intersection at the time step *t* is defined as $L_i(t)$, which can be calculated with the positions of the upcoming intersection and the vehicle. Thus, the predicted time to intersection $TTI_i(t)$ can be calculated as follows,

$$TTI_i(t) = \frac{L_i(t)}{V_i(t)} \tag{3.1}$$

where $V_i(t)$ is the current speed of the vehicle *i* at the time step *t*.

Then the in-vehicle traffic signals can be predicted with the traffic signal information of the upcoming intersection and the time to intersection of the vehicle. As shown in Fig. 3.2, if the current phase of the ground traffic signal is green, the predicted time to intersection $TTI_i(t)$ should be compared with the left time of the current phase $T_L(t)$.

If the predicted time to intersection is smaller than the left time, which means the vehicle will arrive at the intersection within the current phase, then the current traffic signal, a green signal will be displayed to the drivers directly. If the predicted time to intersection is just equal to the left time of the current phase, it is possible that the predicted signal may change frequently. In this case, the drivers can choose to accelerate or decelerate slightly. Then a stable in-vehicle traffic signal can be achieved.

If the predicted time to intersection is larger than the left time of the current phase as shown in Fig. 3.2, the difference between the predicted time to intersection and the left time of the current will be calculated first,

$$\Delta T(t) = TTI_i(t) - T_L(t) \tag{3.2}$$

If the $\Delta T(t)$ is smaller than the signal cycle length T_C, then the $\Delta T(t)$ should be compared with the total length of yellow and red phases. If the $\Delta T(t)$ is smaller than the total length of yellow and red phases, then a red signal will be displayed by the in-vehicle traffic signal system. If the $\Delta T(t)$ is bigger than the total length of yellow and red phases, then a green signal will be displayed.

There is a possibility that the $\Delta T(t)$ is larger than the signal cycle length T_C, in this case, the $\Delta T(t)$ contains more than one signal cycle. A reminder function will then be applied to calculate the reminder $R(t)$ using the calculated $\Delta T(t)$ and the signal cycle length T_C as follows,

$$R(t) = \mathrm{mod}\left(\frac{\Delta T(t)}{T_C}\right) \tag{3.3}$$

Then the reminder $R(t)$ will be within one signal cycle and be compared with the total length of yellow and red phases. If the $R(t)$ is smaller than the total length of yellow and red phases, then a red signal will be displayed by the in-vehicle traffic signal system. If the $R(t)$ is bigger than the total length of yellow and red phases, then a green signal will be displayed.

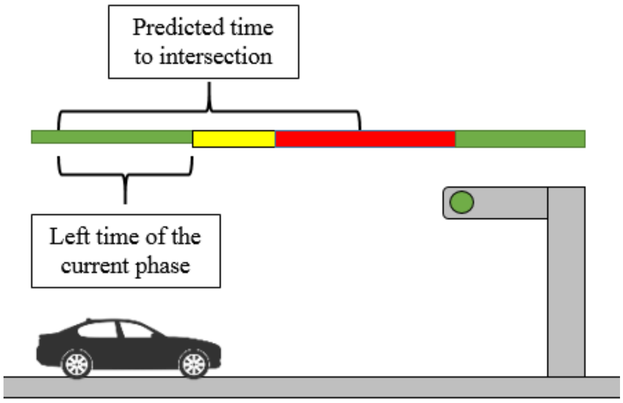

Fig. 3.2. An example when the ground traffic light is green and the predicted time to intersection is larger than the left time of the current phase.

If the current phase of the ground traffic light is red, the calculation process can refer to that when the ground traffic light is green. The left time of the current phase will be compared with the predicted time to intersection first. If the predicted time to intersection is smaller than the left time, a red signal will be displayed. If the predicted time to intersection is larger than the left time, the time difference between them can be calculated as shown in eq. (3.2). If the time difference is smaller than the signal cycle length, then the time difference should be compared with the length of green phase. If the time difference is smaller than the length of green phase, then a green signal will be displayed by the in-vehicle traffic signal system. If the time difference is bigger than the length of green phase, then a red signal will be displayed.

If the current phase of ground traffic light is yellow, the left time of the current phase T_L^Y should be calculated with the following equation for predicting the in-vehicle traffic signals, as the yellow signal is treated as a red one in the predicted mode. The other calculation process can be the same as that when the ground traffic light is red.

$$T_L^Y(t) = T_L(t) + T_R \tag{3.4}$$

An example of the system is shown in Fig. 3.3. A green in-vehicle traffic signal is displayed to the vehicle A, even though the current phase of the ground traffic light controlling its lane is red. In this case, if the vehicle A can maintain its current speed, it will be confronted with a green signal when it arrives at the upcoming intersection.

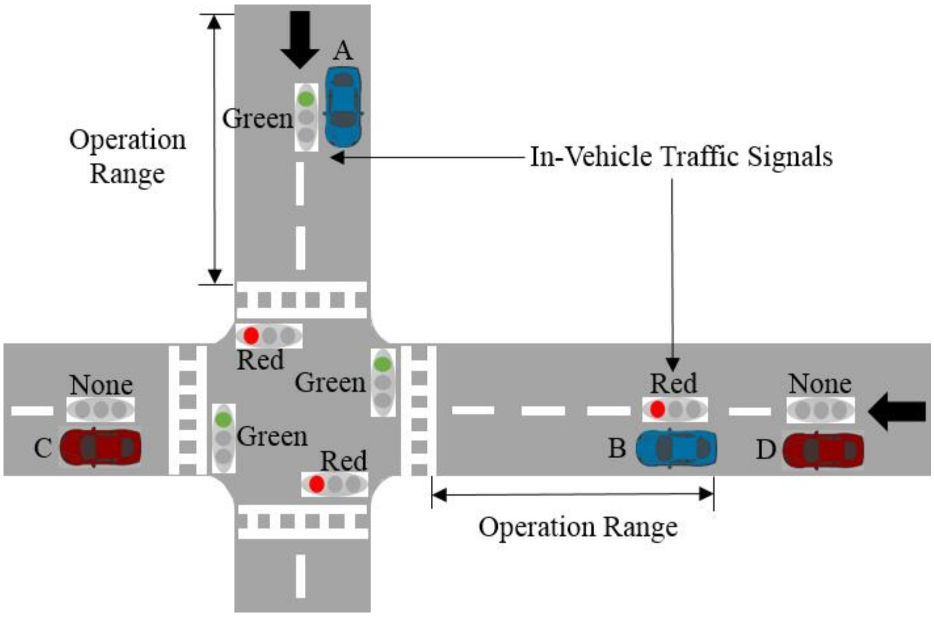

Fig. 3.3. Predicted mode of in-vehicle traffic signals. "None" means no in-vehicle traffic signal is displayed. "Green" indicates that a green signal is displayed and "Red" represents a red signal.

3.2. In-vehicle traffic signals for unsignalized intersections

Unsignalized intersections normally can be classified as two-way stop-controlled intersections and all-way stop-controlled ones.

At a two-way stop-controlled intersection, the roads that are controlled by stop lines are defined as minor roads. Conversely, the roads without stop signs are referred to as major roads. Vehicles on the major roads have the priority and are able to pass through the intersection first. Minor-road vehicles have to stop at the stop line first, then wait for an appropriate gap in the major road traffic flow to enter the intersection. According to the definition of Highway capacity manual, a critical gap G_C is the minimum time interval in the major-road traffic stream that allows intersection entry for one minor road vehicle [78]. The difference in priority between vehicles on the major and minor roads is one of the most essential factors in the design of in-vehicle traffic signals for two-way stop-controlled intersections.

At an all-way stop-controlled intersection, all roads are controlled by stop signs, and vehicles approaching from all the directions are required to stop at the stop line before proceeding through the intersection. As most of the all-way stop-controlled intersections are with limited width, it is assumed that only one vehicle will be allowed to enter the all-way stop-controlled intersection at a time, considering the driving safety.

3.2.1. Application at two-way stop-controlled intersections

For a two-way stop-controlled intersection, as presented in Fig. 3.4, the vehicles *K-1*, *K*, *K+1*, *J-1*, and *J* are on the road without the control of stop line, which are named as major-road vehicles. Oppositely, the vehicle *N* is on the road which has a stop line, therefore, is defined as a minor-road vehicle. The operating principle of the two-way stop-controlled intersection will be explained by taking the vehicle *N* as an example. When the minor-road vehicle *N* arrives at the intersection, the gaps on the major road can be defined as follows,

$$G_K(t) = \frac{d_K(t)}{v_K(t)} \tag{3.5}$$

$$G_J(t) = \frac{d_J(t)}{v_J(t)} \tag{3.6}$$

where $d_K(t)$ and $d_J(t)$ represent the distances to the upcoming intersection, $v_K(t)$ and $v_J(t)$ are the current velocities of the major-road vehicles K and J at the time t, respectively.

The major-road gap $G_N(t)$ for the vehicle *N* will then be determined according to its target moving direction at the intersection, as shown in the Table. 3.3.

Table 3.3. Major-road gap for the minor-road vehicle *N*.

Target Direction	Gap
Forward	$G_N(t)=\min(G_K(t), G_J(t))$
Left-turn	$G_N(t) = G_J(t)$
Right-turn	$G_N(t) = \min(G_K(t), G_J(t))$

Afterwards, by comparing the major-road gap $G_N(t)$ with the critical gap G_C, the operation principle of the two-way stop-controlled intersection for the vehicle *N* can be expressed as follows,

$$P_U(t) + P_V(t) = 1 \tag{3.7}$$

$$P_U(t) = \begin{cases} 1, G_N(t) < G_C \\ 0, G_N(t) \geq G_C \end{cases} \tag{3.8}$$

$$P_V(t) = \begin{cases} 1, G_N(t) \geq G_C \\ 0, G_N(t) < G_C \end{cases} \tag{3.9}$$

where $P_U(t)$ and $P_V(t)$ represent the priority statuses of the major and minor road vehicles, respectively. $P_U(t)$ = 1 means that the major-road vehicles have the priority to cross the intersection, while $P_V(t)$ = 1 means that the priority of crossing has been given to the minor-road vehicle *N*.

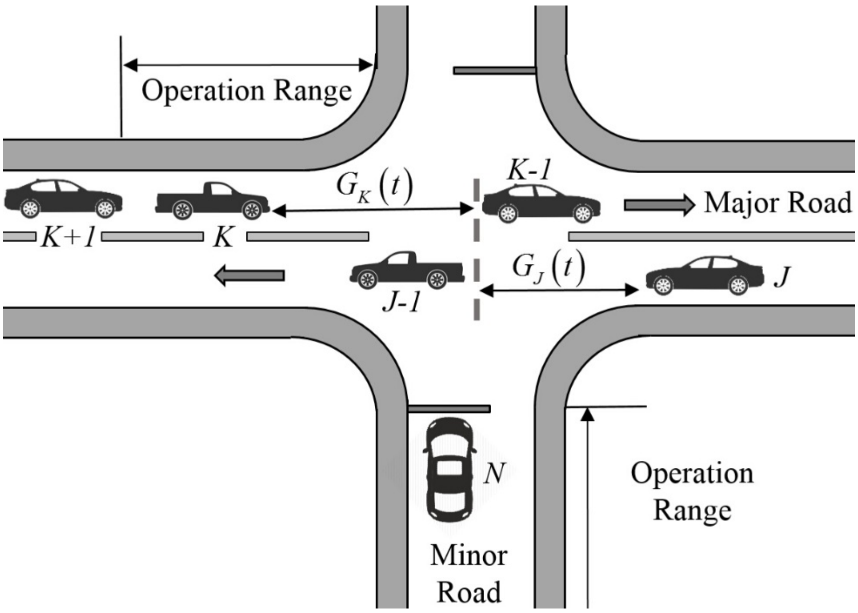

Fig. 3.4. Gaps on the major road at a two-way stop-controlled intersection.

As shown in Fig. 3.5, for a minor-road vehicle N approaching the two-way stop-controlled intersection, the state of the vehicle will be checked in real time to confirm whether it has arrived at the stop line or not. If the vehicle has reached the stop line, the in-vehicle traffic signal system will start recording its waiting time and checking whether an oncoming minor-road vehicle exists or not. If an oncoming vehicle exists, the earlier minor-road vehicle will be selected as the leader, and a waiting list will be created for managing the minor-road vehicles waiting at the stop lines.

An example of the waiting list is shown in the Table. 3.4, according to the traffic condition presented in Fig. 3.5. The minor-road vehicle N reaches the intersection earlier than the vehicle $N+1$, therefore, is selected as the leader. If the vehicle N desires to make a right-turn and turns on its right blinker while the vehicle $N+1$ plans to move forward, it is possible for the vehicles N and $N+1$ to collide inside the intersection as their planned paths intersect. Then the vehicle $N+1$ is ranked the 2*nd*, and will not enter the intersection together with the vehicle N.

Table 3.4. Example of waiting list for minor-road vehicles.

ID	Role	Direction	Rank
N	Leader	Right-turn	1*st*
$N+1$	Follower	Forward	2*nd*

Based on the above considerations, for a minor-road vehicle N, an in-vehicle traffic signal $L_N(t)$ can be designed as follows,

$$L_N(t) = -H\left(R_O - d_N(t)\right) + R_N(t) \cdot P_N(t) \tag{3.10}$$

$$R_N(t) = \begin{cases} 2, Rank = 1st \\ 0, Rank \neq 1st \end{cases} \tag{3.11}$$

$$P_N(t) = \begin{cases} 0, G_N(t) < G_C \\ 1, G_N(t) \geq G_C \end{cases} \tag{3.12}$$

where $R_N(t)$ and $P_N(t)$ are the functions for judging the rank and major-road gap for the vehicle N, respectively; $L_N(t)$ = −1 represents a red signal, $L_N(t)$ = 0 means no signal will be displayed and $L_N(t)$ = 1 represents a green signal; $H\left(R_O - d_N(t)\right)$ is a

Heaviside step function, R_O is the operation range of the in-vehicle traffic signal system and $d_N(t)$ is the distance to intersection of the vehicle *N*.

For a major-road vehicle *K*, as shown in Fig. 3.5, the in-vehicle traffic signal $L_K(t)$ can be expressed as follows,

$$L_K(t) = H\left(R_O - d_K(t)\right) + P_K(t) \tag{3.13}$$

$$P_K(t) = \begin{cases} 0, & G_N(t) < G_C \\ 1, & G_N(t) \geq G_C \end{cases} \tag{3.14}$$

where $P_K(t)$ is the function for judging the entry of the minor-road vehicle for the vehicle *K*; $L_K(t)$ = 0 means that no signal will be displayed, $L_K(t)$ = 1 means a green signal, and $L_K(t)$ = 2 represents a flashing yellow signal for warning major-road drivers to proceed with caution; $H\left(R_O - d_K(t)\right)$ is a Heaviside step function, R_O is the operation range of the in-vehicle traffic signal system and $d_K(t)$ is the distance to intersection of the vehicle *K*.

An example of the in-vehicle traffic signal system is shown in Fig. 3.5, when the major-road gaps are smaller than the critical gap. For the vehicle *K+1* which has not entered the range of in-vehicle traffic signals, or vehicles *K-1* and *J-1* which have crossed the intersection, no in-vehicle traffic signal will be displayed. For minor-road vehicles in the range of in-vehicle traffic signals, including the vehicle *N*, a red signal will be displayed for requiring a stop at the stop line. Afterwards, the minor-road vehicles need to wait for a safe major-road gap to enter the intersection. If a safe gap appears, the signal presented to the minor-road vehicle will turn green.

For a major-road vehicle which has entered the range of in-vehicle traffic signals, including the vehicle *K*, a green signal will be displayed if no minor-road vehicle is allowed to enter the intersection. If the entry of a minor-road vehicle is permitted, the in-

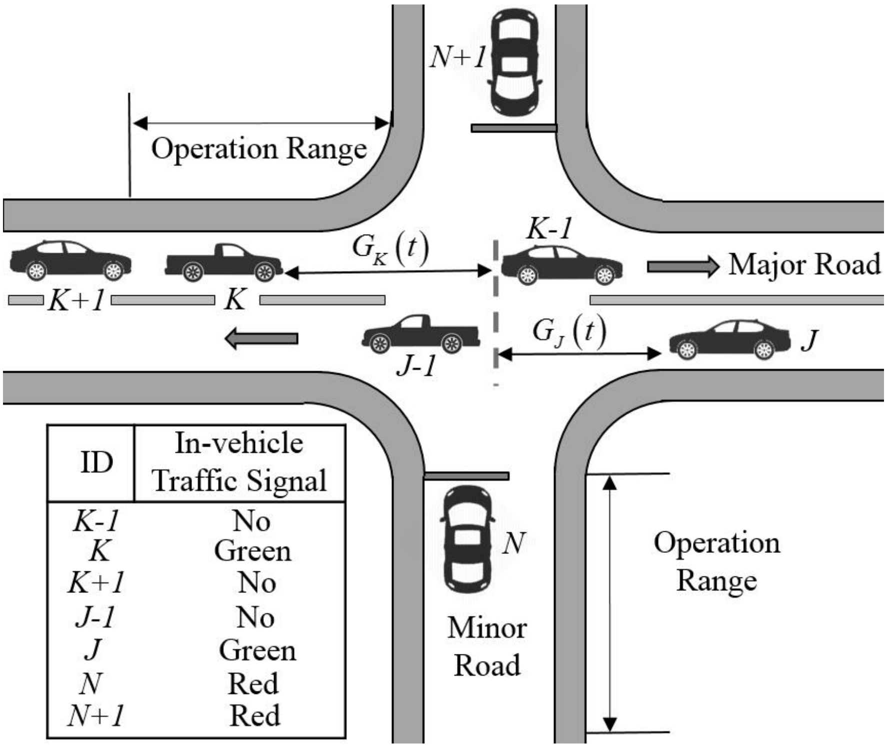

Fig. 3.5. In-vehicle traffic signals at a two-way stop-controlled intersection when the major-road gaps are smaller than the critical gap. "No": no light; "Green": a green light; "Red": a red light.

vehicle traffic signal displayed to major-road vehicles will turn to a flashing yellow signal for warning the drivers to proceed with caution.

In previous studies, the critical gap G_C of the major road was normally considered to be a constant value of 6.5 seconds [79]. However, it was reported that the waiting time had notable effects on the gap acceptance behaviors [80]. The effect of waiting time on drivers' decision can be considered as a behavioral issue [81].

It was observed that, in the actual driving conditions, minor-road drivers pretended to accept smaller critical gaps to enter the intersection if they had waited for a relatively long time [82]. Therefore, the longer a driver waits, the more he is willing to accept risk and the likelihood for accepting shorter gaps increases [83-85]. Then the critical gap may be considered as a variable value. It will decrease with the waiting time at first, and finally converge to a constant value [86], [87].

As shown in Fig. 3.6, the critical gap can be set to 6.5 s if drivers wait for less than 10 s, 5.5 s if the waiting time falls within 10 to 20 s, 5.25 s if the waiting time falls within 20 to 30 s, and 5 s if the waiting time is longer than 30 s, based on the data from observational studies [86].

Then the relationship between the waiting time and critical gap at two-way stop-controlled intersections can be expressed as follows,

$$G_C(T) = 6.5 - H(T-10) - 0.25 \times H(T-20) - 0.25 \times H(T-30) \tag{3.15}$$

where $G_C(T)$ means the critical gap considering waiting time; and T is the waiting time of a minor-road vehicle; the value of 6.5 s is the critical gap when the waiting time is less than 10 s; $H(T-10)$, $H(T-20)$ and $H(T-30)$ are Heaviside step functions that represent the scenarios that drivers have waited for 10 to 20 s, 20 to 30 s, and longer than 30 s, respectively; and 0.25 is a parameter for adjusting the critical gap according to the changes in the waiting time.

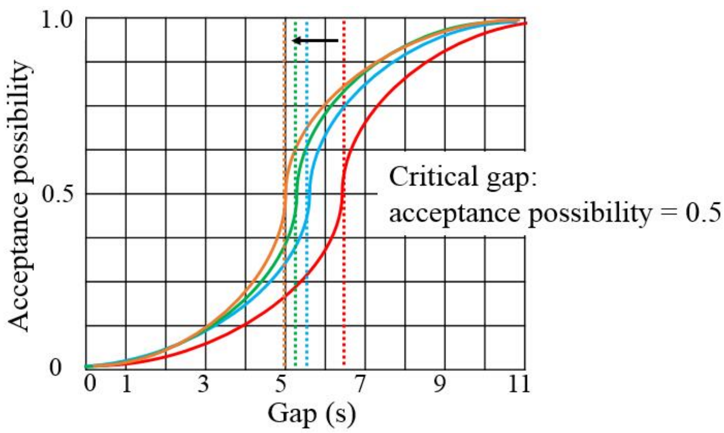

Fig. 3.6. The change of critical gap with waiting time, where the red line means that drivers wait for less than 10 s, and the critical gap can be set to 6.5 s; the blue line indicates the waiting time falls within 10 to 20 s, and the critical gap can be set to 5.5 s; the green line means that the waiting time falls within 20 to 30 s, and the critical gap can be set to 5.25 s; and the orange line indicates the waiting time is longer than 30 s and the critical gap is 5 s.

3.2.2. Application at all-way stop-controlled intersections

At the all-way stop-controlled intersections, the in-vehicle traffic signal system was designed based on a first-come-first-served strategy. Therefore, the passing priority is decided by the order in which vehicles arrive, without other biases or preferences. If more than one vehicles arrive at the intersection at the same time, the "priority to the left" rule will apply that vehicles need to yield to the vehicle coming from the next branch left of them. It is necessary to mention that the system does not consider the rare situation that vehicles from all the directions reach the intersection simultaneously.

For vehicles that are approaching an all-way stop-controlled intersection, a red light will be displayed first if they enter the range of in-vehicle traffic signals. When a vehicle arrives at the stop line, it will exchange the position information with other vehicles inside the operation range to check whether a leader exists. If one vehicle arrives at the intersection earlier than other vehicles, it will be selected as leader and the passing priority will be offered to the vehicle. As shown in Fig. 3.7, the in-vehicle traffic signal displayed to it will turn green.

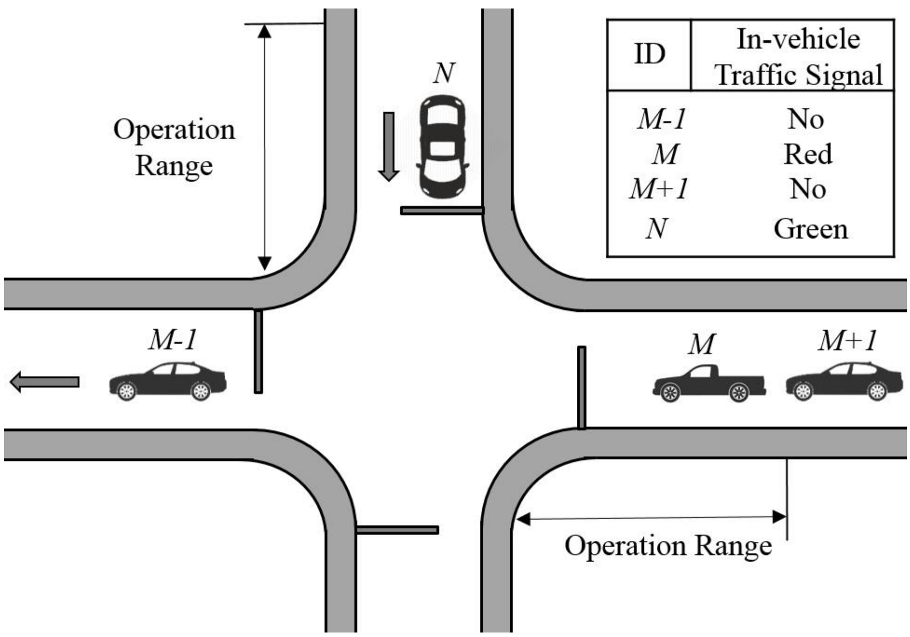

Fig. 3.7. In-vehicle traffic signals at an all-way stop-controlled intersection when one vehicle arriving at the intersection earlier than other vehicles. "No": no light; "Green": a green light; "Red": a red light.

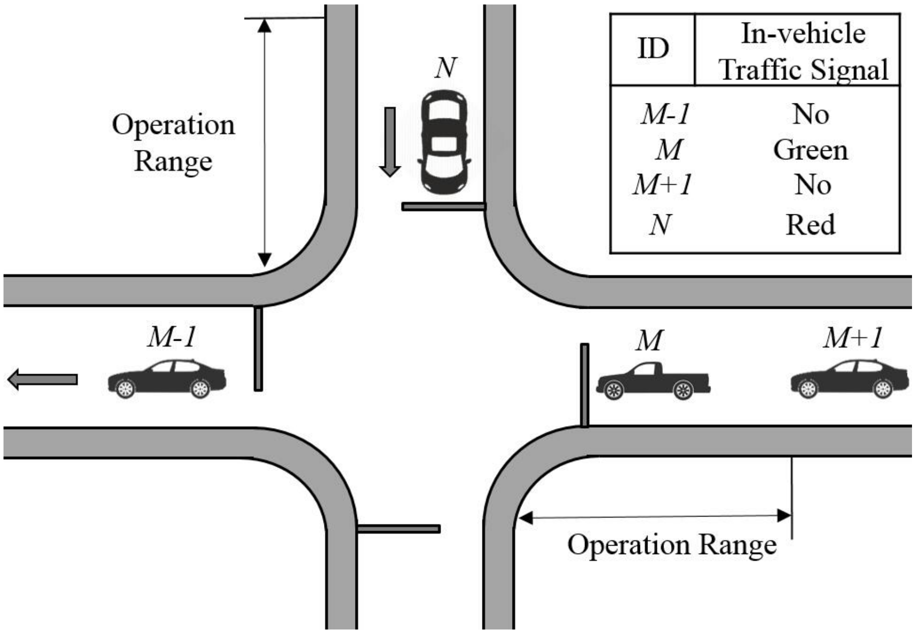

Fig. 3.8. In-vehicle traffic signals at an all-way stop-controlled intersection when multiple vehicles reaching the intersection at the same time. “No”: no light; “Green”: a green light; “Red”: a red light.

If a leader vehicle already exists and is crossing the intersection, the vehicle arriving latter needs to wait at the stop line for its turn to enter. After the passage of the previous leader, the vehicles which arrives at the intersection earliest among all the vehicles waited at the stop lines will be chosen as the new leader. As presented in Fig. 3.8, if multiple vehicles reach the intersection at the same time, the vehicle arriving from the left side will have the priority, enabling it to pass through the intersection first.

Chapter 4

Effect of in-vehicle traffic signals in full deployment scenario

Effect of in-vehicle traffic signals in full deployment scenario

4.1. Full deployment scenario at signalized intersections

4.1.1. Driving simulator experiments at signalized intersections

Driving simulator system

An advanced driving simulator was employed as the experimental platform for the driving experiments. The simulator was equipped with a Stewart motion platform with six degrees of freedom and a field of vision of 140 degrees that produced realistic driving sensations. During the experiment, the experimental data was recorded in real time, and the data sampling frequency was set as 60 Hz.

The in-vehicle traffic signal system was set up based on the driving simulator. The system was composed of a display and a laptop computer which was connected with the host computer of driving simulator via Ethernet cable. In the preparatory stage of the experiment, all the information of the driving route, including the positions of the intersections, were recorded in the program of in-vehicle traffic signals, and the program was finally installed in the laptop computer.

During the experiment, the traffic information in the driving simulator, including the speeds and the positions of vehicles, were updated in real time. The updated information were then transferred to the laptop computer, and used by the program of in-vehicle traffic signals to calculate the distance between the vehicle driven by participants and the upcoming intersection. If the vehicle had entered the range of in-vehicle traffic signals, the position and speed information of all the other vehicles around the upcoming intersection would be analyzed to evaluate the traffic condition, and then the appropriate color of signal would be presented to drivers by the display.

As presented in Fig. 4.1, a red in-vehicle traffic signal at a signalized intersection was displayed using a head-up display iHUD (Springteq Electronics Corporation, New Taipei, Taiwan). The position of the head-up display was determined according to the guidelines for the placement of in-vehicle display systems [88]. It can be observed from Fig. 4.1 that the speedometer was placed in front of drivers. For the vision angles and the distances between the display and drivers' eyes, they may differ among participants because the participants may have different physiques and driving postures. Therefore, the data of a driver with a standard height of 170.0 cm is used as an example. The distance from the head-up display to the driver's eyes was 95.4 cm. The vertical visual angles from the

Fig. 4.1. A red signal displayed by the head-up display at a signalized intersection.

driver’s eyes to the head-up display was 7.8 degrees. And the horizontal visual angles from the driver’s eyes to the head-up display was 9.6 degrees. The actual figure shown in the head-up display was a rectangle 9.0 cm wide and 6.1 cm high. There was nothing else displayed other than a red/green/yellow dot for the in-vehicle traffic signals, and the actual diameters of the displayed dot in the head-up display was 1.9 cm.

A Smart Eye Pro system (Smart Eye AB, Gothenburg, Sweden) was employed in this study to track the eye-gaze behaviors [89]. It is a non-intrusive eye-gaze tracking system that uses the reflections of the infrared flashes on the corneas to find the centers of the eyes. The corneas are the transparent front parts of the eyes that cover the iris and pupil. As shown in Fig. 4.2, the system consisted of three cameras and two infrared flashes, and did not cause any physical burden to the drivers. These cameras were fixed at three different locations to obtain the best measurement of gaze direction.

In this eye tracking system, the line-of-sight measurement is performed by the corneal reflection method at a measurement frequency of 60 Hz to calculate the line-of-sight vector. In addition to this, it is also possible to measure the orientation of the face of drivers and the positions of their eyes, estimate the position of the viewpoint and finally identify the viewpoint of drivers. The cameras used for measurement is non-contact with drivers, and it is possible to perform a running test in a more natural state as compared with a contact type gaze measuring system. By irradiating the faces of drivers with infrared rays by the flashes installed in two places, it is possible to measure the drivers' line of sight stably even under the condition of light and dark change. Since the infrared rays are invisible for drivers, their driving is totally obstructed absent.

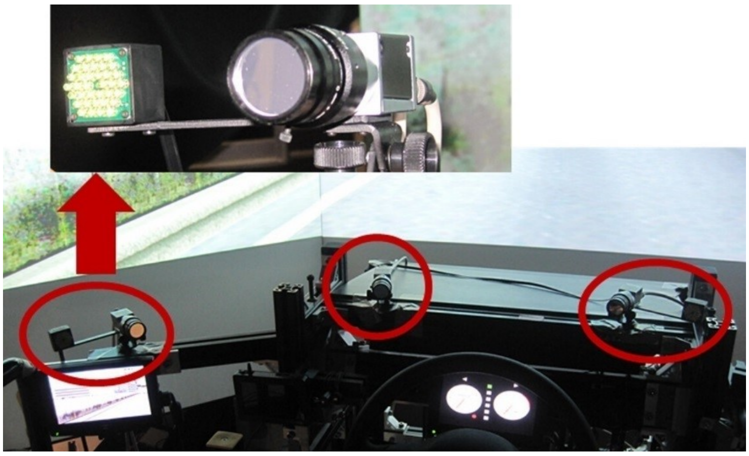

Fig. 4.2. Eye-gaze tracking system.

For the corneal reflection method, it uses the cornea as a convex mirror, and irradiates infrared light arranged near the eyeball and finally converges the virtual image position of the light with a convex lens or the like to detect the real image [90]. When the eyeball rotates, the virtual image position also changes accordingly (when the eyeball rotates by 1°, the position of the virtual image changes by 0.1 mm), and therefore the eye movements can be measured.

Participants of driving simulator experiment at signalized intersections

Eleven healthy participants took part in the driving experiments (sex: nine male/two female, mean age: 32 years old, range: 22–55 years old). All participants had a valid driving license, and had been driving for an average of 8 years (range: 3–44 years). Their mean driving frequency was 2.5 times per week (range: 1–7 times per week). This driving experiment received the approval from the Ethical Examination Committee of the Office of Life Science Research Ethics and Safety at The University of Tokyo (No. 14–44).

Urban scenarios in driving simulator

A driving scenario that realistically reproduced an existing urban road network in the Kinshicho area of Tokyo was designed with Multigen Creator (Presagis Corporation, Quebec, Canada), a three-dimensional software for modelling and real-time simulation. To avoid a learning influence on driver behaviors, three driving courses with different routes were chosen randomly for every participant as shown in Fig. 4.3.

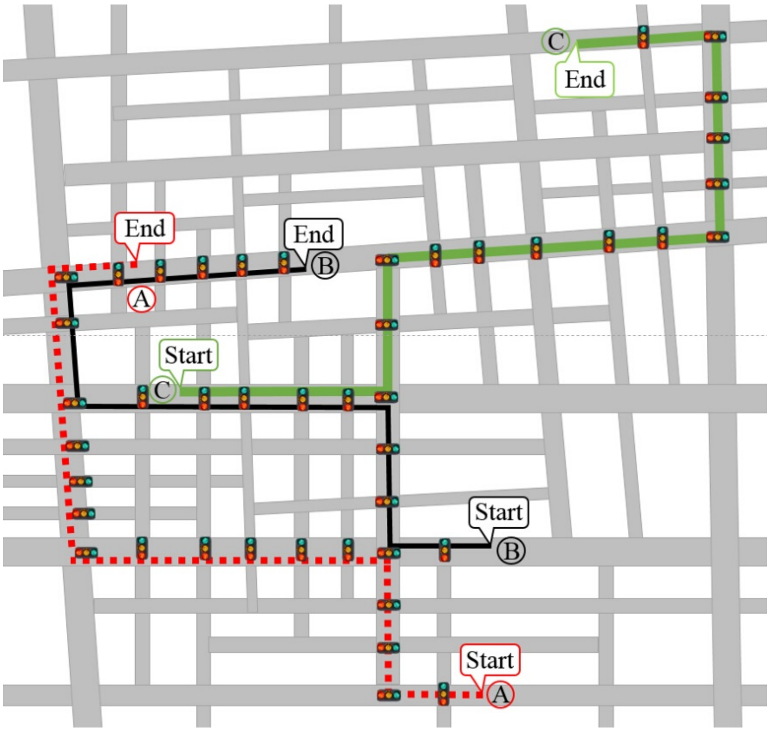

Fig. 4.3. Three driving courses used in the experiment.

Each route in the Fig. 4.3 had a driving distance of 2500 – 2600 meters, and 18 ground traffic lights on the track. Participants were required to make a turn at four of the eighteen intersections for each route.

Conditions of driving simulator experiment at signalized intersection

In this experiment, the range of the in-vehicle traffic signals was defined as 150 m, guaranteeing a high quality of vehicular communication [91].

Two kinds of displays, a normal 4.3-inch display and a head-up display, were used to present the in-vehicle traffic signals. A 4.3-inch display is a conventional device widely used in vehicles for GPS navigation [92]. On the other hand, a head-up display was initially developed for military aviation, and is an emerging device in the automobile arena [93]. In this study, a DP4 field monitor (SmallHD Corporation, Cary, USA) was used as the 4.3-inch display, and an iHUD (Springteq Electronics Corporation, New Taipei, Taiwan) was chosen as the head-up display.

The position of the head-up display has been described in the section 4.1.1. For the position of the 4.3-inch display, it was just 33.0 cm left and 17.0 cm high to the speedometer from drivers' perspective. For the data of a driver with a height of 170.0 cm, the distance from the 4.3-inch display to the driver's eyes was 59.3 cm. The vertical visual angle from the driver's eyes to the 4.3-inch display was 13.9 degrees. And the horizontal visual angle from the driver's eyes to the 4.3-inch display was 29.1 degrees. The actual figure shown in the 4.3-inch display was a rectangle 9.3 cm wide and 5.7 cm high. The actual diameters of the displayed dot in the 4.3-inch display was 1.8 cm.

A total of five experimental conditions were prepared to evaluate driver behaviors, as shown in the Table 4.1. To evaluate the influence of ground traffic lights, drivers completed driving tasks without in-vehicle traffic signals (Condition 1). Two modes of in-vehicle traffic signals (Current, Predicted) and two kinds of in-vehicle device (Head-up display, 4.3-inch display) were applied during the experiment.

Table 4.1. Experimental conditions.

Condition	Ground traffic lights	In-vehicle traffic signals	Device
Condition 1	On	None	None
Condition 2	On	Current mode	Head-up display
Condition 3	On	Current mode	4.3-inch display
Condition 4	On	Predicted mode	Head-up display
Condition 5	On	Predicted mode	4.3-inch display

All the participants received an explanation of the operation of the in-vehicle traffic signals, and were given the opportunity to practice operating the driving simulator prior to data collection. Each subject was required to drive five times, with each time under one different experimental condition and all the five experimental conditions were completed in a random order. Meanwhile, the driving route was also chosen from the three routes each time for the subject, and it was ensured that two different routes were used in two consecutive experiments.

Measured variables and data analysis

Operational and driving data, including the positions, driving velocities, and brake strokes of vehicles were collected to evaluate the driving operations.

At signalized intersections, the driving safety is normally ensured by the ground traffic lights. Therefore, for the application of in-vehicle traffic signals at signalized intersections, the analysis will be mainly focused on its influences on driving operations. Two indexes—acceleration operations and braking operations—were used to evaluate the driving operations at intersections.

For the evaluation of eye-gaze behaviors, eye-gaze vectors and eye positions were recorded using the Smart Eye Pro system. This enabled us to calculate two measures—glance frequency and mean glance duration. Glance frequency is the total number of glances made to the display device during one driving task. The mean glance duration refers to the average value of the glance duration from the instant when the gaze moves to the head-up display to the instant that the gaze moves away from it.

All the participants were required to complete a 5-point scale measurement questionnaire to investigate reliability, and distraction avoidance. Evaluation scores ranged from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high.

Statistical analysis were conducted to distinguish the significant influential factors affecting driving operations and eye-gaze behaviors in the 11 participants.

For the driving operations and eye-gaze behaviors, a two-way repeated measures ANOVA were conducted with the mode of in-vehicle traffic signal (current or predicted) and in-vehicle devices (4.3-inch display or head-up display) as two within-subject factors. The significance level was set at 0.05. A Friedman one-way nonparametric ANOVA and a Wilcoxon signed-rank test were conducted to analyze the results of the subjective evaluation.

4.1.2. Results of driving simulator experiments at signalized intersections

Acceleration and braking operations

Evaluations of driver behaviors were performed mainly on driving operations, including the braking and accelerating, the driving time and eye-gaze behaviors. Dependent measures in this study were defined as follows: the number of braking operations was defined as the total number of braking operations during one driving task, not counting the last braking operation to stop the vehicle after the driving experiment was completed.

Similarly, the number of accelerating operations was defined as the total number of accelerating operations during one driving task. The driving time was collected as the total driving time from the moment when a participant was required to start driving to the moment when the participant was required to stop the vehicle during one driving task.

Evaluations of eye-gaze behaviors were performed based on the analysis of glance frequency and mean single glance time. As explained in the last paragraph, glance frequency is defined as the total number of glances made to the display device during one driving task. Mean single glance time refers to the mean glance duration, in seconds, from the instant when gaze moves to the device to the instant it moves away from the device during one driving task.

According to the experimental conditions, the effects of two factors (mode of in-vehicle traffic signals and in-vehicle device) were tested. To investigate the influence on driving operations of both factors at the 0.05 level of significance, a two-way repeated ANOVA with the mode of in-vehicle traffic signals (Current, Predicted) and in-vehicle display device (4.3-inch, Head-up) as within-subject factors was performed, comprising a 2×2 design.

The results of the ANOVA analysis of braking operations are presented in Fig. 4.4. A non-significant interaction existed between the mode of in-vehicle traffic signals and in-vehicle device ($p > 0.05$). There was a significant main effect of the mode of in-vehicle traffic signals ($F(1,10) = 29.78$, $p < 0.001$) and a non-significant main effect of in-vehicle device ($F(1,10) = 0.242$, $p = 0.633$).

A similar ANOVA analysis was conducted for the accelerating operations. As shown in Fig. 4.5, a non-significant interaction existed between the mode of in-vehicle traffic signals and in-vehicle device ($p > 0.05$). A significant main effect of the mode of in-vehicle traffic signals ($F(1,10) = 9.988$, $p = 0.01$) and a non-significant main effect of in-vehicle device ($F(1,10) = 3.135$, $p = 0.107$) was found in the two-way repeated ANOVA.

Based on the results of the two-way repeated ANOVA analysis as shown in Figs. 4.4 and 4.5, a non-significant main effect of in-vehicle device on both the braking and accelerating operations was observed.

As shown in Fig. 4.6, when the head-up display was applied (conditions 1, 2, and 4), the influence of different modes of in-vehicle traffic signals on braking operations were investigated. A one-way ANOVA with the same in-vehicle display (Head-up) and three different modes of in-vehicle traffic signals (None, Current, Predicted) was performed. The data satisfied the requirement of homogeneity of variance ($p > 0.05$).

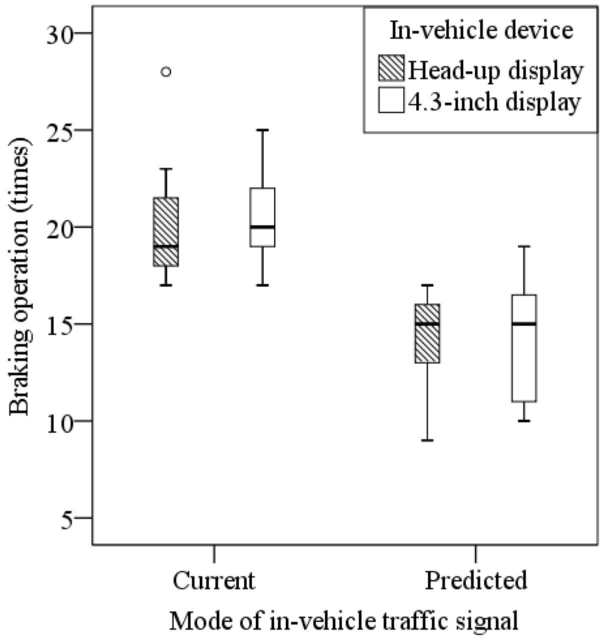

Fig. 4.4. Braking operations. A rectangle represents the middle fifty percent of a set of data. A horizontal line drawn through a rectangle corresponds to the median value of a set of data. An upper bar indicates the maximum value of a set of data, excluding outliers. A lower bar represents the minimum value of a set of data, excluding outliers. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range).

No significant difference in braking operations was found when current mode was applied compared with that of no in-vehicle traffic signal (p = 0.119). In contrast, a significant difference in braking operations was observed when predicted mode was applied compared with the conditions when no in-vehicle traffic signal was used ($p <$ 0.001) and when current mode was applied ($p <$ 0.001).

When the 4.3-inch display was chosen as the in-vehicle device (conditions 1, 3, and 5), the influence of different modes of in-vehicle traffic signals on braking operations were investigated as shown in the Fig. 4.7. A one-way ANOVA with the same in-vehicle display (4.3-inch) and three different modes of in-vehicle traffic signals (None, Current, Predicted) was performed. The data satisfied the requirement of homogeneity of variance ($p >$ 0.05).

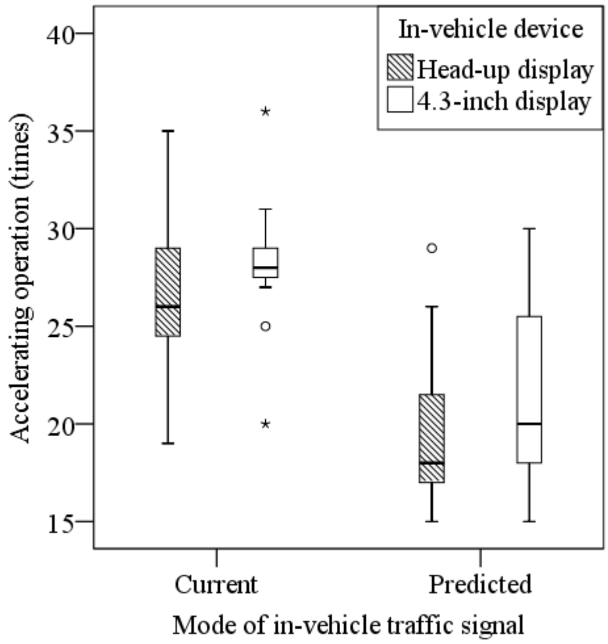

Fig. 4.5. Accelerating operations. A rectangle represents the middle fifty percent of a set of data. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range). Extreme outliers are indicated by stars (calculated as >3x the interquartile range)

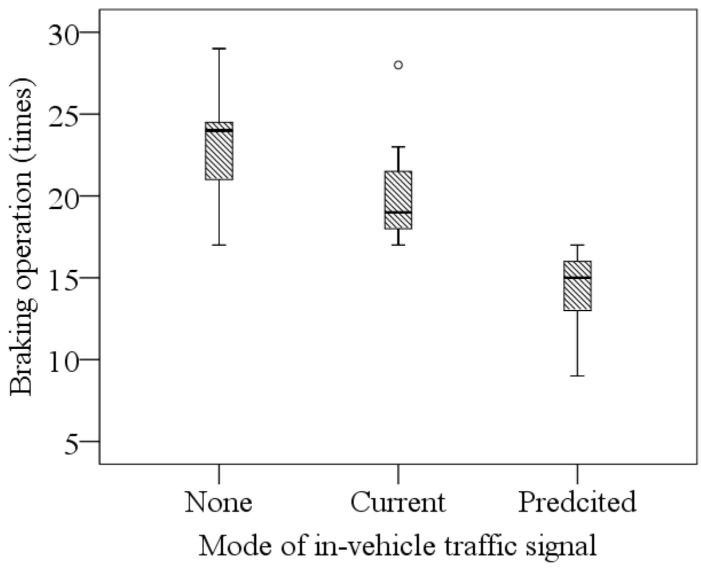

Fig. 4.6. Braking operations in three different modes of in-vehicle traffic signals when the head-up display was applied. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range)

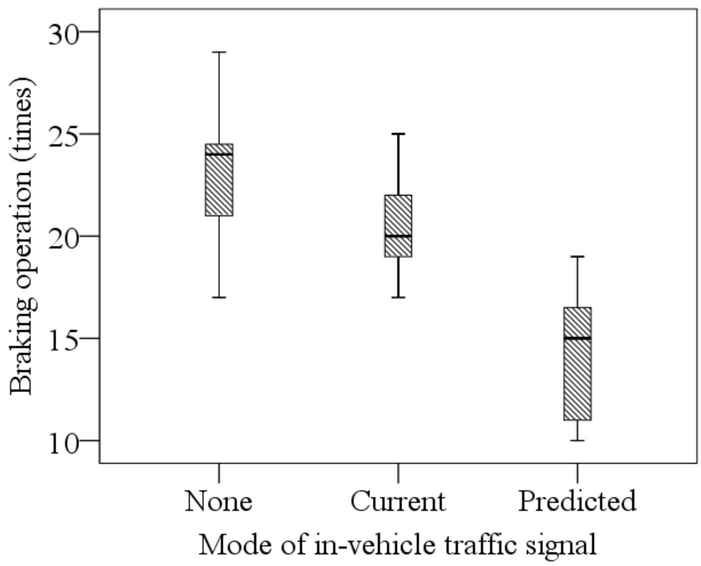

Fig. 4.7. Braking operations in three different modes of in-vehicle traffic signals when the 4.3-inch display was applied.

No significant difference in braking operations was found when current mode was applied compared with that of no in-vehicle traffic signal (p = 0.201). However, a significant difference in braking operations was observed when predicted mode was applied compared with the conditions when no in-vehicle traffic signal was used (p < 0.001) and when current mode was applied (p < 0.001).

Accelerating operations were analyzed in the same manner as braking operations. As presented in Fig. 4.8, when the head-up display was applied (conditions 1, 2, and 4), the influence of different modes of in-vehicle traffic signals on accelerating operations were investigated. A one-way ANOVA with the same in-vehicle display (Head-up) and three different modes of in-vehicle traffic signals (None, Current, Predicted) was performed. The data satisfied the requirement of homogeneity of variance (p > 0.05).

No significant difference in accelerating operations was found when current mode was applied compared with that of no in-vehicle traffic signal (p = 0.361). In contrast, a significant difference in accelerating operations was observed when predicted mode was applied compared with the condition when no in-vehicle traffic signal was applied (p < 0.001). Meanwhile, the accelerating operations were significantly reduced when the predicted mode was applied compared with the current mode (p = 0.01).

The acceleration results are reported in Fig. 4.9 for the conditions in which the 4.3-inch display was chosen as the in-vehicle device (conditions 1, 3, and 5). A one-way ANOVA with the same in-vehicle display (4.3-inch) and three different modes of in-vehicle traffic lights (None, Current, Predicted) was performed. The data satisfied the requirement of homogeneity of variance ($p > 0.05$).

No significant difference in accelerating operations was found when current mode was applied compared with that of no in-vehicle traffic signal ($p = 0.772$). However, a significant difference in accelerating operations was observed when predicted mode was applied compared with the conditions with no in-vehicle traffic signal ($p = 0.002$) and when current mode was applied ($p = 0.01$).

The travel time of drivers was collected for different conditions. Under the condition 1 (ground traffic lights only), the mean travel time was 504 s, ranging from 393 s to 673 s. Under the condition 2 (current mode of in-vehicle traffic signals, displayed by the head-up display), the mean travel time was 501 s, ranging from 366 s to 646 s. Under the condition 3 (current mode of in-vehicle traffic signals, displayed by the 4.3-inch display), the mean travel time was 472 s, ranging from 365 s to 562 s. Under the condition 4 (predicted mode of in-vehicle traffic signals, displayed by the head-up display), the mean travel time was 451 s, ranging from 384 s to 478 s. Under the condition 5 (predicted mode

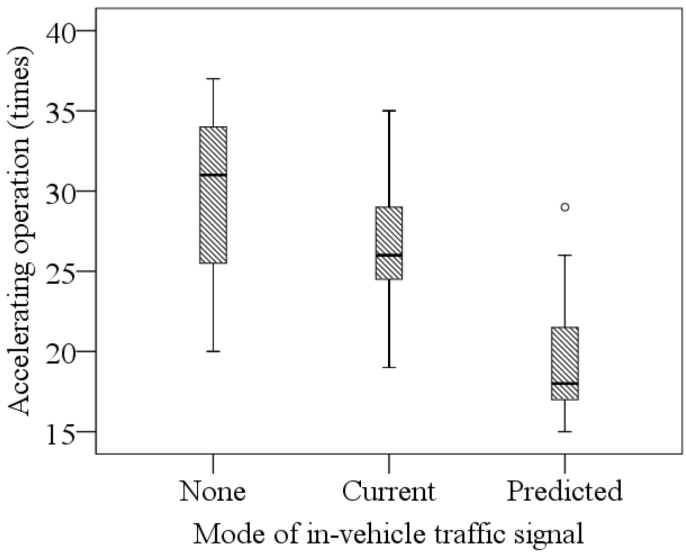

Fig. 4.8. Accelerating operations in three different modes of in-vehicle traffic signals when the head-up display was applied. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range).

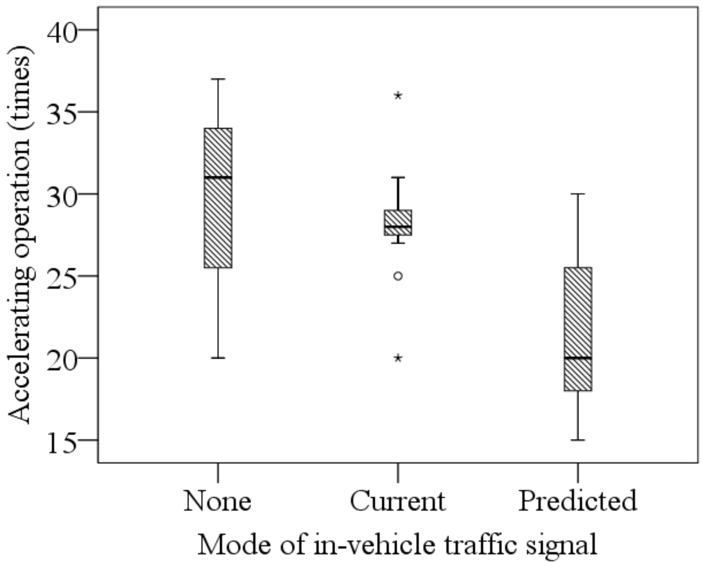

Fig. 4.9. Accelerating operations in three different modes of in-vehicle traffic signals when the 4.3-inch display was applied. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range). Extreme outliers are indicated by stars (calculated as >3x the interquartile range).

of in-vehicle traffic signals, displayed by the 4.3-inch display), the mean travel time was 475 s, ranging from 390 s to 565 s.

According to the experimental conditions, the effects of two factors (mode of in-vehicle traffic signals and in-vehicle device) were tested. To investigate the influence on driving time of both factors at the 0.05 level of significance, a two-way repeated ANOVA with the mode of in-vehicle traffic signals (Current, Predicted) and in-vehicle display device (4.3-inch, Head-up) as within-subject factors was performed. The results of the ANOVA analysis indicated that a non-significant interaction existed between the mode of in-vehicle traffic signals and in-vehicle device ($p > 0.05$). There was a non-significant main effect of the mode of in-vehicle traffic signals ($p = 0.147$) and a non-significant main effect of in-vehicle device ($p = 0.878$).

As shown in Fig. 4.10, when the head-up display was applied (conditions 1, 2, and 4), the influence of different modes of in-vehicle traffic signals on travel time were investigated. A one-way ANOVA with the same in-vehicle display (Head-up) and three different modes of in-vehicle traffic signals (None, Current, Predicted) was performed. The data satisfied the requirement of homogeneity of variance ($p > 0.05$).

No significant difference in travel time was found when current mode was applied compared with that of no in-vehicle traffic signal ($p = 0.796$). In contrast, a significant difference in travel time was observed when predicted mode was applied compared with the conditions when no in-vehicle traffic signal was used ($p < 0.05$) and when current mode was applied ($p < 0.05$).

The average speed results are reported in Fig. 4.11 for the conditions in which the head-up display was chosen as the in-vehicle device (conditions 1, 2, and 4). A one-way ANOVA with the same in-vehicle display (Head-up) and three different modes of in-vehicle traffic lights (None, Current, Predicted) was performed. The data satisfied the requirement of homogeneity of variance ($p > 0.05$).

No significant difference in average speed was found when current mode was applied compared with that of no in-vehicle traffic signal ($p = 0.661$). However, a significant difference in average speed was observed when predicted mode was applied compared with the conditions with no in-vehicle traffic signal ($p = 0.001$) and when current mode was applied ($p = 0.024$).

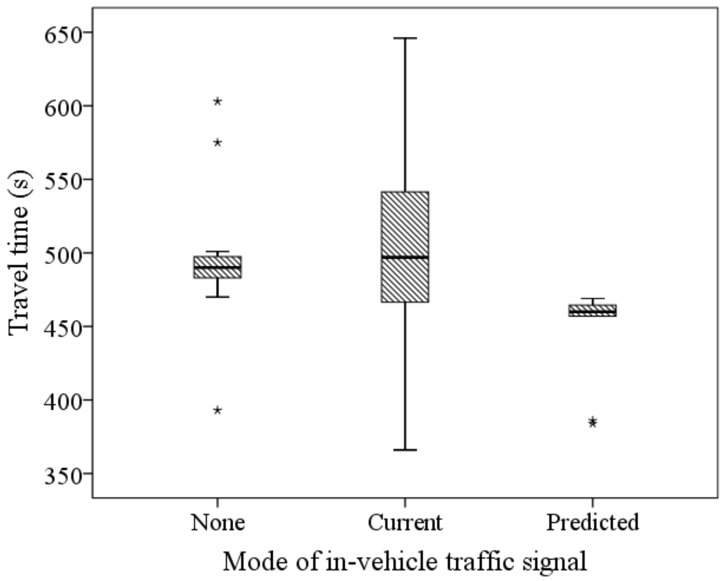

Fig. 4.10. Travel time in three different modes of in-vehicle traffic signals when the head-up display was applied. Extreme outliers are indicated by stars (calculated as >3x the interquartile range).

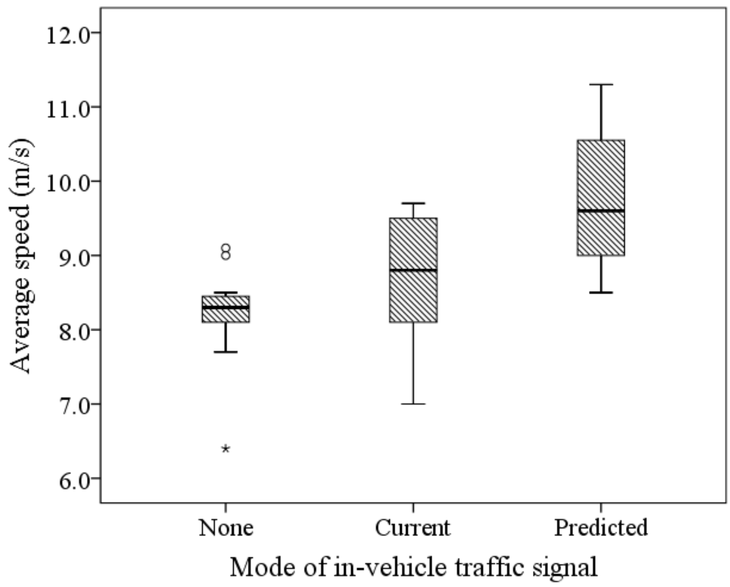

Fig. 4.11. Average speed in three different modes of in-vehicle traffic signals when the head-up display was applied. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range). Extreme outliers are indicated by stars (calculated as >3x the interquartile range).

Glance frequency and mean glance time

The analysis result of glance frequency is illustrated in Fig. 4.12 with a clustered boxplot. At the 0.05 level of significance, a two-way repeated ANOVA with mode of in-vehicle traffic signals (Current, Predicted) and in-vehicle display devices (4.3-inch, Head-up) as within-subject factors was conducted, comprising a 2×2 design.

There was a significant main effect of the mode of in-vehicle traffic signals ($F(1,10) = 5.57$, $p = 0.04$) and a significant main effect of in-vehicle device ($F(1,10) = 32.77$, $p < 0.001$). However, a significant interaction existed between the mode of in-vehicle traffic signals and in-vehicle device ($F(1,10) = 13.94$, $p = 0.004$). Therefore, simple effects should be investigated.

When in-vehicle traffic signals were in the current mode, a significant main effect of in-vehicle device was observed ($F(1,10) = 17.42$, $p = 0.002$). Meanwhile, when in-vehicle traffic signals were in the predicted mode, a significant main effect of in-vehicle device was also found ($F(1,10) = 35.50$, $p < 0.001$).

When the head-up display was used to display in-vehicle traffic signals, there was a significant main effect of the mode of in-vehicle traffic signals ($F(1,10) = 11.02$, $p = 0.008$). However, when the 4.3-inch display was applied, a non-significant main effect of the mode of in-vehicle traffic signals was observed ($F(1,10) = 0.15$, $p = 0.711$).

The mean single glance time was calculated and shown in Fig. 4.13. At the 0.05 level of significance, a two-way repeated ANOVA with the mode of in-vehicle traffic signals (Current, Predicted) and in-vehicle display device (4.3-inch, Head-up) as within-subject factors was conducted, comprising a 2×2 design. A non-significant interaction existed between the mode of in-vehicle traffic signals and in-vehicle display device ($F(1,10) = 0.198$, $p = 0.666$). There was a non-significant main effect of the mode of in-vehicle traffic signals ($F(1,10) = 0.694$, $p = 0.424$). Conversely, a significant main effect of in-vehicle display device was found ($F(1,10) = 121.48$, $p < 0.001$).

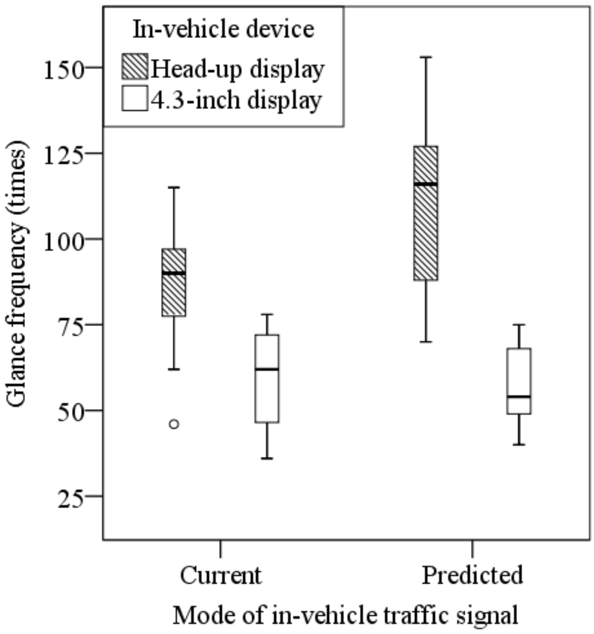

Fig. 4.12. Glance frequency. A rectangle represents the middle fifty percent of a set of data. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range).

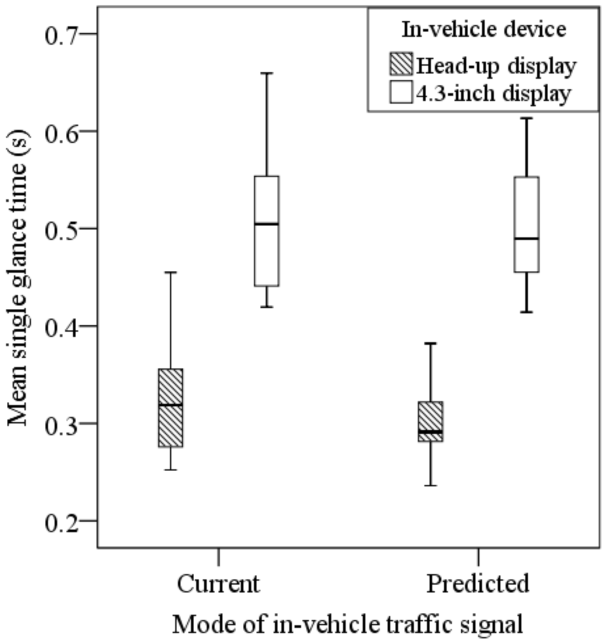

Fig. 4.13. Mean single glance time. A rectangle represents the middle fifty percent of a set of data.

Subjective evaluations at signalized intersections

Subjective evaluations were performed for all the participants. As for the choice of mode, seven of the total eleven participants gave their preferences to the predicted mode, two participants would like to choose the current mode and two participants evaluated both the current and predicted modes acceptable.

As shown in the Fig. 4.14, for the distraction avoidance evaluations, significant higher scores were given to the head-up display ($p < 0.001$). The participants believed that the usage of head-up display could help the in-vehicle traffic signal system avoid distractions to them.

As shown in Fig. 4.15, for the reliability evaluations, the application of head-up display also obtained significant higher scores ($p = 0.001$). It was considered that the usage of head-up display could make it easier for the participants to feel at ease.

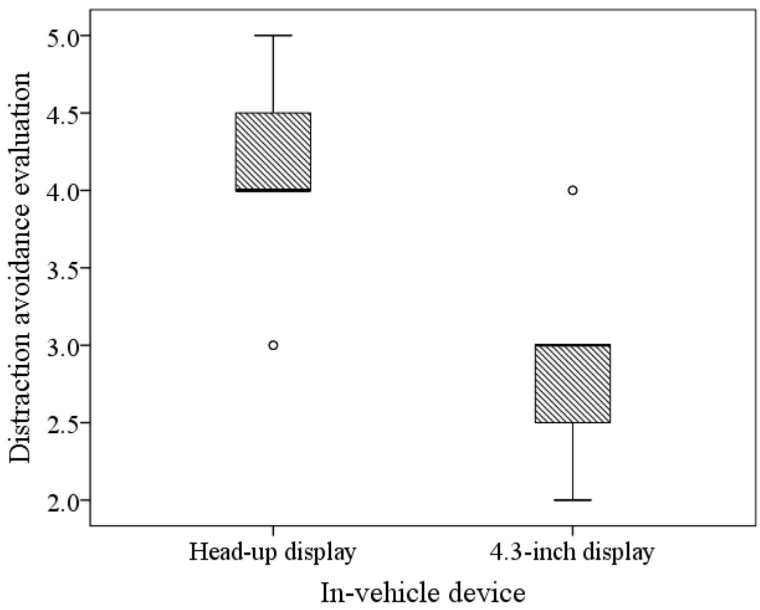

Fig. 4.14. Distraction avoidance evaluation. A rectangle represents the middle fifty percent of a set of data. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range).

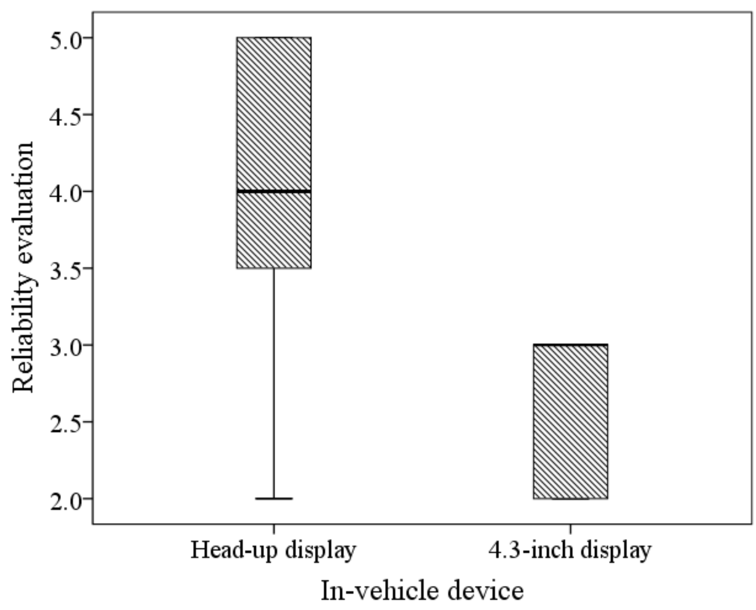

Fig. 4.15. Reliability evaluation. A rectangle represents the middle fifty percent of a set of data.

4.2. Full deployment scenario at unsignalized intersections

4.2.1. Driving simulator experiments at unsignalized intersections

Apparatus applied

An example of the in-vehicle traffic signal system at unsignalized intersections, in which a red signal was displayed to drivers, is presented in Fig. 4.16. The range of in-vehicle traffic signals was set as 80 meters, considering of the quality of vehicular communications and the speed limit of the driving route [94].

Participants of experiment at unsignalized intersections

Twenty-three healthy men, ranging in age from 21 to 40 years (mean age = 25.6 years), participated in this experiment. All participants had a valid driving license and had been driving for an average of 4.6 years, ranging from 1 to 10 years. The participants reported a mean driving frequency of 1.4 times per week, ranging from one to four times. This experiment was performed with the approval of the Office for Life Science Research Ethics and Safety at the University of Tokyo.

Fig. 4.16. Red in-vehicle traffic signal displayed to drivers at an unsignalized intersection.

Unsignalized driving scenario

As shown in Fig. 4.17, the driving route used in this experiment is highlighted in red on the map. There are six unsignalized intersections in the track, including five two-way stop-controlled intersections, I – V, and one all-way stop-controlled intersection, VI.

After departing from the start point, participants were required to move forward on the major road through intersections I and II. As the road connecting intersections II and III was a minor road, participants had to stop at intersection III and then turn right from the minor road to a major road. After completing a right-turn at intersection III, participants crossed intersection IV on the major road and performed a left turn from the major road to a minor road at intersection V. Finally, they passed through intersection VI and stopped the vehicle at the end point.

Conditions of experiment at unsignalized intersection

To investigate the influence of in-vehicle traffic signals with and without auditory cues on driver behaviors, we incorporated an auditory warning system in the driving simulator, which provided audio messages such as "Please stop the car" and "Please start the car" spoken in Japanese.

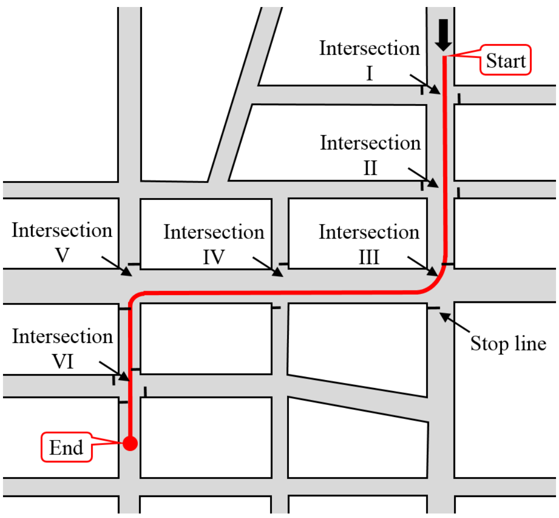

Fig. 4.17. Driving route of the experiment. Two-way stop-controlled intersections: I, II, III, IV, and V; All-way stop-controlled intersection: VI

Table 4.2 Experimental conditions.

Condition	In-vehicle traffic signal	Auditory warning
Condition 1	Signal-off	Audio-off
Condition 2	Signal-off	Audio-on
Condition 3	Signal-on	Audio-off
Condition 4	Signal-on	Audio-on

The experiment was performed under four conditions, as presented in Table 4.2. There were two in-vehicle traffic signal conditions: signal-off and signal-on, and two auditory warning conditions: audio-on and audio-off. All participants received driving simulator training before the experiment, and were required to drive under all four conditions (which were presented in a random order) with a speed limit of 40 km/h.

Evaluation indexes

At unsignalized intersections, there is no ground traffic light to manage the traffic flow and guide drivers to pass through the intersections. How to keep the safety of drivers while crossing the unsignalized intersections is one of the most important issues to be considered. Therefore, for the application of in-vehicle traffic signals at unsignalized intersections, the evaluation will be mainly focused on its influences on driving safety. Operational and driving data, including the positions, driving velocities, and brake strokes of vehicles were collected to evaluate the driving operations at intersections III and VI.

As shown in Fig. 4.17, among all the two-way stop-controlled intersections I – V, participants were on the major roads which were not controlled by stop lines at intersections I, II, IV and V. Thus, participants had the passing priority at these intersections. However, for intersection III, participants were on the minor road which was controlled by a stop line. They had to enter the intersection from the minor road to the major road. Therefore, intersection III was the only one two-way stop-controlled intersection where participants had no passing priority. Driving across intersection III was thus considered to be more challenging than driving at intersections I, II, IV, and V. We used two indexes—post-encroachment time and maximum brake stroke—to evaluate the driving operations at intersection III.

Post-encroachment time is defined as the time lag between the passage of an offending vehicle and that of a conflicting vehicle in a conflict area. The offending and conflicting vehicles in this experiment referred to the upcoming major-road vehicle and the vehicle operated by participants, respectively. A smaller post-encroachment time suggests greater risk of collision. It is therefore considered to be a suitable indicator for evaluating driving safety at intersections. The post-encroachment time could be calculated as follows,

$$T_p = \frac{L_n}{v_n} \tag{4.1}$$

where T_p is the post-encroachment time, and L_n and v_n are the instantaneous distance to the conflict area and the current velocity of the upcoming major-road vehicle, respectively.

However, it was possible that the drivers may choose to brake severely for having a larger post-encroachment time to satisfy their subjective safety margin. The maximum brake stroke index should be added for evaluating the driving safety together with the post-encroachment time. The brake stroke variable represented the extent of brake pedal stroke during each trial, and we used its maximum value to evaluate braking performance. The brake stroke data, which ranged from 0 to 1, was recorded by the driving simulator.

Intersection VI was the only all-way stop-controlled intersection in the driving route. We used two indexes, maximum brake stroke and stopping type, to evaluate the driving operations at intersection VI.

The drivers' stopping type at all-way stop-controlled intersections can be classified as either a complete stop or no stop [95]. In this experiment, a complete stop was defined as the condition in which a vehicle reached a velocity of zero before crossing the stop line. Therefore, we were able to calculate the percentage of complete stops based on the position and velocity of the simulated vehicle driven by participants.

For the evaluation of eye-gaze behaviors, eye-gaze vectors and eye positions were recorded using the Smart Eye Pro system. This enabled us to calculate two measures—percent road center and mean glance duration. The percent road center refers to the percentage of gaze that falls within the road center area, which is a circular region with an eight-degree radius located around the driver's most frequent fixation point [96-98].

The mean glance duration refers to the average value of the glance duration from the instant when the gaze moves to the head-up display to the instant that the gaze moves away from it.

All the participants were required to complete a 5-point scale measurement questionnaire to investigate safety, acceptability, and fatigue. Evaluation scores ranged from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high.

Statistical analysis was conducted to distinguish the significant influential factors affecting the post-encroachment time, maximum brake stroke, percent road center, and mean glance duration in the 23 participants. For the post-encroachment time, maximum brake stroke, and percent road center, we conducted a two-way repeated measures ANOVA with the in-vehicle traffic signals (signal-off or signal-on) and auditory warnings (audio-off or audio-on) as two within-subject factors. The significance level was set at 0.05. Therefore, we used a 2×2 factorial design with the combination of signal–off or signal–on and audio–off or audio–on.

For the mean glance duration, we conducted a one-way repeated measures ANOVA with auditory warnings (audio–off or audio–on) as the within-subject factor. Finally, we conducted a Friedman one-way nonparametric ANOVA and a Wilcoxon signed-rank test to analyze the results of the subjective evaluation.

Experiment considering waiting time

For the experiment considering the influences of waiting time at unsignalized intersections, twelve males were involved in the study, ranging from 20 to 30 years old (average 24.5 years old). All the participants had a valid driving license and reported that they were in a good health condition which would not affect the driving performances. They had been driving for 4.7 years on average, ranging from one year to eight years, and had a mean driving frequency of 1.2 times per week, ranging from one time to three times.

It was expected that the driving performances of minor-road drivers would be influenced if their waiting time were considered by the in-vehicle traffic signal system. Meanwhile, the driving safety of major-road drivers should also be assessed as the minor-road vehicles were allowed to enter intersections with smaller major-road gaps while considering waiting time. Therefore, a minor-road and a major-road experiments were prepared for all the participants to evaluate their driver behaviors.

During the minor-road experiment, the participants were required to drive the vehicle *A* to complete a right-turn at the intersection III. As shown in Fig. 4.18, to analyze the influences of waiting time, a congested major-road traffic flow was designed to make the participants wait for more than 30 seconds. Then three major-road gaps $G1$, $G2$ and $G3$ were provided as a chance for the participants to cross the intersection.

To avoid learning effects, three orders of $G1$, $G2$ and $G3$ were prepared as shown in the Table. 4.3. Meanwhile, three assistance conditions were provided for every participant as presented in the Table. 4.4. The orders of $G1$, $G2$ and $G3$ and the assistance conditions were combined for the participants, considering counterbalancing.

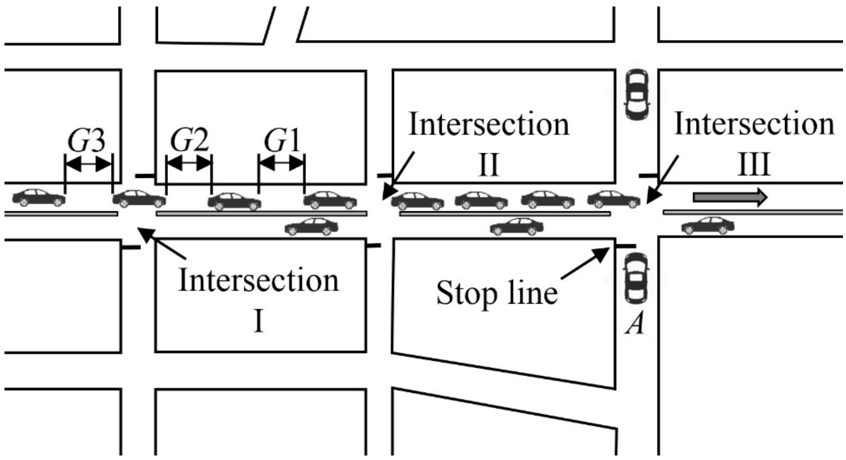

Fig. 4.18. Driving scenario of the minor-road experiment and the participants were in the vehicle *A*.

Table 4.3. Orders of major-road gaps.

Gap	Order 1	Order 2	Order 3
$G1$	5.5 s	6.0 s	6.5 s
$G2$	6.0 s	6.5 s	6.0 s
$G3$	6.5 s	5.5 s	5.5 s

Table 4.4. Assistance conditions of minor-road experiment.

No.	Condition
1	Without in-vehicle traffic signal
2	In-vehicle traffic signal without considering waiting time
3	In-vehicle traffic signal considering waiting time

For major-road drivers, the in-vehicle traffic signal system was expected to warn them the entry of minor-road vehicles at intersections. According to the relationship between the critical gap and waiting time as shown in the Eq. (3.15), the smallest critical gap for the minor-road vehicles was 5 seconds if their waiting time were more than 30 seconds.

To assess the driving safety of major-road drivers, the driving scenario of the major-road experiment is presented in Fig. 4.19. The participants were in the major-road vehicle *B*. Another major-road vehicle *C* was set to keep a gap of 5 seconds with the vehicle *B* until the vehicle *C* crossed the intersection III. At the intersection III, a minor-road vehicle *D* was waiting to make a right-turn. The major-road vehicles before the vehicle *C* were used to make the vehicle *D* wait for more than 30 seconds. After the vehicle *C* crossed the intersection III, the vehicle *D* would accept the gap between the vehicles *B* and *C*, and enter the intersection. The participants in the vehicle *B* were required to react and avoid collisions with the vehicle *D*.

The assistance conditions of the major-road experiment are presented in the Table. 4.5. As the gap of 5 seconds would not be accepted by the in-vehicle traffic signal system without considering waiting time, the driver behaviors under only two conditions were analyzed.

Driving data, including the positions, velocities and accelerations of all the vehicles, were recorded with the driving simulator. Meanwhile, eye-gaze data was also measured with the Smart Eye Pro system.

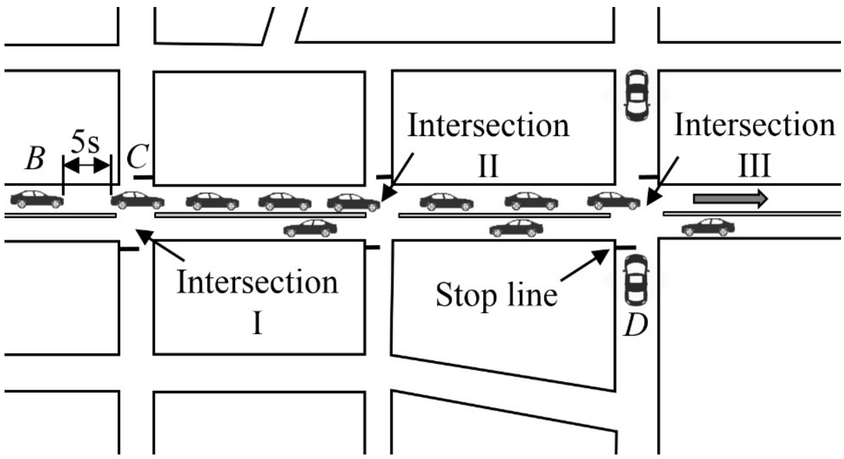

Fig. 4.19. Driving scenario of the major-road experiment and the participants were in the vehicle *B*.

Table 4.5. Assistance conditions of major-road experiment.

No.	Condition
1	Without in-vehicle traffic signal
2	In-vehicle traffic signal considering waiting time

To evaluate driver behaviors in the minor-road experiment, four indexes were applied: maximum gas pedal stroke, blink rate, maximum lateral acceleration and post-encroachment time. For the major-road experiment, perception response time was analyzed, besides the post-encroachment time.

For the maximum gas pedal stroke, previous studies pointed out that acceleration related indexes including maximum acceleration were suitable for evaluating aggressive or emotional driving [99], [100]. Therefore, the maximum extent of accelerate pedal stroke of the vehicle *A* at the intersection III was recorded, ranging from 0 to 1.

The analysis of blink rate was conducted based on the hypothesis that the feeling of frustration could be detected by monitoring the blink rate [101]. Previous studies suggested that the blink rate might be raised with a frustration emotion [102], [103]. Blink rate was then calculated with the waiting time of the participants at the intersection III and the times of blink during the period.

Maximum lateral acceleration was the extreme value of lateral accelerations when the vehicle *A* turned right at the intersection III. It was believed that less maximum lateral accelerations might represent fewer deviations from idealized curved paths during a turn at intersections [104].

Post-encroachment time was the time lag between the passage of an offending vehicle and that of a conflicting vehicle in a conflict area. As shown in the Figs. 4.18 and 4.19, the conflict area referred to the intersection III in this study. During the minor-road experiment, the minor-road vehicle *A* driven by the participants was the offending vehicle. For the major-road experiment, the major-road vehicle *B* operated by the participants acted as the conflicting vehicle.

Perception response time was defined as the total time elapsed from the entry of minor-road vehicle *D* to the brake pedal of major-road vehicle *B* was depressed, as shown in the Fig. 4.19.

Feelings of frustration and task difficulty were evaluated in the minor-road experiment. For the major-road experiment, the feeling of safety was assessed. The evaluation scores were collected using a 5-point scale measurement questionnaire at the conclusion of every experimental session.

Statistical analysis were conducted to distinguish whether the consideration of waiting time significantly affected the driver behaviors and subjective evaluations for the 12 participants. The significance level was set at 0.05.

For the driver behaviors including maximum gas pedal stroke, blink rate, maximum lateral acceleration, and post-encroachment time and perception response time, a one-way repeated measures ANOVA was conducted. For the subjective evaluations, a Wilcoxon signed-rank test was performed.

4.2.2. Results of driving simulator experiments at unsignalized intersections

Post encroachment time and braking operations

To validate the proposed in-vehicle traffic signal system in assisting drivers at unsignalized intersections, driving operations and eye-gaze behaviors were analyzed using carefully selected indexes. Of the available indexes for evaluating driving operations, we used post-encroachment time to evaluate driving safety when participants were inside intersections, and the maximum brake stroke to analyze braking performance before entering intersections. However, it was difficult to calculate the post-encroachment time for intersection VI, because of the low traffic flow at all-way stop controlled intersections. It was considered that the number of conflicts at unsignalized intersections could be reduced when drivers completed stops at the stop line. Therefore, we analyzed stopping types to investigate driving safety at intersection VI. For the evaluation of eye-gaze behaviors, we chose to assess percent road center as it is sensitive to visual distraction, and is the only measure that can be used to compare both visual and auditory tasks with respect to baseline driving performance.

As shown in Fig. 4.20, in terms of post-encroachment time, we found significant main effects of the in-vehicle traffic signals ($F[1, 22] = 43.09$, $p < 0.001$) and the auditory warnings ($F[1, 22] = 5.99$, $p = 0.023 < 0.05$). However, we also observed a significant interaction between the in-vehicle traffic signals and the auditory warnings ($F[1, 22] = 19.56$, $p < 0.001$). Therefore, it was necessary to perform pairwise comparison to analyze the effects of in-vehicle traffic signals on post-encroachment time.

The pairwise comparison analysis revealed that, when there was no auditory warning (audio–off conditions), driving safety might be significantly improved by applying in-vehicle traffic signals as the post-encroachment time was significantly longer for the signal-on condition compared with the signal–off condition ($p < 0.001$). Likewise, when auditory warnings were provided (audio–on conditions), the in-vehicle traffic signals should also be applied to improve driving safety since a significantly longer post-encroachment time was also found for the signal–on condition compared with the signal–off condition ($p < 0.01$).

The results indicated that post-encroachment time was significantly improved by the application of in-vehicle traffic signals. Moreover, the influence of in-vehicle traffic signals on post-encroachment time was not significantly affected by the usage of auditory warnings.

As presented in Fig. 4.21, for the maximum brake stroke at intersection III, which was a two-way stop-controlled intersection, a non-significant interaction existed between the in-vehicle traffic signals and the auditory warnings. We found a significant main effect of the in-vehicle traffic signals ($F[1, 22] = 4.52$, $p = 0.045 < 0.05$) and a non-significant main effect of the auditory warnings, which means that the maximum brake stroke would be significantly influenced by the usage of in-vehicle traffic signals, while not by auditory warnings. According to the pairwise comparison analysis, when there was no auditory warning (audio–off conditions), the in-vehicle traffic signals should be employed to reduce maximum brake stroke as a significantly lower maximum brake stroke was observed for the signal–on condition compared with the signal–off condition ($p = 0.018 < 0.05$).

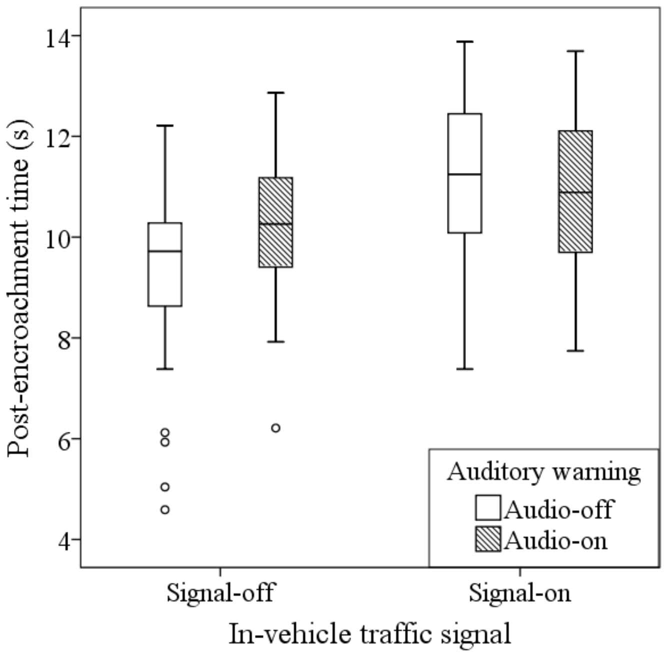

Fig. 4.20. Post-encroachment time at a two-way stop-controlled intersection (intersection III). Circles: mild outliers calculated as 1.5 – 3 × the interquartile range.

As shown in Fig. 4.22, for the maximum brake stroke at intersection VI, which was an all-way stop-controlled intersection, we also found a non-significant interaction between the in-vehicle traffic signals and the auditory warnings. We observed a significant main effect of the in-vehicle traffic signals ($F[1, 22] = 4.50$, $p = 0.045 < 0.05$) and a non-significant main effect of the auditory warnings. According to the pairwise comparison analysis, when no auditory warning was offered to drivers (audio–off conditions), the maximum brake stroke could be significantly reduced by applying in-vehicle traffic signals since the maximum brake stroke was significantly lower for the signal–on condition compared with the signal–off condition ($p = 0.002 < 0.05$).

These results suggest that the maximum brake stroke was significantly decreased by the in-vehicle traffic signals. Furthermore, we did not observe a significant difference in the maximum brake stroke between the conditions in which the in-vehicle traffic signals were used with or without auditory warnings.

At the intersection VI, the participants made a complete stop 69.57% of the time in the signal–off with audio–off condition. In contrast, the participants performed complete stops 82.61% of the time in the signal–off with audio–on condition, and 86.96% of the time in the signal–on with audio–off condition. For the signal-on with audio–on condition,

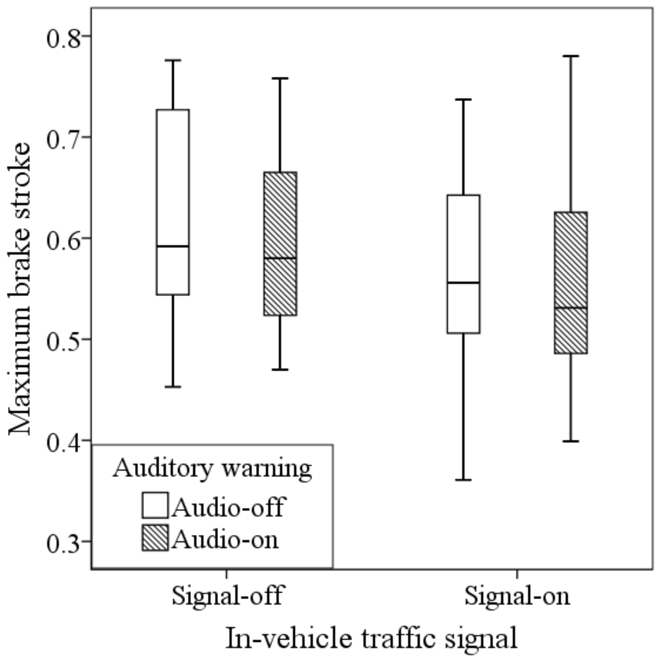

Fig. 4.21. Maximum brake stroke at a two-way stop-controlled intersection (intersection III).

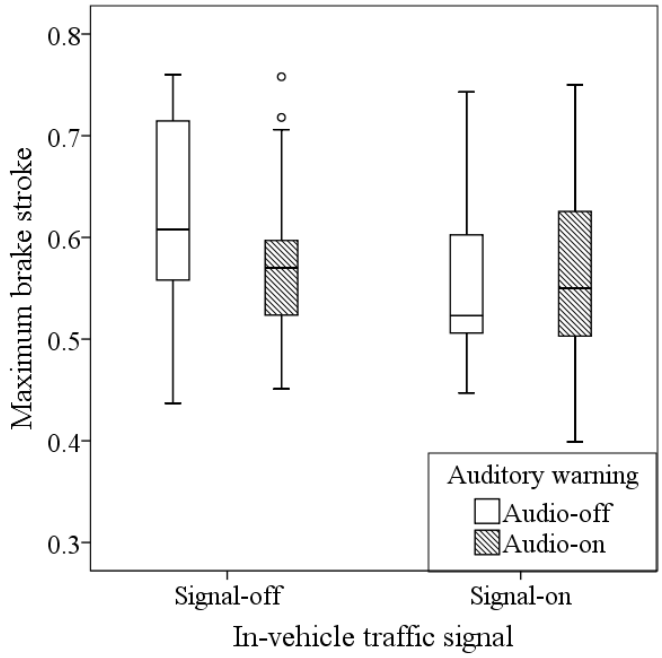

Fig. 4.22. Maximum brake stroke at an all-way stop-controlled intersection (intersection VI). Circles: mild outliers calculated as 1.5 – 3 × the interquartile range.

the participants performed a complete stop 91.30% of the time before crossing the stop line. The results indicate that the application of in-vehicle traffic signals might prompt drivers to make complete stops at unsignalized intersection.

Eye-gaze behaviors

As presented in Fig. 4.23, for the percent road center, we found a non-significant interaction between the in-vehicle traffic signals and the auditory warnings. Additionally, we found non-significant main effects of the in-vehicle traffic signals and the auditory warnings. Thus, the percentage of the participant's gaze falling within the road center area was not significantly affected by the application of in-vehicle traffic signals and auditory warnings, although an increasing trend was observed in the audio-on conditions.

As shown in Fig. 4.24, for the mean glance duration to the head-up display, we found no significant difference between the signal–on with audio–off and signal–on with audio–on conditions. Meanwhile, the maximum values of mean glance duration under both conditions were smaller than 0.6 s.

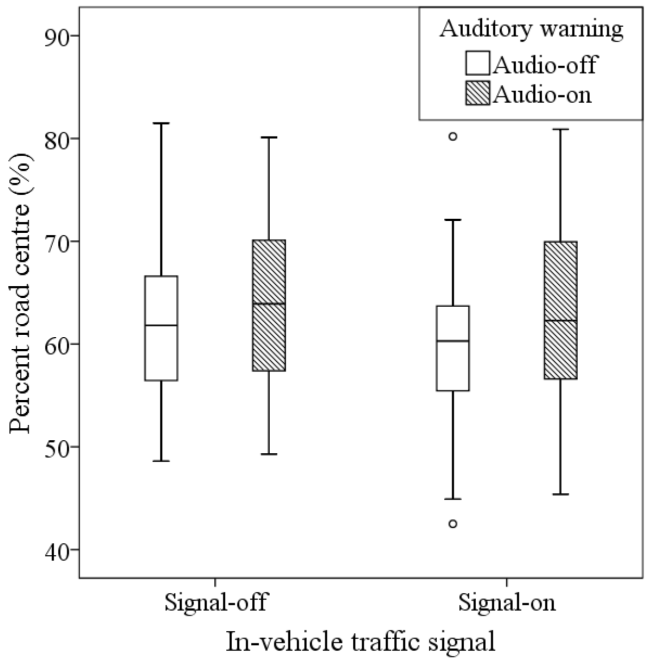

Fig. 4.23. Percent road center. Circles: mild outliers calculated as 1.5 – 3 × the interquartile range.

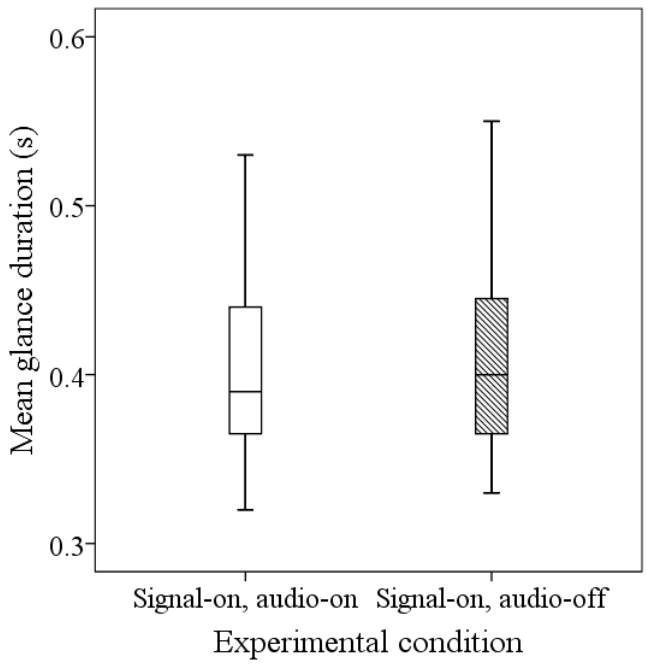

Fig. 4.24. Mean glance duration to the in-vehicle traffic signals.

Subjective evaluations of safety and acceptability

As demonstrated in Fig. 4.25, for the safety evaluation scores, we found a significant main difference among the four conditions ($F_r[3, 23]$ = chi-squared = 34.42, $p < 0.001$). Furthermore, when there was no auditory warning, drivers felt much safer to be assisted by the in-vehicle traffic signals as the pairwise comparison analysis revealed a significantly higher score in the signal–on with audio–off condition compared with that in the signal–off with audio–off condition ($z[23] = -3.83$, $p < 0.001$).

As shown in Fig. 4.26, for the acceptability evaluation scores, a significant main difference was also found among the four conditions ($F_r[3, 23]$ = chi-squared = 48.11, $p < 0.001$). Moreover, when auditory warnings were not applied, the usage of in-vehicle traffic signals was highly regarded by drivers as a significantly higher score was found in the signal–on with audio–off condition compared with that in the signal–off with audio–off condition ($z[23] = -3.93$, $p < 0.001$).

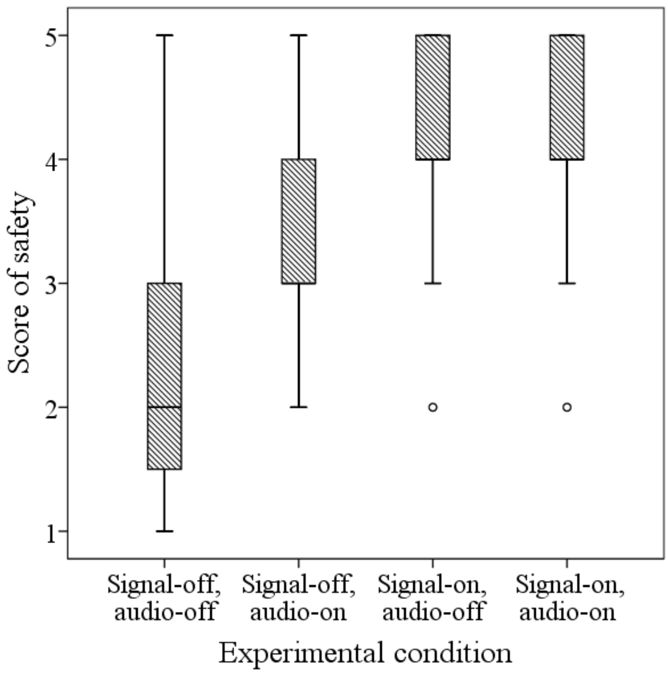

Fig. 4.25. Score of safety. Evaluation scores ranging from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high. Circles: mild outliers calculated as 1.5 – 3 × the interquartile range.

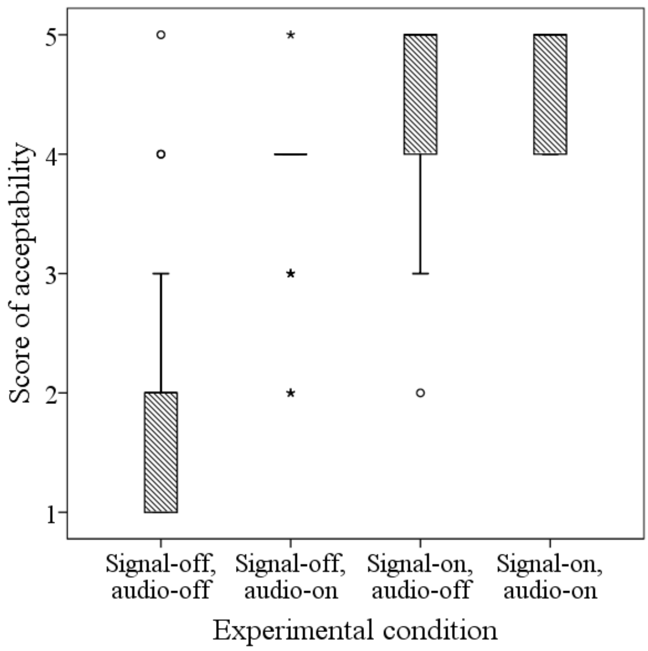

Fig. 4.26. Score of acceptability. Evaluation scores ranging from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high. Circles: mild outliers calculated as 1.5 – 3 × the interquartile range. Stars: extreme outliers calculated as > 3 × the interquartile range.

As illustrated in Fig. 4.27, for the fatigue evaluation scores, we found a significant main difference among the four conditions ($F_r[3, 23]$ = chi-squared = 39.85, $p < 0.001$). Meanwhile, for the conditions without auditory warnings, drivers found it much more difficult to feel fatigued with driving when they were assisted by in-vehicle traffic signals, since a significantly higher score was observed in the signal–on with audio–off condition compared with that in the signal–off with audio–off condition ($z[23] = -3.56$, $p < 0.001$).

These results indicate that the in-vehicle traffic signals were evaluated as performing well in terms of safety, acceptability, and fatigue. Additionally, the subjective evaluation scores did not significantly increase when the in-vehicle traffic signals were supplemented with auditory warnings.

Influences of waiting time on driver behaviors

The maximum gas pedal stroke was used in the minor-road experiment for analyzing the acceleration behaviors of the participants at the intersection III. As presented in the

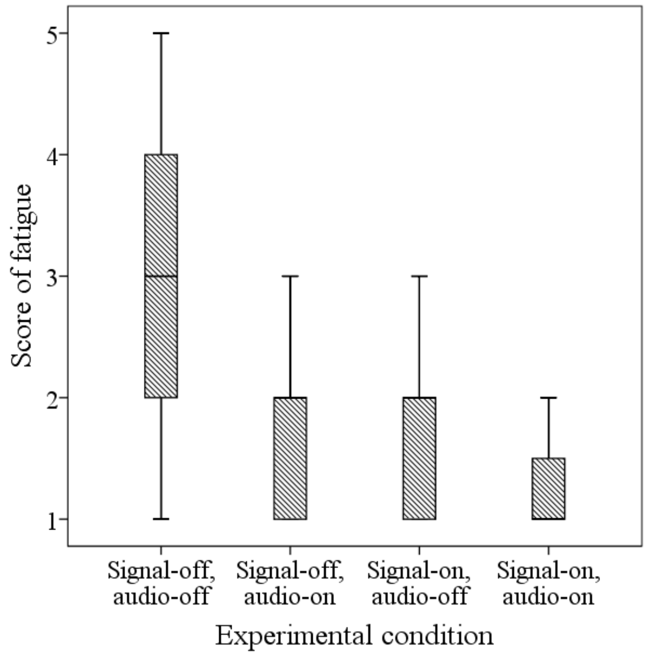

Fig. 4.27. Score of fatigue. Evaluation scores ranging from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high.

experiment introduction part, the maximum gas pedal stroke, which is an index related with acceleration, is considered suitable for evaluating aggressive or emotional driving. A higher value of maximum gas pedal stroke indicates a higher possibility of aggressive driving.

As presented in Fig. 4.28, there was no significant difference existed in the maximum gas pedal stroke between the conditions when there was no in-vehicle traffic signal and that when in-vehicle traffic signal without considering waiting time was used, although a decreasing trend could be observed. For the results when the in-vehicle traffic signal considering waiting time was applied, a significant decrease could be found, compared to the condition without in-vehicle traffic signals ($p = 0.001 < 0.05$).

The blink rate was used for analyzing the mental states of drivers during the minor-road experiment. It was expected that the feeling of frustration could be detected by monitoring the blink rate, and the blink rate might be raised with a frustration emotion. Therefore, a higher blink rate might be considered as the result of frustration.

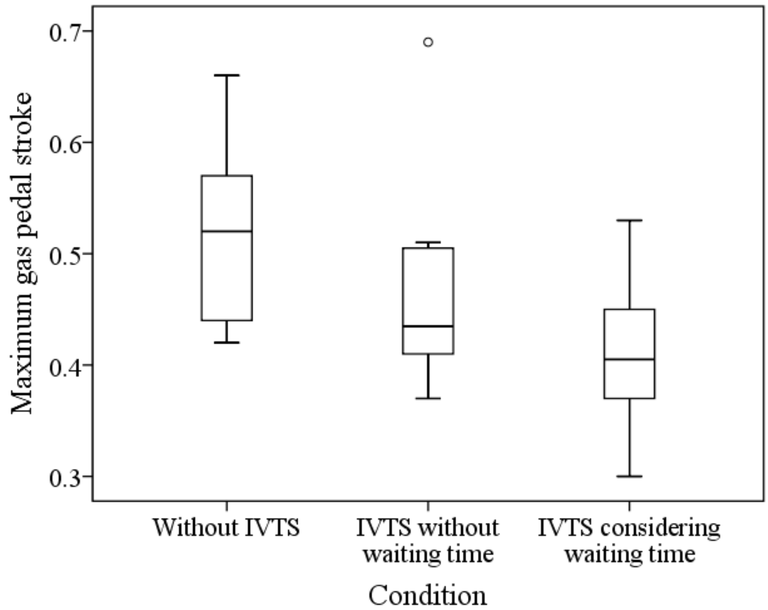

Fig. 4.28. Results of maximum gas pedal stroke in the minor-road experiment. IVTS is short for in-vehicle traffic signals.

As presented in Fig. 4.29, when the in-vehicle traffic signal considering waiting time was applied, the blink rate significantly decreased, compared to that of in-vehicle traffic signal without considering waiting time (p = 0.033 < 0.05). Meanwhile, a significant difference in the blink rate was observed between the conditions when no in-vehicle traffic signal was offered and that of in-vehicle traffic signal considering waiting time (p = 0.044 < 0.05). There was no significant difference between the conditions when no in-vehicle traffic signal was provided and that of in-vehicle traffic signal without considering waiting time. The results of blink rate revealed that the frustration emotion of drivers might be significantly reduced with the application of in-vehicle traffic signal considering waiting time.

The maximum lateral acceleration was applied to evaluate the steering stability in the minor-road experiment. A lower value of maximum lateral acceleration indicates a better steering performance.

As shown in Fig. 4.30, the maximum lateral acceleration of the minor-road vehicle was significantly reduced by using the in-vehicle traffic signal considering waiting time, compared to that without the consideration of waiting time (p = 0.049 < 0.05). A significant difference was also observed between the conditions when there was no in-

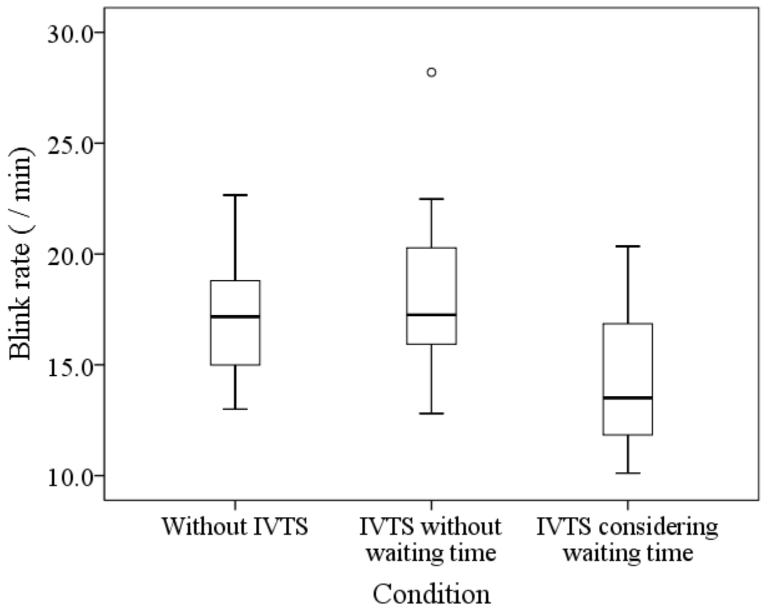

Fig. 4.29. Results of blink rate in the minor-road experiment. IVTS is short for in-vehicle traffic signals.

vehicle traffic signal and that of in-vehicle traffic signal without considering waiting time ($p = 0.043 < 0.05$).

The post-encroachment time were calculated for evaluating the driving safety in both the minor-road and major-road experiments. The results of the minor-road experiment were presented in Fig. 4.31. The application of in-vehicle traffic signal considering waiting time significantly increased the post-encroachment time, compared to that when no in-vehicle traffic signal was provided ($p = 0.01 < 0.05$). Meanwhile, there was no significant difference in the post-encroachment time between the in-vehicle traffic signals with and without the consideration of waiting time.

For the results of the major-road experiment, as shown in the Fig. 4.32, when the in-vehicle traffic signal considering waiting time was adopted, the post-encroachment time was significantly improved with a mean value of 5.5 seconds, compared to that without in-vehicle traffic signals ($p = 0.037 < 0.05$).

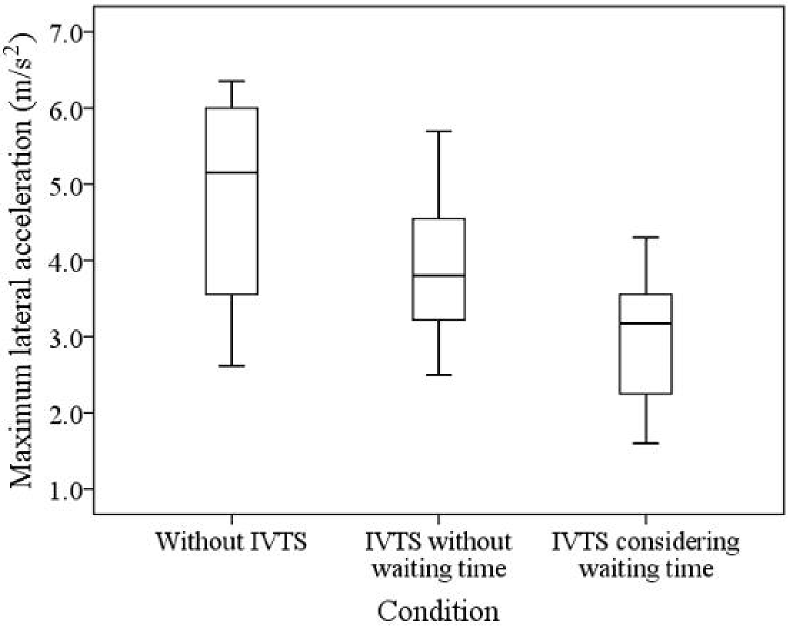

Fig. 4.30. Results of maximum lateral acceleration in the minor-road experiment. IVTS is short for in-vehicle traffic signals.

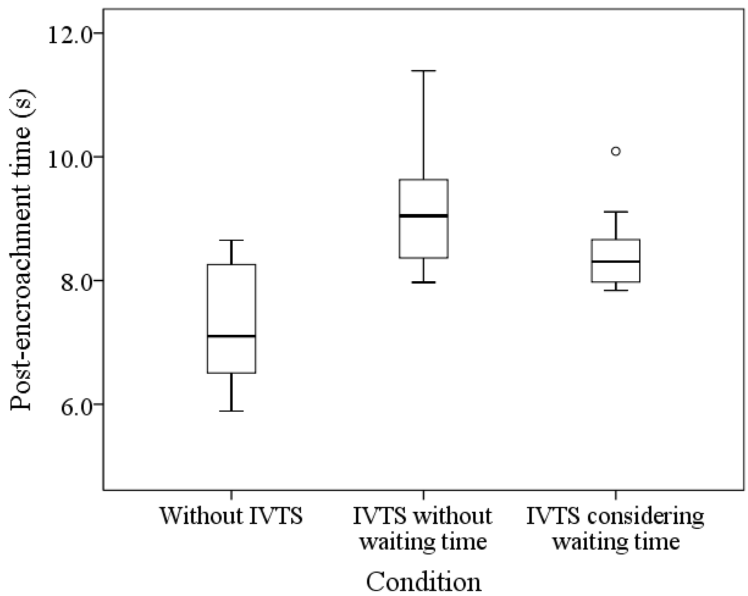

Fig. 4.31. Results of post-encroachment time in the minor-road experiment. IVTS is short for in-vehicle traffic signals.

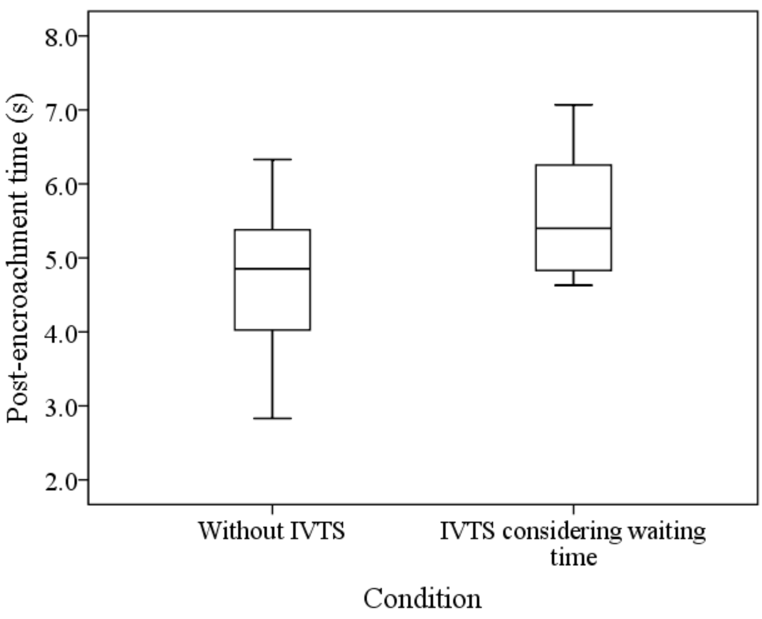

Fig. 4.32. Results of post-encroachment time in the major-road experiment. IVTS is short for in-vehicle traffic signals.

A larger post-encroachment time indicates a smaller possibility of collision at intersections. Therefore, it suggests that the driving safety in the minor-road experiment might not be significantly influenced when the waiting time was considered. For the major-road experiment, the results implied that the driving safety of major-road drivers could be ensured, when the smallest critical gap of 5 seconds was accepted by minor-road vehicles with the application of in-vehicle traffic signal considering waiting time.

The perception response time was applied to evaluate the driver reactions to the entry of minor-road vehicles in the major-road experiment. A smaller perception response time indicates a faster reaction to the entry of minor-road vehicles. It can be observed from Fig. 4.33 that, the perception response time was significantly reduced when the in-vehicle traffic signal considering waiting time was used ($p = 0.002 < 0.05$).

The frustration evaluation was performed to analyze the mental conditions of drivers in the minor-road experiment. As shown in Fig. 4.34, the participants felt significant more frustrated when there was no in-vehicle traffic signal, compared to that when the in-vehicle traffic signal without considering waiting time was applied ($p = 0.002 < 0.05$).

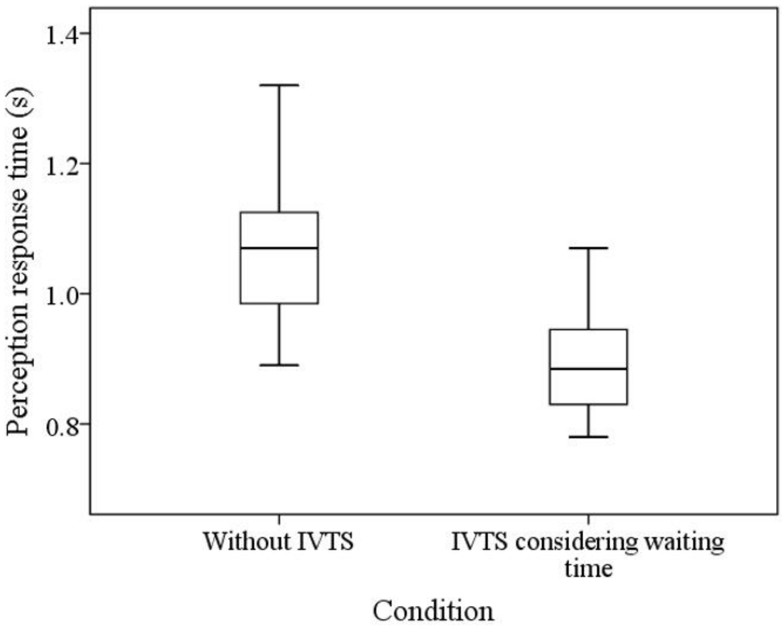

Fig. 4.33. Results of perception response time in the major-road experiment. IVTS is short for in-vehicle traffic signals.

Moreover, the feelings of frustration were significantly reduced when the in-vehicle traffic signal considering waiting time was used, compared to that without the consideration of waiting time ($p < 0.001$).

The difficulties of completing the same driving task under different assistance conditions were evaluated in the minor-road experiment. As presented in Fig. 4.35, although the participants were required to turn right at the same intersection, they felt that it was significant more difficult to complete the driving task without the in-vehicle traffic signal, compared to the other two conditions ($p < 0.001$). No significant difference in task difficulty evaluation was observed between the in-vehicle traffic signals with and without the consideration of waiting time.

For the major-road experiment, the results of driving safety evaluation of major-road drivers were demonstrated in Fig. 4.36. A significant difference was observed between the conditions when there was no in-vehicle traffic signal and that of in-vehicle traffic signal considering waiting time ($p < 0.001$), indicating that the participants felt much safer when assisted by the in-vehicle traffic signal considering waiting time.

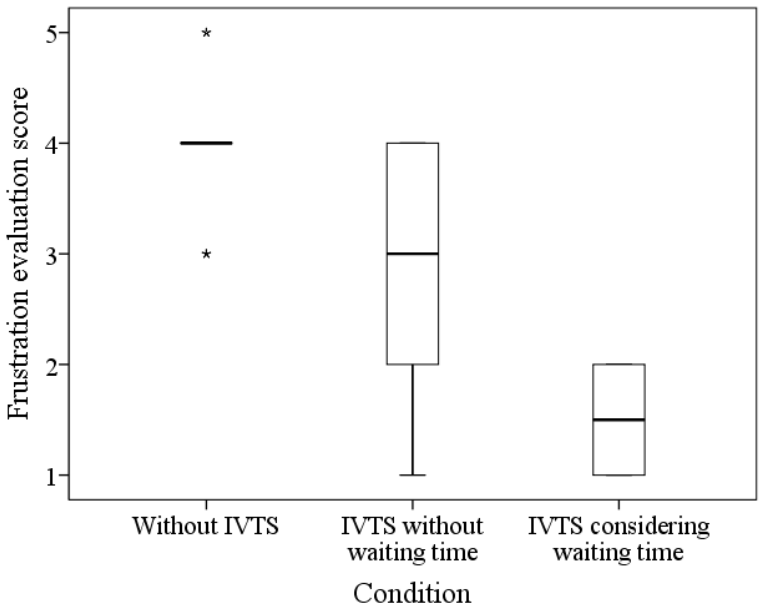

Fig. 4.34. Scores of frustration evaluation in the minor-road experiment, ranging from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high. IVTS is short for in-vehicle traffic signals.

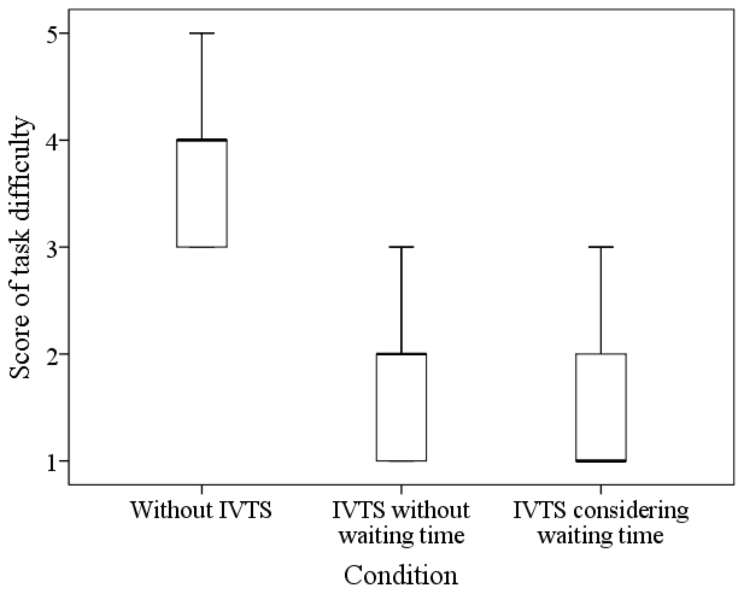

Fig. 4.35. Scores of task difficulty evaluation in the minor-road experiment, ranging from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high. IVTS is short for in-vehicle traffic signals.

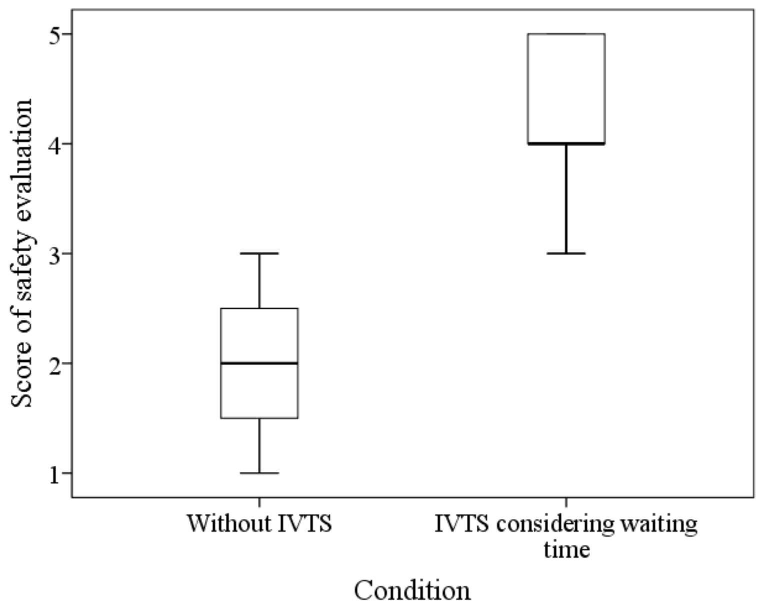

Fig. 4.36. Scores of safety evaluation in the major-road experiment, ranging from 1 to 5: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high. IVTS is short for in-vehicle traffic signals.

Chapter 5

Effect of in-vehicle traffic signals in partial deployment scenario

Effect of in-vehicle traffic signals in partial deployment scenario

5.1. Partial deployment scenario at signalized intersections

5.1.1. Actual vehicle experiments at signalized intersections

For a scenario when multiple vehicles are approaching an intersection, if both the preceding and the following vehicles were without the in-vehicle traffic signals, the driver in the following vehicle would only rely on the ground traffic light and the preceding vehicle to control the vehicle. If the preceding vehicle is equipped with the in-vehicle traffic signal system and the following vehicle is unequipped, the driver behaviors of the preceding vehicle will be influenced by the in-vehicle traffic signals. As for the driver behaviors of the following vehicle, it may be influenced by the behaviors of the preceding vehicle, considering the car following model. Therefore, it is possible that the driver behaviors of the following vehicle may be indirectly influenced by the in-vehicle traffic signals.

On the other hand, there is another possibility that the preceding vehicle is unequipped, and the following vehicle is equipped with the in-vehicle traffic signal system. In this case, the preceding vehicle will only be influenced by the ground traffic light and the following vehicle may be not only influenced by the in-vehicle traffic signal system but also the behaviors of the preceding vehicle.

Moreover, as shown in Figs. 5.1 and 5.2, even for the scenario when only the following vehicle is equipped with the in-vehicle traffic signals, it should be divided into two parts: a pass scenario and a stop scenario. In the pass scenario, the ground traffic signal will turn to green just before the vehicles arrive at the intersection. Therefore, for the preceding vehicle, the driver behaviors will be influenced by the red signal, while for the following vehicle equipped with in-vehicle traffic signals, a green signal will be displayed to the driver in advance and the driver behaviors may be affected by the condition that the ground traffic light is red while the in-vehicle traffic signal is green. In the stop scenario, the ground traffic light will change from green to red when vehicles reach the intersection. Therefore, for the preceding vehicle, it will be influenced by the green signal, while for the following vehicle equipped with in-vehicle traffic signal system, a red signal will be displayed to the driver in advance and the car following behavior may be affected by the condition that the ground traffic light is green while the in-vehicle traffic signal is red.

Therefore, it is essential to analyze the influences of in-vehicle traffic signals on driver behaviors, considering all the possible scenarios.

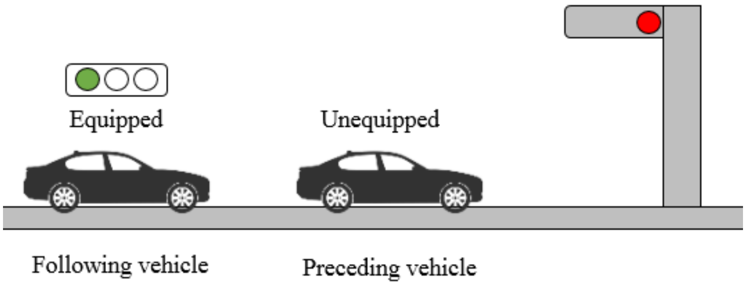

Fig. 5.1. Pass scenario when only the following vehicle is equipped with the in-vehicle traffic signals, and a green signal is displayed by the in-vehicle traffic signal system while the ground traffic light is red.

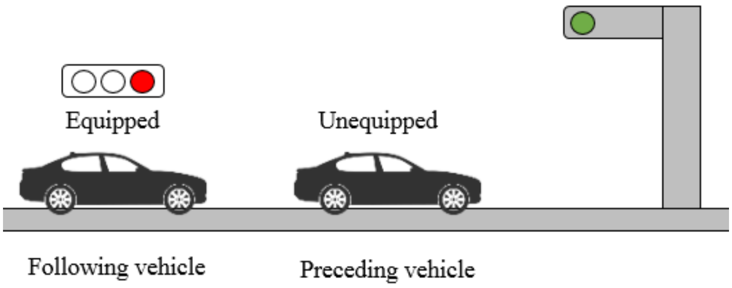

Fig. 5.2. Stop scenario when only the following vehicle is equipped with the in-vehicle traffic signals, and a red signal is displayed by the in-vehicle traffic signal system while the ground traffic light is green.

Employed vehicles

For the system diagram of in-vehicle traffic signals in actual driving environment, as shown in Figs. 5.3 and 5.4, when a vehicle equipped with on-board unit is approaching a signalized intersection, the vehicle-to-infrastructure communication with roadside unit should be firstly established, and the ground traffic light information will be transferred to the on-board unit.

Then the status of the GPS receiver will be checked and the real-time speed and location information of the vehicle will be used to estimate the time to arrival at the upcoming intersection. Afterwards, the predicted traffic signal information will be generated, and finally the in-vehicle traffic signals will be displayed to drivers if the vehicle enters the range of in-vehicle traffic signal system.

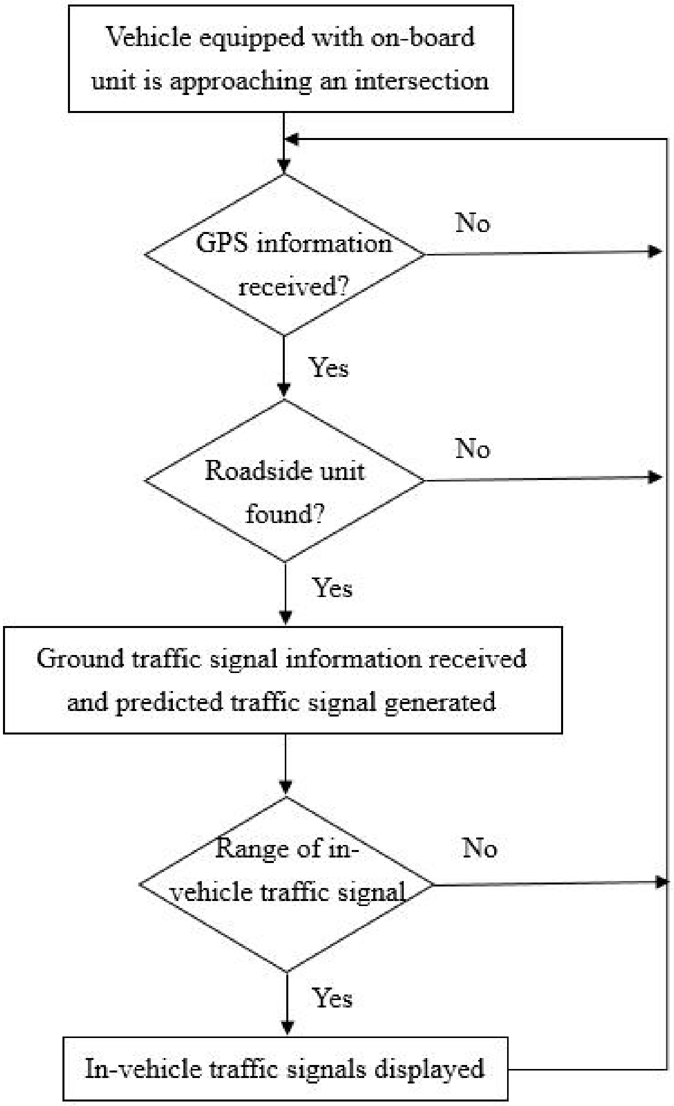

Fig. 5.3. System diagram of in-vehicle traffic signals for actual vehicle experiment.

As presented in Fig. 5.5, two super compact electric vehicles CMOS, which were produced by Toyota Body Company, were used in the actual vehicle experiment. The length, width and height of the vehicle were 2.3, 1.1 and 1.5 meters, respectively. And the maximum speed of the vehicle could be 60 km/h. To implement the in-vehicle traffic signal system for on-road assessment, four subsystems were required: communication system, data collection system, data processing system and display system. The detailed information of these four subsystems were introduced in the following parts.

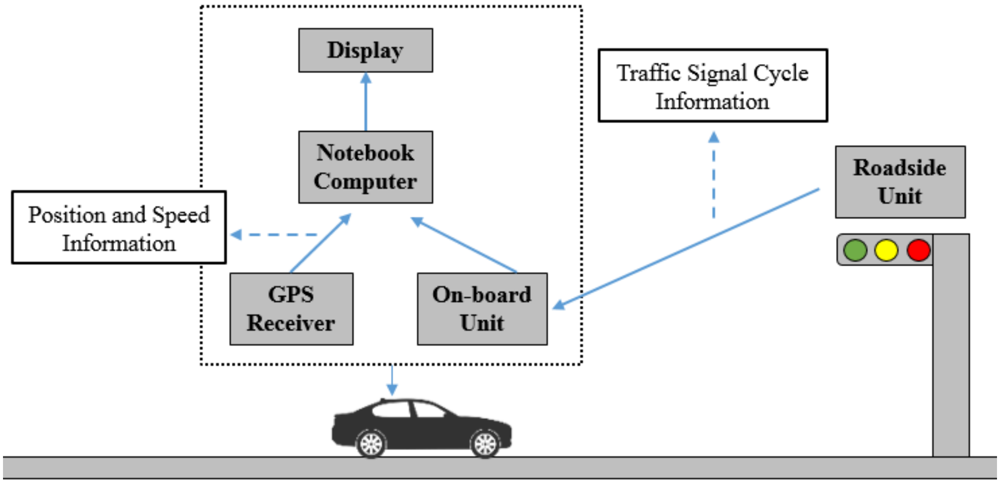

Fig. 5.4. Information exchange between the vehicle and roadside unit.

Fig. 5.5. Super compact electric vehicles applied in the experiment.

For the communication system, this study adopted the vehicle-to-infrastructure communication which used the 700 MHz band to transfer information between on-board unit and roadside unit. For the data collection system, a Globalsat BU-353S4 GPS receiver was applied to collect the speed and location information of the vehicle, as shown in Fig. 5.6. The receiver had an update rate of 20 Hz. The accuracy of the position was below 2.5 meters and the accuracy of the speed was 0.1m/s. Moreover, it is pointed out that the GPS receiver is possible to be used only when at least four satellites are visible from the position of the receiver. In this study, there was no interfering objects around the experimental area and there were at least nine satellites visible during the experiment, which assured the availability of GPS information.

Furthermore, a laptop computer was used for the data processing system, which calculated the predicted time to arrival at the intersection based on the speed and location information of the vehicle, and compared the predicted arrival time with the phase of the ground traffic light. In this experiment, the phase of the ground traffic light was set as follows: green signal phase for nine seconds, yellow signal phase for three seconds and red signal phase for 18 seconds. Finally, for the display system, an 8-inch display was chosen to display the in-vehicle traffic signals to drivers (LCD-8000V, Century Company). It was made of non-glare panel making it easier to be observed by drivers, and was positioned according to the guideline for in-vehicle display systems, as shown in Fig. 5.7.

Participants of actual vehicle experiments

Twelve participants were involved in the experiment (twelve male with a mean age of 24.3 years old, range: 22.1–26.5 years old). All participants had a valid driving license, with a mean driving frequency of 1.8 times per week (range: 1.0–3.0 times per week), and an average driving experience of 3.4 years (range: 1.2–6.1 years).

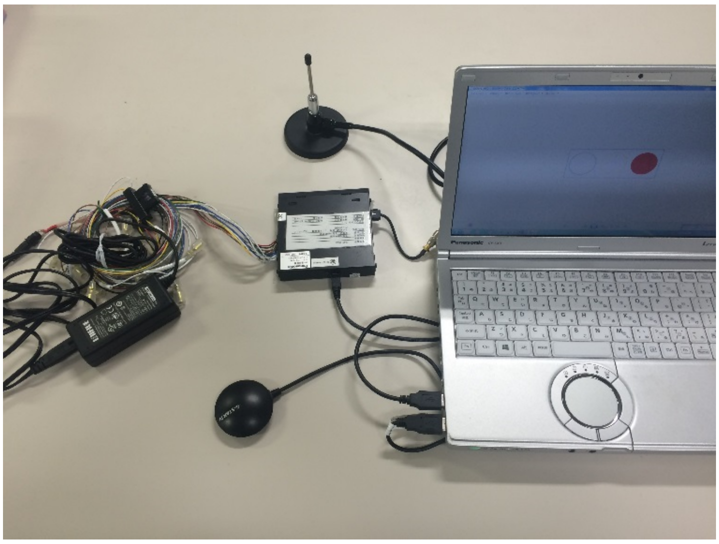

Fig. 5.6. Implementation of in-vehicle traffic signals for actual vehicle experiments.

Fig. 5.7. In-vehicle traffic signals for on-road assessment.

Test course

The experiment was conducted in the Chiba experimental campus of the University of Tokyo, and had received the approval from the Ethical Examination Committee of the Office of Life Science Research Ethics and Safety.

As shown in Fig. 5.8, there was only one signalized intersection in this scenario. To investigate the influence on driver behaviors of in-vehicle traffic signals in a partial deployment environment, two same electric vehicles were applied. The preceding car started 50 meters away from the intersection, and the following car started 10 meters behind the preceding car, taking into account the minimum stopping distance, to keep driving safety [105]. Considering the speed limit of the campus, participants were required to drive with a speed limit of 20 km/h.

The experimental environment was shown in Fig. 5.9. There were no tall building and trees near the driving route. Therefore, the conditions of the GPS devices were good enough for the experiment. To avoid the influences of the ground traffic light for pedestrian, the ground traffic light for pedestrian was turned off during the experiment. Meanwhile, during the preparation phase of the experiment, every participant had the chance to practice to accelerate to 20 km/h from both the preceding and following cars.

To make sure that both the two cars started at the same time, a countdown of three seconds was performed before the start. For the stop scenario, the countdown was started from the timing when the ground traffic light had been red for 16 s. For the pass scenario, the countdown was started from the timing when the ground traffic light had been red for five seconds.

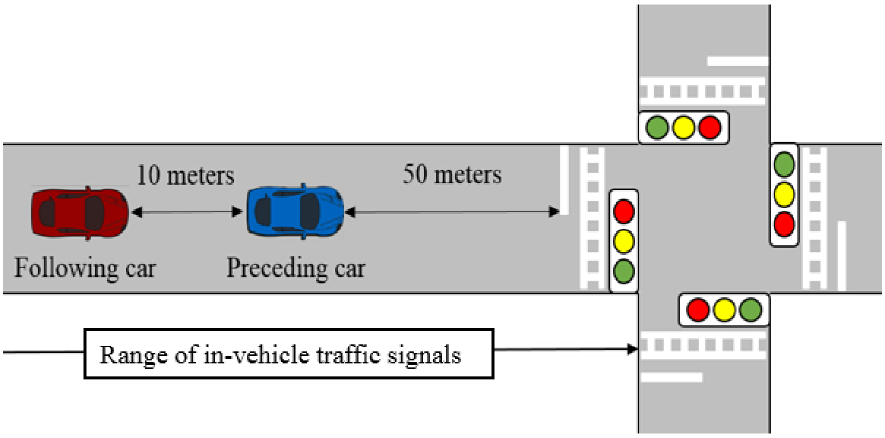

Fig. 5.8. Experimental scenario.

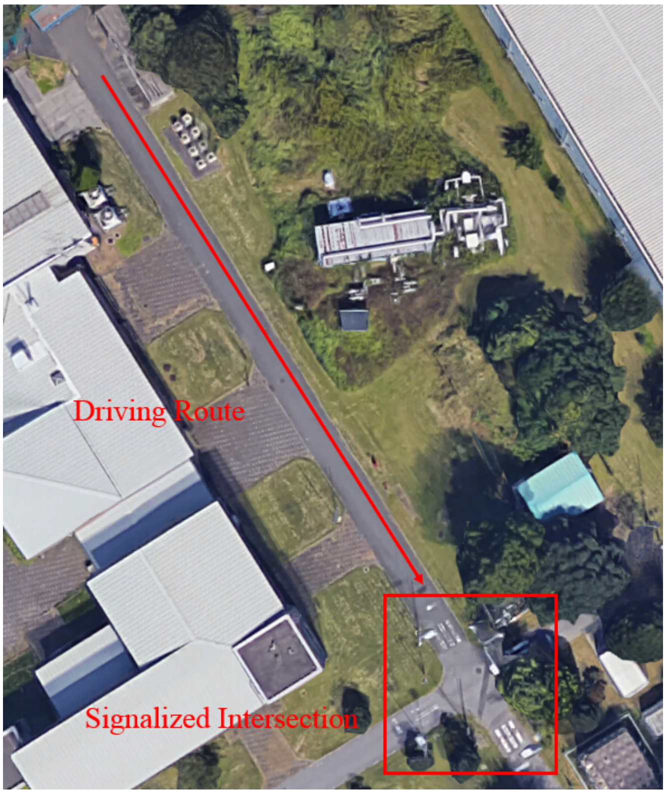

Fig. 5.9. Experimental environment without tall trees and buildings (free open street map [106]).

Driving conditions

Twelve experimental conditions were prepared for every participant, as shown in Table. 5.1. It was designed based on three factors: either stop at or pass through the intersection (stop scenario or pass scenario), the place of the participant (preceding car or following car), and the deployment conditions of in-vehicle traffic signals (both the two cars unequipped, only the preceding car equipped, and only the following car equipped). In the stop scenario, the ground traffic light would change from green to red when the vehicles reached the intersection. Oppositely, in the pass scenario, the ground traffic light would turn to green just before the vehicles arrived at the intersection.

Table 5.1. Experimental conditions. IVTS is short for in-vehicle traffic signals.

Condition	Preceding car	Following car	Place of driver	Scenario
Condition 1	IVTS unequipped	IVTS unequipped	Preceding	Stop
Condition 2	IVTS unequipped	IVTS unequipped	Following	Stop
Condition 3	IVTS equipped	IVTS unequipped	Preceding	Stop
Condition 4	IVTS equipped	IVTS unequipped	Following	Stop
Condition 5	IVTS unequipped	IVTS equipped	Preceding	Stop
Condition 6	IVTS unequipped	IVTS equipped	Following	Stop
Condition 7	IVTS unequipped	IVTS unequipped	Preceding	Pass
Condition 8	IVTS unequipped	IVTS unequipped	Following	Pass
Condition 9	IVTS equipped	IVTS unequipped	Preceding	Pass
Condition 10	IVTS equipped	IVTS unequipped	Following	Pass
Condition 11	IVTS unequipped	IVTS equipped	Preceding	Pass
Condition 12	IVTS unequipped	IVTS equipped	Following	Pass

All the participants received driving training for electric vehicles before the experiment. The twelve participants were divided randomly into six groups. Every group has two participants, of which one drove the preceding car, and the other drove the following car. And the experiment was conducted considering counterbalancing.

Data collection and analysis

The acceleration data of the vehicle were recorded by a wireless motion sensor. The range of the motion sensor was ± 16 G, and the sampling frequency was set as 20 Hz. Moreover, the experiment time, location and speed information were recorded by the GPS receiver. The GPS receiver and motion sensor were fixed on each vehicle, and were simultaneously controlled by a laptop computer. Therefore, all the information of the two vehicles could be recorded at the same time.

Effects of penetration rate at signalized intersections

As it is difficult to have enough equipment, including numerous vehicles and vehicular communication devices, simulations are considered to be an effective method to carry on the analysis for different levels of penetration rate at signalized intersections.

As shown in the Fig. 5.10, the traffic simulations were performed for an isolated intersection. The intersection connected with an upstream road and a downstream road. During the simulations, the vehicles would cross the intersection from the upstream to the downstream.

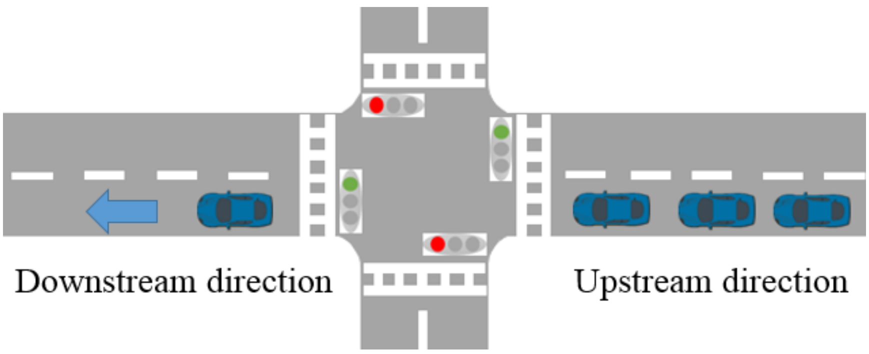

Fig. 5.10. An isolated signalized intersection.

The simulations were performed with MATLAB software. As a signalized intersection, the signal cycle information of the ground traffic light was needed to control the traffic flow. During the simulations, the signal cycle was set as green for 32 seconds, yellow for three seconds, and red for 25 seconds.

For other variables related with the intersection, they were listed as follows: the length of the upstream and downstream roads were set as 500 meters; the length of intersection was set as 20 meters; and the intersection capacity was set as 1200 vehicle/hour. The main parameters related with the vehicle were listed in Table 5.2.

Table 5.2. Parameters applied at signalized intersections.

Parameters	Values
Free flow speed / speed limit	50 km/h
Time step between iteration computations	0.1 s
Number of cars per simulation run	1000
Time after a green light that a car can enter intersection	1.2 s
Time before a red light that a car can enter intersection	2 s
Absolute value of the maximum braking deceleration	4 m/ s^2
Maximum forward acceleration	3 m/ s^2
Safe spacing between stopped cars	7 m

The time after a green signal that a car can enter intersection was set based on the consideration of reaction time of drivers. The time before a red light that a car can enter the intersection was set as 2 seconds.

A control method of a leading vehicle is needed for carrying on the simulations. The leading vehicle can be defined as the vehicle for which no other vehicles exist between the vehicle and the upcoming intersection. The behaviors of the leading vehicle will mainly depend on the predicted signal of the system. If the predicted signal is green, the stop distance of the vehicle will be calculated with the current speed and the absolute value of the maximum braking deceleration. If the distance to the upcoming intersection of the vehicle is bigger than the calculated stop distance, the vehicle will travel with the speed limit. If the distance to the upcoming intersection of the vehicle is smaller than the calculated stop distance, the vehicle will keep the current speed. If the predicted signal is red, the stop distance of the vehicle will be calculated with the current speed and the absolute value of the maximum braking deceleration. If the distance to the upcoming intersection of the vehicle is bigger than the calculated stop distance, the vehicle will keep the current speed. If the distance to the upcoming intersection of the vehicle is smaller than the calculated stop distance, then the vehicle needs to decelerate with the maximum braking deceleration.

Moreover, in order to avoid collisions at the beginning of the simulation, the initial speed of the vehicles should be decided. It is considered that the initial speed should be a function of the position and the speed of the vehicle in front. Therefore, the maximum stop distance should be calculated with the speed limit and the absolute value of the maximum braking deceleration. If the distance to the preceding vehicle is bigger than the maximum stop distance, then set the speed limit as the initial speed. If the distance to the preceding vehicle is smaller than the maximum stop distance, then set the initial speed of the vehicle k according to the following equation,

$$v = \sqrt{2 \times a_{\max} \times \Delta x} \tag{5.1}$$

where $a_{\max}$ is the maximum braking deceleration, Δx is the distance between the vehicle k and its preceding vehicle k-1.

There are some assumptions for performing the simulation. In the simulation, it is considered that no overtaking will happen for all the vehicles. A driver in the following vehicle will react to the change in the speed of the preceding vehicle after a reaction time. The position and speed of all the vehicles will be governed by the Newton's laws of motion, and the acceleration will be governed by the car following behaviors. To decide which vehicle in the simulation is in-vehicle traffic signal system equipped and which is not, the Random function in the MATLAB will be used to distribute the vehicles with and without in-vehicle traffic signals.

For the evaluation of the influences of in-vehicle traffic signals at signalized intersections, the travel time was chosen as the index. It was calculated based on the following equation,

$$t_{travel\,k} = t_{d\,k} - t_{a\,k} - \frac{length(\text{upstream} + \text{downstream} + \text{intersection})}{v_{\text{limit}}} \tag{5.2}$$

where $t_{travel\,k}$ was the modified travel time of the vehicle K, $t_{d\,k}$ was the system time when the vehicle K finished the simulation, $t_{a\,k}$ was the time when the vehicle K entered the simulation, and v_{limit} was the speed limit.

5.1.2. Results of actual vehicle experiments at signalized intersections

Results of actual vehicle experiments

For the stop scenario, the maximum deceleration index was used to evaluate the driving operations. For the maximum deceleration, it was the largest value of deceleration from the starting time to the moment when the vehicle arrived at the intersection.

For the evaluation of driving operations in the pass scenario, two indexes—maximum deceleration and travel time were applied. As for the travel time, it was defined as the period from the starting time to the moment when the vehicle crossed the intersection. Therefore, the travel time was calculated only for the pass scenario:

$$\Delta T = T_p - T_s \tag{5.3}$$

where T_p is the time when the vehicle crossed the intersection, and T_s means the starting time.

Maximum deceleration and travel time were analyzed using one-way repeated measures ANOVA with the deployment conditions of in-vehicle traffic signals (both the two cars unequipped, only the preceding car equipped, only the following car equipped) as the within-subject factor. And the Bonferroni correction was applied as the adjustment method.

Results of stop scenario

The results of a preceding car in a stop scenario were shown in Fig. 5.11. The data satisfied the requirement of homogeneity of variance ($p > 0.05$). When only the preceding car was equipped with in-vehicle traffic signals, the maximum deceleration was significantly reduced, compared to the condition when both the two cars were in-vehicle traffic signals unequipped ($p = 0.042 < 0.05$). And for the preceding car, there was no significant difference between the conditions when only the following car was equipped with in-vehicle traffic signals and that when both the two cars were in-vehicle traffic signals unequipped ($p = 1.00$).

It was suggested that the application of in-vehicle traffic signals could significantly reduce the maximum deceleration for a preceding car in a stop scenario.

As presented in Fig. 5.12, for the results of a following car, the data also satisfied the requirement of homogeneity of variance ($p > 0.05$). When only the following car was in-

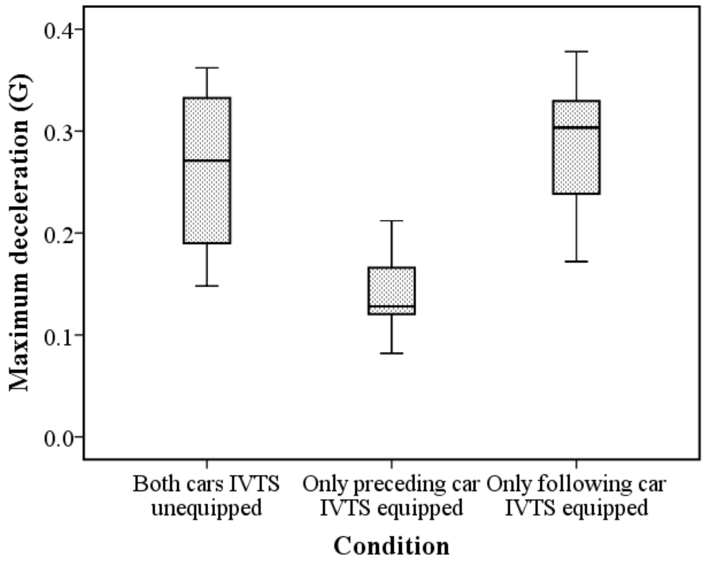

Fig. 5.11. Maximum deceleration of the preceding car in the stop scenario. IVTS is short for in-vehicle traffic signals.

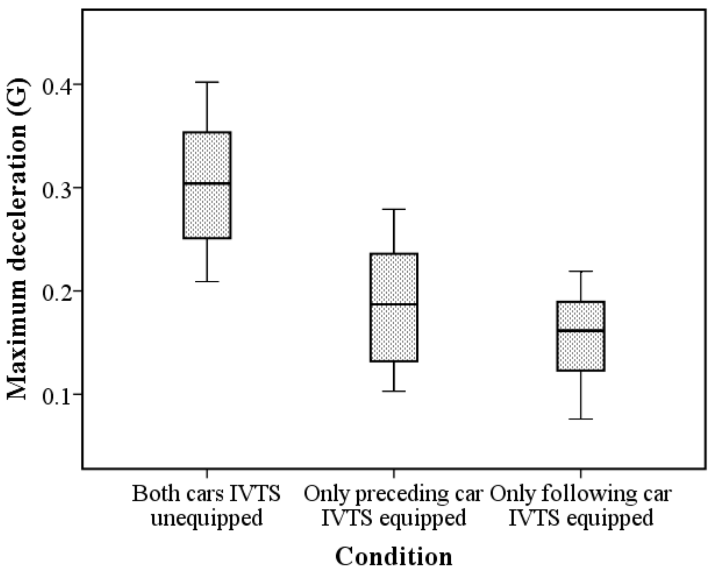

Fig. 5.12. Maximum deceleration of the following car in the stop scenario. IVTS is short for in-vehicle traffic signals.

vehicle traffic signals equipped, the maximum deceleration significantly decreased, compared to the condition when both the two cars were without in-vehicle traffic signals ($p = 0.002 < 0.05$). However, for the following car, there was no significant difference between the conditions when the car itself used in-vehicle traffic signals and that when only its preceding car was equipped with in-vehicle traffic signals ($p = 0.59$).

It was indicated that, for a following car, the maximum deceleration significantly decreased when in-vehicle traffic signals were applied in it. Interestingly, a significant reduction of maximum deceleration could also be observed when only its preceding car was equipped with in-vehicle traffic signals.

Results of pass scenario

For the maximum deceleration of a preceding car in a pass scenario, the results were provided in Fig. 5.13. The data satisfied the requirement of homogeneity of variance ($p > 0.05$). It can be observed that, if the preceding car itself was in-vehicle traffic signals equipped, the maximum deceleration could be significantly reduced, compared to the condition when both the two vehicles were without in-vehicle traffic signals ($p < 0.001$). And for the preceding car, there was no difference between the conditions when only the following car used the in-vehicle traffic signals and that when both the two vehicles were without in-vehicle traffic signals ($p = 1.00$). It could be concluded that, in a pass scenario, the maximum deceleration of a preceding car significantly decreased by applying the in-vehicle traffic signals.

The results of a following car in a pass scenario were presented in Fig. 5.14. The data satisfied the requirement of homogeneity of variance ($p > 0.05$). When the following car was equipped with in-vehicle traffic signals, the maximum deceleration significantly decreased, compared to the condition when both the two cars were without in-vehicle traffic signals ($p = 0.001 < 0.05$). Moreover, for the following car, compared to the condition when both the two cars were without in-vehicle traffic signals, the maximum deceleration was also significantly reduced even when only its preceding car used in-vehicle traffic signals ($p < 0.001$).

The result suggested that, for a following car, the application of in-vehicle traffic signals could significantly reduce the maximum deceleration. Furthermore, even the following car itself was without in-vehicle traffic signals, the maximum deceleration could also be significantly reduced if its preceding car was in-vehicle traffic signals equipped.

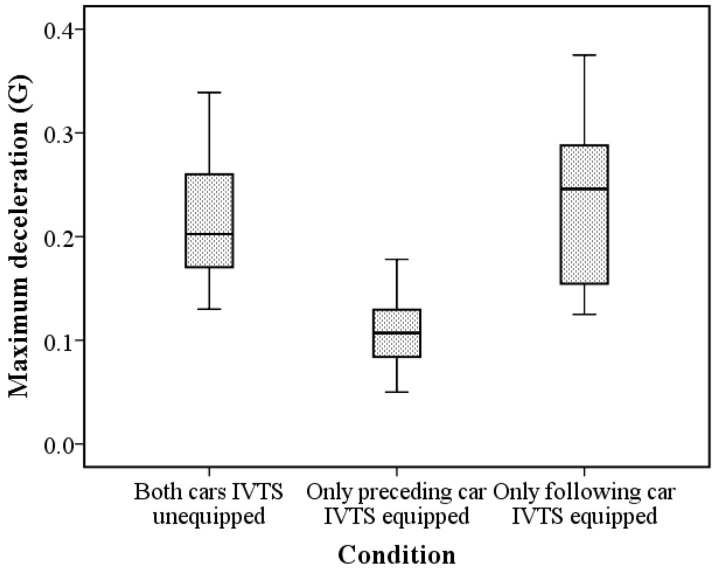

Fig. 5.13. Maximum deceleration of the preceding car in the pass scenario. IVTS is short for in-vehicle traffic signals.

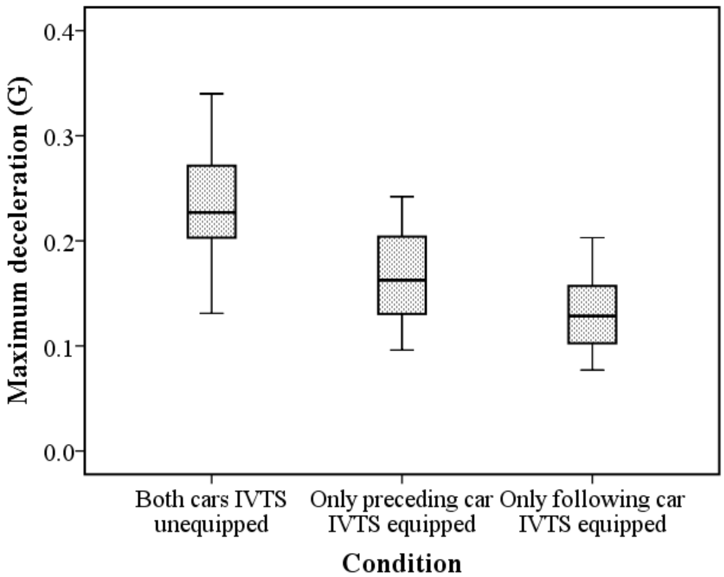

Fig. 5.14. Maximum deceleration of the following car in the pass scenario. IVTS is short for in-vehicle traffic signals.

For the travel time of a preceding car, the results can be observed from Fig. 5.15. The data satisfied the requirement of homogeneity of variance ($p > 0.05$). When the preceding car was equipped with in-vehicle traffic signals, the travel time was significantly reduced, compared to the condition when both the two cars were without in-vehicle traffic signals ($p < 0.001$). And for the preceding car, there was no significant difference between the conditions when only the following car used in-vehicle traffic signals and that when both the two cars were without in-vehicle traffic signals ($p = 1.00$).

It was indicated that the travel time of a preceding car could be significantly reduced with the application of in-vehicle traffic signals in the pass scenario.

As shown in Fig. 5.16, for the travel time of a following car, the data satisfied the requirement of homogeneity of variance ($p > 0.05$). Surprisingly, when only the following car was equipped with in-vehicle traffic signals, there was no significant difference in travel time, compared to the condition when both the two vehicles were without in-vehicle traffic signals ($p = 1.00$). However, for the following car, compared to the condition when both the two cars were without in-vehicle traffic signals, the travel time significantly deceased if the preceding car was equipped with in-vehicle traffic signals ($p = 0.003 < 0.05$).

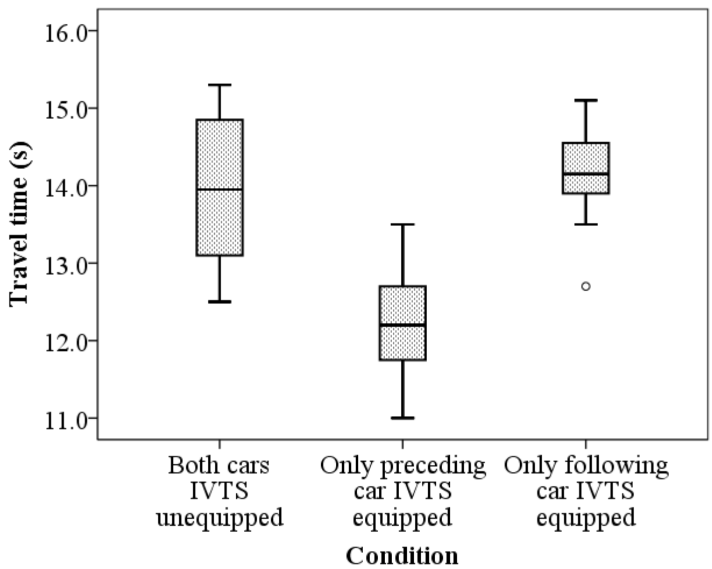

Fig. 5.15. Travel time of the preceding car in the pass scenario. IVTS is short for in-vehicle traffic signals. Mild outliers are indicated by circles (calculated as 1.5-3x the interquartile range).

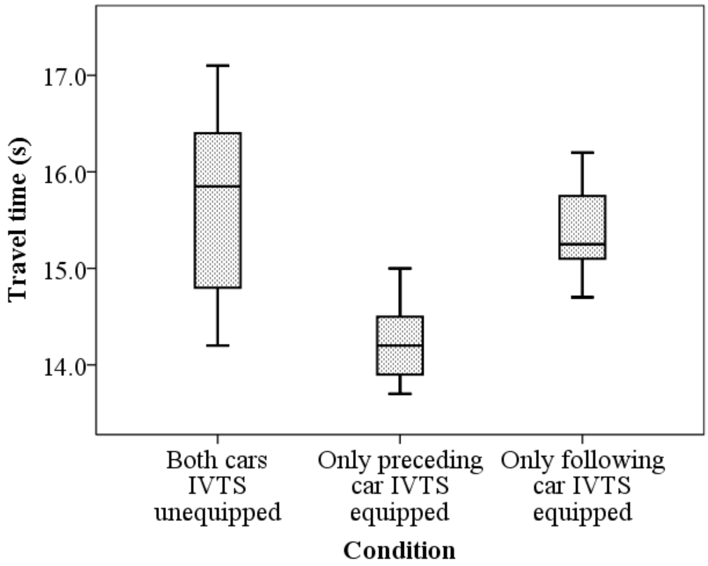

Fig. 5.16. Travel time of the following car in the pass scenario. IVTS is short for in-vehicle traffic signals.

The results indicated that, for a following car, the travel time could be significantly reduced if its preceding car was in-vehicle traffic signals equipped. However, no significant reduction in travel time could be observed even when the following car was equipped with in-vehicle traffic signals if its preceding car was in-vehicle traffic signals unequipped.

Effects of penetration rate at signalized intersections

To evaluate the influences of penetration rate on the effectiveness of the system at signalized intersections, simulations were performed for the following penetration rates: 0%, 20%, 40%, 60%, 80%, and 100%. And the average travel time of all the vehicles in the simulations were chosen as the index.

The results of the average travel time in different penetration rates of in-vehicle traffic signals at signalized intersections were shown in Fig. 5.17. It could be observed that the average travel time was in a decreasing trend with an increase in the penetration rate of in-vehicle traffic signals.

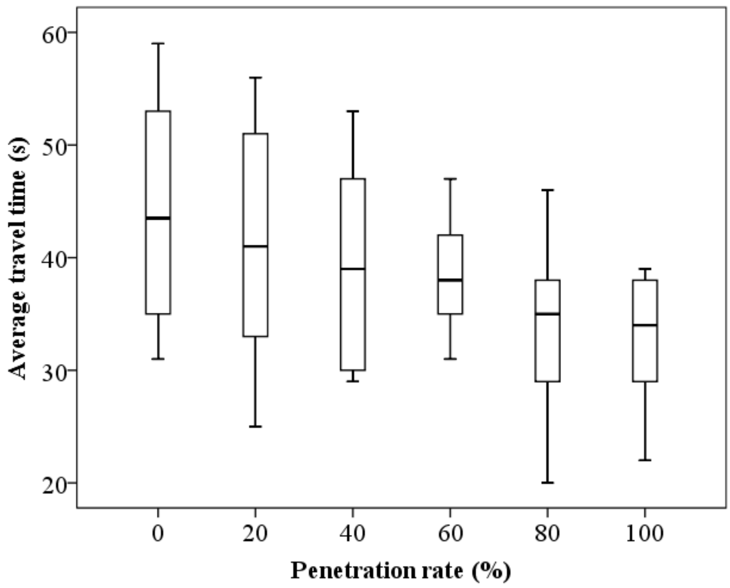

Fig. 5.17. Average travel time in different penetration rate of in-vehicle traffic signals.

It might be concluded from the results that the application of in-vehicle traffic signals at signalized intersections might improve traffic flow at intersections by reducing the average travel time. Moreover, as has been explained in Fig. 5.16, the results of the actual vehicle experiments also revealed that the application of in-vehicle traffic signals might significantly reduce the travel time. Therefore, it could be considered that the results of the simulations were in coincide with the results of the actual vehicle experiments.

5.2. Partial deployment scenario at unsignalized intersections

The availability of in-vehicle traffic signal system at unsignalized intersections in a partial deployment scenario is highly related with drivers' trust on the system. However, for the drivers' trust model, there are still a lot of contents remain unclear. To determine the necessary parameters of the trust model, a driving simulator experiment would be performed to obtain data on the change of drivers' trust, and related driver behaviors while using the in-vehicle traffic signal system. Then traffic simulations will be performed based on the results of the experiment.

5.2.1. Experiments and simulations at unsignalized intersections

Driving simulator experiments for analyzing drivers' trust

For the investigation of drivers' trust, a driving simulator and smart eye system were applied to record drivers' behaviors. Twelve healthy participants, ranging in age from 21 to 29 years (mean age = 24.6 years), participated in this experiment. All the participants had a valid driving license and had been driving for an average of 3.3 years, ranging from 0.5 to 4.5 years. The participants reported a mean driving frequency of 1.3 times per week, ranging from one to four times. This experiment was performed with the approval of the Office for Life Science Research Ethics and Safety at the University of Tokyo.

Experimental procedure

At the beginning of the experiment, all the participants were required to complete a practice for evaluating their' trust on a system. They were asked to report their trust on the following cases that whether the train will arrive on time during the rush hour, and during noon time, respectively. During the experiment, all the evaluation scores were collected using a 10-point scale measurement questionnaire, and the higher the score is, the more trust on the system.

After the practice, the in-vehicle traffic signals were introduced to the participants. The participants would be informed that the in-vehicle traffic signal system would assist them to cross unsignalized intersections. Then the first questionnaire about the trust on the in-vehicle traffic signal system was performed. Afterwards, an introduction that the in-vehicle traffic signal system might make a mistake in some cases would be presented to the participants. The introduction would be presented as follows: at unsignalized intersections, the in-vehicle traffic signal system calculated the arrival time of other vehicles based on V2V communication. If some vehicles were unequipped with the in-vehicle traffic signal system and therefore, could not communicate with other vehicles equipped with the system. Then the arrival time of other vehicles might not be calculated correctly. A green light might be displayed to the drivers at a wrong time.

The participants could then be informed that the penetration rate of the in-vehicle traffic signal system might influence the effectiveness of the system. Then the second questionnaire about the trust on the in-vehicle traffic signal system was performed after the introduction. The participants were required to report their trust on the in-vehicle traffic signal system for different penetration rates, including 0%, 25%, 50%, 75%, and

100%. It was considered that the data obtained with the first and second questionnaires could be used for the evaluation of drivers' initial trust on the system. After the survey of initial trust, an opportunity to practice driving with the driving simulator would be offered for every participant.

Then experiments would be performed to verify the changes in drivers' trust by making the participants experience successful and failed usages of the system. Before starting the experiment, all the participants would be informed that the experiments would be performed without telling them the penetration rate. The data related with drivers' trust were mainly recorded using questionnaire survey, and changes in driver behaviors were analyzed by using smart eye and the data recorded with the driving simulator.

The driving scenario of the experiments was presented in Fig. 5.18. The participants were required to cross an unsignalized intersection from the minor road to the major road. After departing from the start point, which was 300 meters away from the intersection, the participants would firstly move forward and stop at the stop line of the intersection. Then they would turn right from the minor road to a major road. After completing a right-turn at the intersection, they would stop the vehicle at the end point.

As shown in Table. 5.3, two conditions were prepared for every participant to investigate the influences of successful and failed experience on the trust. For the condition of successful usage, the participants would experience the successful usage of the in-vehicle traffic signal system for multiple times until the trust reaches its maximum value. The evaluation of trust would be performed based on the questionnaire, and the trust of the participants would be set to the minimum value before the experiment through failed usages.

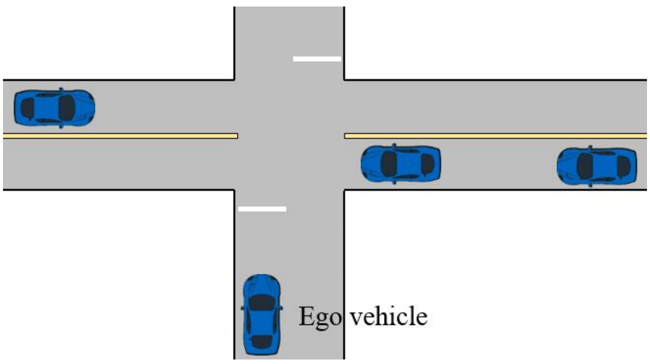

Fig. 5.18. Driving scenario for evaluating drivers' trust.

Table 5.3. Experimental conditions for analyzing the change of trust.

Participant	Experimental condition	
1	Successful usage	Failed usage
2	Failed usage	Successful usage
3	Successful usage	Failed usage
4	Failed usage	Successful usage
5	Successful usage	Failed usage
6	Failed usage	Successful usage
7	Successful usage	Failed usage
8	Failed usage	Successful usage
9	Successful usage	Failed usage
10	Failed usage	Successful usage
11	Successful usage	Failed usage
12	Failed usage	Successful usage

For the condition of failed usage, the participants would experience the failed usage of the in-vehicle traffic signal system for multiple times until the trust reaches its minimum value. The evaluation of trust would be performed based on the questionnaire, and the trust of the participants would be set to the maximum value before the experiment through successful usages. The order of the two conditions would be provided for the participants, considering the counter balance. By conducting experiments with the two conditions, the change of drivers' trust on the system could be evaluated.

Then the participants would be informed that the first experiment for evaluating the initial trust and the change of trust had been completed, and the second experiment for evaluating the influences of penetration rate on the application of the system would be started. The participants were required to reset their trust on the system. Afterwards, the second experiment to investigate the driving safety or the times of near miss accidents would be performed for six conditions, including the condition that no in-vehicle traffic signal system was applied and the conditions that the penetration rate is 0%, 25%, 50%, 75%, and 100%, as presented in the Table 5.4.

For every condition, at the beginning and the end of the experiment, the participants were required to reset their trust to avoid the influences on other conditions. Moreover, to avoid the learning effect, 10 scenarios were prepared for every condition, and the scenario

Table 5.4. Experimental conditions for analyzing the influences of penetration rate.

Participant	Penetration rate					
1	None	0	100	25	75	50
2	0	25	None	50	100	75
3	25	50	0	75	None	100
4	50	75	25	100	0	None
5	75	100	50	None	25	0
6	100	None	75	0	50	25
7	None	0	100	25	75	50
8	0	25	None	50	100	75
9	25	50	0	75	None	100
10	50	75	25	100	0	None
11	75	100	50	None	25	0
12	100	None	75	0	50	25

was chosen in a random order during the experiment. For every condition, the experiment would be conducted for 10 times.

At unsignalized intersections, there is no ground traffic light to manage the traffic flow and guide drivers to pass through the intersections. How to keep the safety of drivers while crossing the unsignalized intersections is one of the most important issues to be considered. Therefore, for the second experiment, questionnaire survey would be performed for all the participants to investigate the trust on the system and the feeling of near miss accidents. Meanwhile, the gaze behaviors would be recorded with the smart eye system. The driving operations would be recorded with the driving simulator.

Simulation at unsignalized intersections

Considering the limited times of experiments and the number of participants, traffic simulations were performed for a deeper analysis on the influences of different penetration rates.

The parameters of drivers' trust model, including the initial trust and the change of trust on the system could be obtained, based on the data from the driving simulator experiment. Moreover, a driver behavior model is also needed to perform the simulations. It was assumed that the drivers would start to confirm the traffic conditions and try to enter the intersection if a green signal was displayed by the system. The driver behaviors, including the right and left confirming behaviors, were considered to be related with drivers' trust on the system. It was believed that a driver would confirm the traffic condition and check the left and right more carefully if their trust on the system is lower, and they would not enter the intersection if they observed a vehicle which might collide with the ego vehicle.

When drivers did not trust on the system at all, the confirming behaviors could be expressed as follows [107]: the largest angle for the left and right confirmation was 90 °; the effective field of view was 20 °, the gaze movement speed was 60 °/s, and the viewing distance was 60 m. As for the driving operations, the speed was set to 5 km /h based on the Road Traffic Act [108]. The acceleration could be set to 2 m/s^2; the brake could be set to 3 m/s^2; the sudden brake could be set to 4 m/s^2, and the reaction time could be set to 1 s. When the drivers totally trusted on the system, the confirming behaviors might be expressed as follows: the largest angle for left and right confirmation was 45 °, the effective field of view was 20 °, the gaze movement speed was 60 °/s, and the viewing distance was 60 m. As for the driving operations, the acceleration was set to 3 m/s^2; the brake was set to 3 m/s^2; the sudden brake was set to 4 m/s^2; and the reaction time was set to 1 s. When drivers' trust on the system ranged from 0, which meant that they did not trust the system at all, to 1, which meant that they totally trusted the system, the confirming behaviors might be expressed as follows: the largest angle for left confirmation was 90 °- 45 °× Trust value and the largest angle for right confirmation was 90 °-45 °× Trust value. The effective field of view was 20 °, the gaze movement speed was 60 °/s, and the viewing distance was 60 m. As for the driving operation, the acceleration was set to 2+Trust value m/s^2; the brake was set to 3 m/s^2; the sudden brake was set to 4 m/s^2; and the reaction time was set to 1 s.

Number of simulations was set to 5000 times for each penetration rate in one condition. Traffic flow was controlled by the time headway. The distribution of the inter-vehicle time headway was approximated by a normal distribution, of which the average was set to seven seconds and the dispersion was set to three seconds [109]. Meanwhile, the minimum inter-vehicle time headway was set to 1.5 seconds, considering the driving safety. The position, speed and acceleration of the vehicles were controlled by the free flow model and the car following model. The maximum speed of vehicles were set to 40 km / h.

For the control of the vehicles on the major road, the worst case was considered in the simulations as follows: the major road vehicles had a high awareness of the priority, and would like to pass through the intersection without deceleration. The vehicles on the major road would try to avoid collisions or reduce the damage of the collision with emergency automatic brake, only when the minor road vehicles entered the lane of the major road vehicles and a possibility of collision existed. Meanwhile, the trust of major road vehicles was not considered in the simulation, to be consistent with that of driving simulator experiments, as it was difficult to set trust for other vehicles in the driving simulator. Moreover, for the comparison with the condition when there was no in-vehicle traffic signal system, it was reported that there were only 15 vehicles out of 101 vehicles completely stopped at the stop line when passing through unsignalized intersections [110]. Meanwhile, it was found that about 30% of the minor road vehicles would not temporarily stop at the stop line in our conducted driving simulator experiments. On the other hand, around 91% of the minor road vehicles would stop temporarily at the stop line if in-vehicle traffic signal system was applied [61]. Therefore, it was considered that when in-vehicle traffic signals were displayed for minor-road vehicles, it would urge the drivers to temporarily stop at the stop line, even when the penetration rate was 0%.

The simulations will be performed with MATLAB software, and the times of near miss accidents will be chosen as the evaluation index. To simulate an unsignalized intersection without the assistance of in-vehicle traffic signals, the simulation model in a previous study would be used, in which all the vehicles were controlled with gap acceptance theory [111]. The critical gaps were distributed to each vehicle according to a log normal distribution [112]. The parameters μ and σ could be set to 1.87 and 0.5, respectively. And it was assumed that no driver would accept a gap that the driver thought will certainly lead to a collision. Therefore, the minimum gap in the model was set to two seconds, which means no driver would accept a gap smaller than two seconds.

The Random function in the MATLAB was used to distribute the vehicles with and without in-vehicle traffic signals. The vehicle equipped with in-vehicle traffic signal system was distributed with the state value of one, while the vehicle without in-vehicle traffic signals would have the state of zero. The gap on the major road would only be calculated for the vehicles with the state value of one. Therefore, a minor-road vehicle may enter the intersection when a major-road vehicle without in-vehicle traffic signals exists and the gap between the major-road vehicle and the intersection in this condition may be smaller than the critical gap. Near miss accidents, which were defined as the situations when PET was smaller than three seconds, may occur in this condition [64].

5.2.2. Results of experiments and simulations at unsignalized intersections

Results of driving simulator experiment

The initial trust on the system and the change of trust while using the system were analyzed based on the data obtained from the driving simulator experiments with 12 participants. As shown in Fig. 5.19, the initial trust on the in-vehicle traffic signals were presented for different penetration rates. The data of initial trust were collected with a 10-point scale measurement questionnaire, where one point means the participant did not trust the system at all, and 10 points represent that the participant totally trust the system. It can be observed from the figure that most of the participants did not trust the system at all when the penetration rate was around zero, and highly trust the system when the penetration rate was near 100%. The initial trust on the system would increase slowly with the increasing of penetration rate at first and then start to increase rapidly when the penetration rate was high enough.

For the change of trust while using the in-vehicle traffic signal system, the results of the changes of trust while experiencing continuous failures were offered in Fig. 5.20. The data of trust were also collected with a 10-point scale measurement questionnaire. It was found that all the participants would not trust the system at all if they had experienced

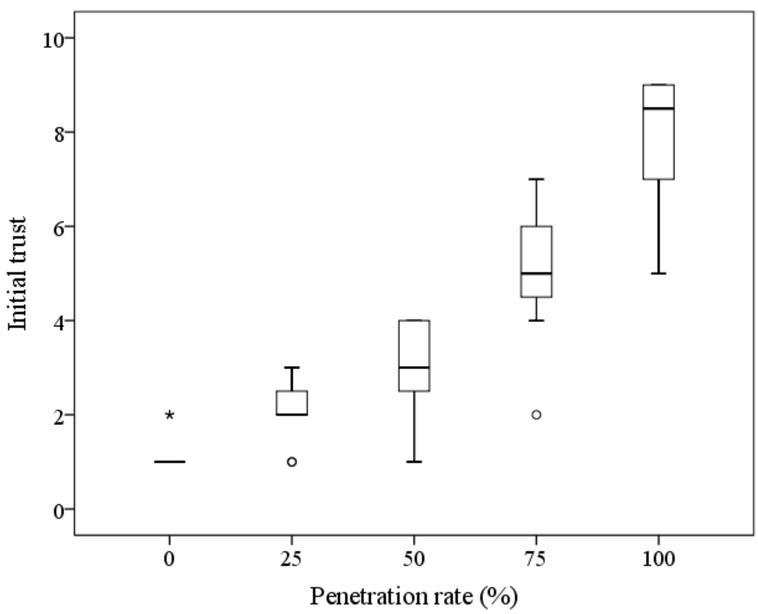

Fig. 5.19. Initial trust of the participants on the in-vehicle traffic signals.

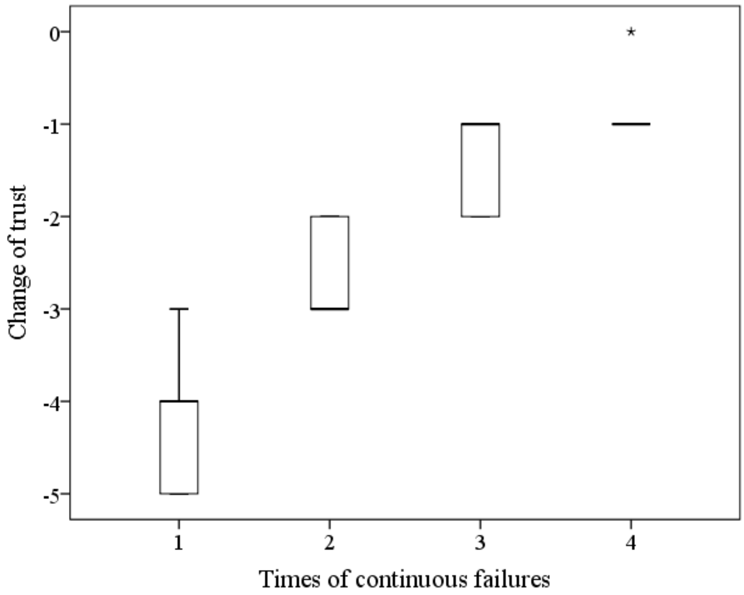

Fig. 5.20. Change of trust while experiencing continuous failures.

continuous failures for more than four times. It could be observed from Fig. 5.20 that the trust on the system would have the largest drop when the participants experienced the failure of using the system for the first time. The reason could be considered that all the participants received an introduction of the in-vehicle traffic signal system, including the possible failure caused by low penetration rate, before the experiment. Therefore, they might recognize that the penetration rate was not 100% when a failure occurred, without considering the failure as a sporadic event. Afterwards, their trust on the system would become lower and lower with continuous failures until they did not trust the system at all.

The results of the changes of trust while experiencing continuous success were provided in Fig. 5.21. It can be observed that the differences between individuals might be more obvious while experiencing continuous success, compared to those of continuous failures. Meanwhile, the trust on the system would increase slowly with the times of continuous success and have the largest increase when the participants experienced the success of using the system for around four time. Afterwards, the trust on the system would have a slow increase again as the trust was already in a comparatively high state.

Experiments were also performed to investigate the driving safety in different conditions. The participants were required to drive in ten different scenarios in the conditions when no in-vehicle traffic signal was applied, and when the penetration rates of in-vehicle traffic signals were 0%, 25%, 50%, 75% and 100%. The times of near miss accidents were chosen as the evaluation index. The subjective evaluations of the

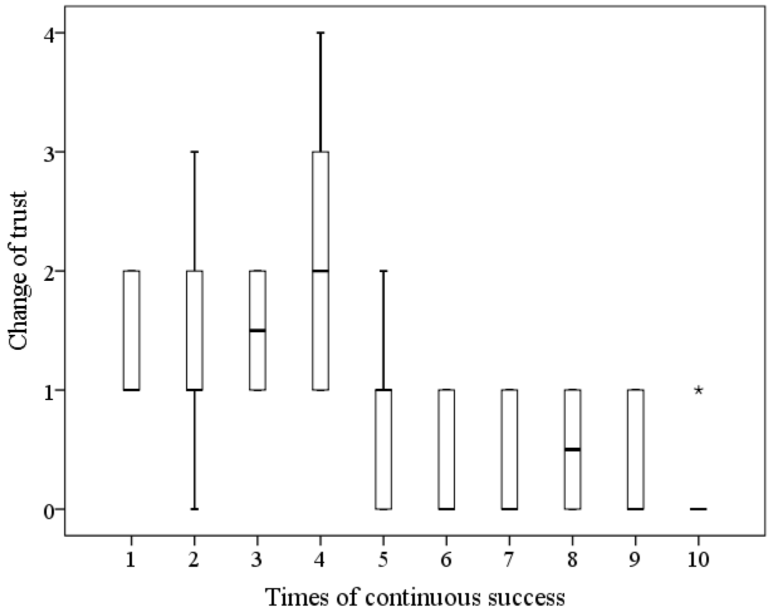

Fig. 5.21. Change of trust while experiencing continuous success.

participants on the near miss accidents and their trust on the system were collected with a 10-point scale measurement questionnaire, where one point means the participant did not feel the near miss accident at all in the near miss accidents evaluation and did not trust the system at all in the trust evaluation, and 10 points represent that the participant have a strong feeling of near miss accident in the near miss accidents evaluation and totally trust the system in the trust evaluation. It was observed that the changes of trust were mainly related with the performance, either success or failure, and were similar within different states of trust.

For the near miss accident evaluation, an evaluation score larger than five would be counted as a near miss accidents. As shown in Fig. 5.22, the participants felt the most near miss accidents when no assistance was provided. For the influences of penetration rate, the participants reported more near miss accidents when the penetration rate was 50%, compared to other penetration rates. Meanwhile, there was almost no difference when the penetration rates were 0% and 25%, and the times of near miss accidents started to decrease when the penetration rate was larger than 50%.

For the post-encroachment time of the ego vehicle while crossing intersections in different driving conditions, the results were presented in Fig. 5.23. As shown in the figure, the median value of the post-encroachment time was the smallest when no in-vehicle

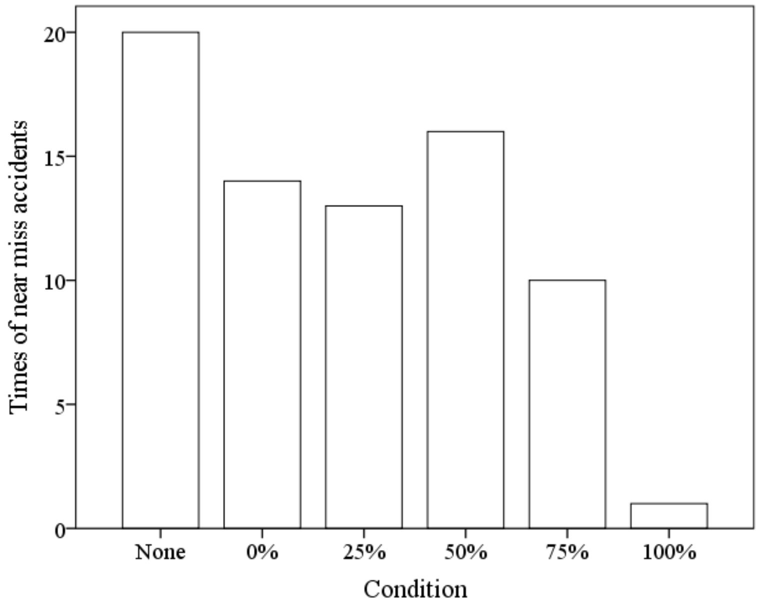

Fig. 5.22. Subjective evaluations of times of near miss accidents in different driving conditions.

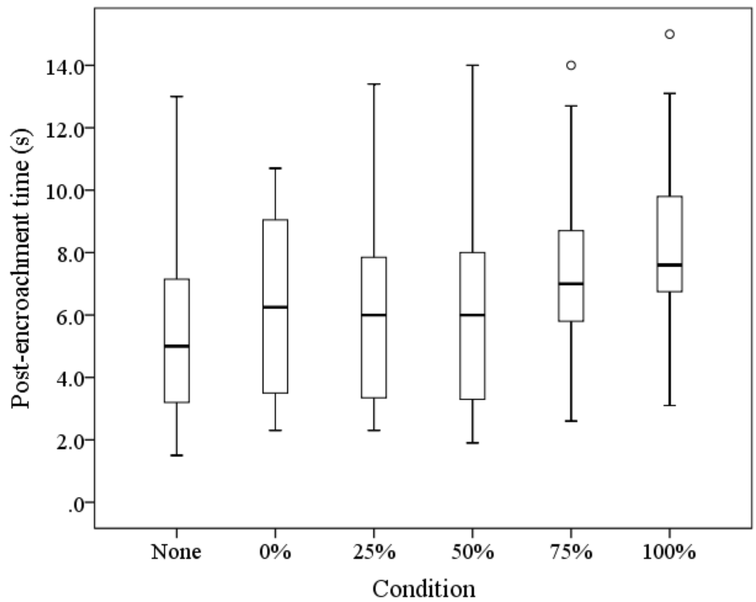

Fig. 5.23. Post-encroachment time of the ego vehicle while crossing intersections in different driving conditions.

traffic signal was applied. For the influences of penetration rate, the median value of the post-encroachment time started to decrease slightly when the penetration rate changed from 0% to 50%, and then began to increase when the penetration rate was larger than 50%. There was no significant difference existed among the conditions when no in-vehicle traffic signal was applied and when the penetration rate was 0%, 25%, and 50%. Moreover, a significant difference was found between the conditions when no in-vehicle traffic signal was used and when the penetration rate was 100% (p=0.01). A significant difference might also existed between the conditions when no in-vehicle traffic signal was applied and when the penetration rate was 75% if more participants would attend the experiments (p=0.08).

Results of simulations at unsignalized intersections

Simulations were performed for unsignalized intersections, based on the data of initial trust on the system and the change of trust while using the system, which were obtained from the driving simulator experiments.

The initial trust on the system in different penetration rates were presented in Table. 5.5. They were the mean values of the initial trust of 12 participants. For the change of trust, the change of trust while continuous failures and success were provided in Tables. 5.6 and 5.7, respectively. In the case that a failure occurred, and the current value of drivers' trust was smaller than the absolute value of the change of trust, it was considered that the drivers would then not trust on the system at all. In the case of a success usage, the sum of the current value of drivers' trust and the change of trust was larger than the maximum value, it was considered that the drivers' trust would totally trust on the system.

Afterwards, traffic simulations were performed for each condition, and the results of the simulations for 2500 times were presented in Fig. 5.24.

Table 5.5. Initial trust on the system in different penetration rates.

	Penetration rate				
	0%	25%	50%	75%	100%
Initial trust	1.17	2.08	3.08	5.08	7.91

Table 5.6. Change of trust with continuous failures.

	Times of continuous failures			
	1	2	3	4
Change of trust	-4.17	-2.67	-1.33	-0.83

Table 5.7. Change of trust with continuous success.

	Times of continuous success									
	1	2	3	4	5	6	7	8	9	10
Change of trust	1.33	1.33	1.50	2.16	0.83	0.33	0.33	0.50	0.33	0.17

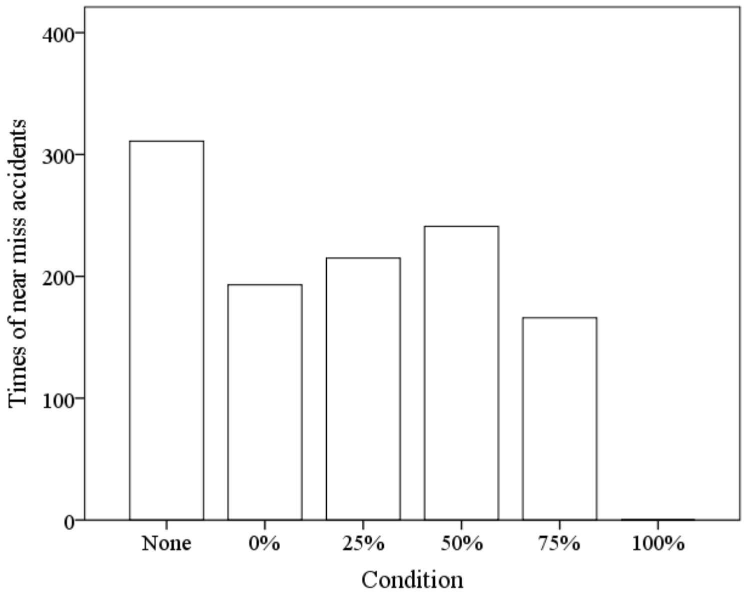

Fig. 5.24. Results of times of near miss accidents in different driving conditions.

It can be observed that there were the most near miss accidents when no in-vehicle traffic signal was provided. For the influences of penetration rate, there were more near miss accidents when the penetration rate was 50%, compared to all the other penetration rates. Meanwhile, the times of near miss accidents would increase at first with the increase in the penetration rate. Afterwards, the times of near miss accidents could be reduced with the increase of the penetration rate when the penetration rate was larger than 50%. It was considered that the improvement in drivers' stopping behaviors at the stop line while in-vehicle traffic signals were applied might contribute to the reduction of near miss accidents at intersections, compared to the condition when no in-vehicle traffic signal was applied.

Chapter 6

Discussions

Discussions

6.1. Influences of in-vehicle traffic signals on driving behaviors

The objectives of the study were to investigate the influences of in-vehicle traffic signals on driving behaviors based on driver models considering look ahead information, and demonstrate that the in-vehicle traffic signals could still have positive effects even in a partial deployment situation. The discussions would therefore be conducted, from the viewpoint of driving safety, traffic flow and visual distraction.

6.1.1. Driving safety

For analyzing the influences of in-vehicle traffic signals on driving safety in full deployment situations, as shown in Fig. 4.20, the post-encroachment time at unsignalized intersections were significantly improved with the application of in-vehicle traffic signals. It was considered that a lower value of post-encroachment time indicated a higher possibility of conflict [63], [64]. The results revealed that the driver assistances provided by the proposed system might be effective in improving driving safety. A previous study found that drivers who drove a vehicle with an intersection collision warning system had a shorter response time [113]. Therefore, it is possible that the in-vehicle traffic signals, working as one type of visual warning signal, shortened the response time of drivers to an appropriate gap on the major road, which contributed to a longer post-encroachment time. Moreover, the results of maximum brake stroke were presented in Figs. 4.21 and 4.22. We observed a significant decrease in the maximum brake stroke when the participants had access to the in-vehicle traffic signals. A previous study reported that an increase in the brake stroke significantly deteriorated the vehicle performance during an emergency stop [114]. Our results regarding maximum brake stroke implied that driving safety could be improved during the braking period when in-vehicle traffic signals were applied. In terms of stopping types, the results suggested that more participants would perform a complete stop when the in-vehicle traffic signals were used. It was introduced that many collisions at intersections were related with the uncomplete stop of drivers [95]. It was, therefore, revealed that the conflict risk at unsignalized intersections might also be reduced by applying the in-vehicle traffic signal system.

For the results of driving simulator experiment considering waiting time at unsignalized intersections, it was expected that the driving performances of the minor-road vehicles would be improved, by considering the waiting time in the implementation of in-vehicle traffic signals, without detriment to the driving safety of major-road vehicles. For the results of maximum gas pedal stroke, as shown in Fig. 4.28, the application of in-vehicle traffic signal considering waiting time significantly reduced the maximum gas pedal stroke of minor-road vehicles. The acceleration related indexes including maximum acceleration were considered suitable for evaluating aggressive or emotional driving [99], [100]. Therefore, the results revealed that the consideration of waiting time might be effective in avoiding aggressive driving for minor-road vehicles. As for the cause of aggressive driving, it was reported that aggressive driving was more likely to occur in dense traffic situations [115]. During the minor-road experiment, the continuous major-road traffic flow was considered challenging for the minor-road drivers, which might result in aggressive driving if the waiting time were not considered. Meanwhile, it had been demonstrated that challenging or unexpected traffic situations could induce frustration and other negative emotional states for drivers [116]. According to the frustration–aggression hypothesis, the frustration emotions of drivers might also lead to risky and aggressive driving behaviors, including strong accelerations [117], [118].

The evaluations of frustration emotions were performed with the blink rate analysis and subjective evaluations. It was considered that the feeling of frustration could be detected by monitoring the blink rate [101]. Previous studies pointed out that the blink rate might be raised with a frustration emotion [102], [103]. Normally, an average blink rate is around 14 blinks per minute [119]. During the minor-road experiment, it was found that the measured blink rates ranged from 12 to 22 times, therefore, were considered reliable for evaluation. As presented in Fig. 4.29, when the in-vehicle traffic signal considering waiting time was applied, the blink rate significantly decreased. Therefore, it indicated that the frustration emotions of drivers might be reduced by considering their waiting time while applying the in-vehicle traffic signals. Meanwhile, according to the subjective evaluation of frustration, as shown in Fig. 4.34, drivers felt less frustrated with the in-vehicle traffic signal considering waiting time, compared to that without the consideration of waiting time, which was coincided with the blink rate analysis. However, no significant diffidence in the blink rate was observed between the conditions when no in-vehicle traffic signal was provided and that of in-vehicle traffic signal without considering waiting time, although the participants reported more frustrated feelings without in-vehicle traffic signal in the subjective evaluation. It was considered as the influence of task difficulty. It was suggested that the blink rate tended to decrease if the task difficulty was increased [120]. As presented in Fig. 4.35, the participants reported that it was more difficult to complete the driving task without in-vehicle traffic signals, which might reduce the blink rate.

For the analysis of maximum lateral acceleration, as shown in Fig. 4.30, when the in-vehicle traffic signal considering waiting time was applied, the maximum lateral acceleration significantly decreased, compared to that without the consideration of waiting time. The results implied that the steering stability of minor-road vehicles might be significantly improved by considering the waiting time while using the in-vehicle traffic signals. It was believed that less maximum lateral accelerations might represent fewer deviations from idealized curved paths during a turn at intersections [104].

A major-road experiment was also performed at unsignalized intersections to evaluate the driving safety of major-road drivers. A critical part of driving safety is the ability to detect and respond to emergency traffic hazards. The entry of minor-road vehicles in the major-road experiment was considered as an emergency hazard, therefore, perception response time was applied to analyze the detection and response ability of major-road drivers. As shown in Fig. 4.33, when there was no in-vehicle traffic signal, the values of perception response time ranged from 1.01 s to 1.15 s. When the in-vehicle traffic signal considering waiting time was applied, the perception response time decreased, ranging from 0.84 s to 0.96 s. It was reported that the mean value of perception response time was around one second [121]. Meanwhile, to analyze drivers' perception response time to intruding vehicles at intersections, another study found that the mean time from the start of motion until brake pedal application was 1.14 s, which was in accordance with the results when no in-vehicle traffic signal was applied [122], [123]. It should be noted that, by applying the in-vehicle traffic signal, the major-road drivers had an advantage to detect the entry of minor-road vehicles, as they would be immediately warned once other vehicles started entering intersections.

For the effects of in-vehicle traffic signals on driving safety in partial deployment situations, as shown in Fig. 5.23, the post-encroachment time at unsignalized intersections were the smallest when no in-vehicle traffic signal was applied, compared to the conditions when the penetration rates of in-vehicle traffic signals changed from 0% to 100%. Meanwhile, there were the most near miss accidents when no in-vehicle traffic signal was provided according to the simulation results, as shown in Fig. 5.24. It was, therefore, considered that the driving safety might be improved with the application of in-vehicle traffic signals even in a partial deployment scenarios.

It could be concluded that the in-vehicle traffic signal system might improve driving safety for both full deployment and partial deployment scenarios.

6.1.2. Traffic flow

This study mainly focused on the analysis of acceleration and braking operations to evaluate the influence of in-vehicle traffic signals on traffic flow. As shown in Figs. 4.4-

4.7, braking and accelerating operations in the driving simulator experiment at signalized intersections were significantly reduced when the predicted mode of in-vehicle traffic signals was applied. Conversely, no significant difference existed between the condition when current mode was applied and that of no in-vehicle traffic signal. The results indicated that the application of predicted mode of in-vehicle traffic signals might improve the traffic flow. It was pointed out that several characteristics of driving behaviors including avoiding unnecessary stops, braking and acceleration, were significantly related with eco-driving [124], [125]. A previous study introduced that fuel economy was maximized when accelerating and braking events were minimized [126]. Meanwhile, a similar conclusion was reported that the improvement in driver behaviors had the potential to generate fuel savings of up to 20% [127]. It was expected that fewer braking and accelerating operations, resulting from the application of predicted mode of in-vehicle traffic signals, might provide drivers with a comfortable driving experience. Based on a smart-driving report by the University College London, successful anticipation of traffic conditions avoids unnecessary braking and acceleration, which makes driving smoother [128].

Moreover, for the evaluations of driving operations while using in-vehicle traffic signals in the actual vehicle experiment, as shown in Figs. 5.11 and 5.12, the significant decrease in maximum deceleration also verified that the application of in-vehicle traffic signal system might significantly prompt drivers to ecological driving. A significant decrease in the maximum deceleration could be observed from a car without in-vehicle traffic signals if its preceding car was in-vehicle traffic signals equipped. It suggested that the influences on ecological driving of a vehicle equipped with in-vehicle traffic signals might affect its following traffic flow, even when the following vehicles were without in-vehicle traffic signals. Besides, the braking operations were also considered to have great influences on ecological driving. It was reported that approximately seven percent energy of a vehicle was lost due to braking [129]. Hence, reducing hard braking and assisting drivers in achieving smoother braking operations was assumed a direct fuel savings strategy for eco-driving. It was pointed out that the inherent benefit of avoiding hard braking was reducing fuel-consumption and emission levels due to smoother driver behavior [130]. A previous study believed that an automobile was able to make more efficient use of its power by accelerating and decelerating smoothly [131]. It was also introduced that driving styles had a great influence on energy consumption for the same physical driving conditions because aggressive driving with speeding, rapid acceleration and hard braking wastes energy considerably [132].

For the application of in-vehicle traffic signals in a partial deployment scenario, the simulation results of average travel time in different penetration rates of in-vehicle traffic signals were shown in Fig. 5.17. It could be observed that the average travel time was in a decreasing trend with the increase of penetration rates.

It might be concluded that the application of in-vehicle traffic signals at signalized intersections might improve traffic flow by reducing unnecessary braking and acceleration operations, and travel time, based on the experiments and simulation results.

6.1.3. Visual distraction

As a visual-based ADAS system, driver distraction is an important safety concern for the in-vehicle traffic signal system, therefore, the visual distraction of the system should be analyzed [133]. Compared with a normal display, a head-up display is considered a suitable device for displaying information inside vehicles and does not require drivers to look away from their usual viewpoints [134]. Still, there is concern that head-up devices may be unsafe for displaying in-vehicle information.

As presented in Fig. 4.12, based on the analysis of the glance frequency in the experiments performed at signalized intersections, drivers tended to glance significantly more at the head-up display than at the normal 4.3-inch display. It was found that curiosity about the presence of the head-up display tended to increase the frequency of glancing at it [135], which might be an explanation for the high glance frequency when head-up display was applied. Furthermore, it was reported that, when comparing the speed gauge in a head-up display with a conventional speedometer, subjects had a higher glance frequency to the head-up display than to the speedometer [136]. Based on the high glance frequency, it was deemed that the head-up display, which was located high in the field of view and closer to the line of sight to the forward roadway, was placed conveniently for driver to observe [136]. However, if the glance frequency was the only metric that was taken into consideration, it might lead to the conclusion that head-up display was more distracting. It was noted that glance metrics, including glance frequency and mean glance duration, should not be interpreted separately as individual metrics, or it might lead to wrong conclusions because glance frequency and mean glance duration might be reciprocal [136]. Thus it is essential to analyze the mean single glance time together with the glance frequency to reach a dependable conclusion.

According to the mean single glance time results shown in Fig. 4.13, the mean single glance time to the head-up display was significant shorter than to the 4.3-inch display. When comparing Figs. 4.12 and 4.13, a negative correlation existed between glance frequency and mean single glance time, which was in agreement with the conclusions provided in [136]. Individual driver choice, resulting in two different glance strategies (more glances of a short glance duration compared with fewer glances of a long glance duration), were considered as a suitable explanation [137], [138]. Moreover, according to the research reported by Federal Highway Administration, the acceptable mean glance time away from the roadway was less than one second [140]. The mean single glance time on the head-up display of every participant, as shown in Fig. 4.13, was less than 0.5 s, which indicated that this type of display device did not affect driving safety. Also, when the head-up display and the 4.3-inch display were applied, the median values of mean single glance time were around 0.3 s and 0.5 s, respectively. An on-road driving study analyzed glance behaviors when using an in-vehicle smart driving aid, and found that the mean single glance duration to the in-vehicle information system was 0.43 s [141], which was comparable to this study and added further evidence of the reliability and accuracy of the method that was used here to process eye-gaze behaviors.

For the analysis of eye-gaze behaviors at unsignalized intersections, as shown in Fig. 4.23, the mean percent road center values were between 60% and 70% for all the conditions. A previous study reported that the percent road center values for attentive drivers were around 70−80% [142]. Another study also stated that the percent road center value under normal conditions was 75% [143]. The percent road center values obtained in this research were significantly smaller than those in the two previous studies. However, it was found that the percent road center was generally lower during a general driving session, ranging from 44% to 73% [96]. Therefore, we considered our percent road center data to be valid for evaluation. Moreover, the non-significant main effect of the in-vehicle traffic signals suggested that no significant increase in visual distraction was induced by the proposed system. Furthermore, the maximum percent road center values in all the conditions were around 80%. One study suggested that a percent road center value of more than 92% could be an indication of cognitive distraction [98]. The percent road center data in this experiment indicated that the in-vehicle traffic signals did not increase the level of cognitive distraction. For the results of mean glance duration, the mean values in the two conditions were around 0.4 s, as presented in Fig. 4.24. As a comparison, the mean glance duration to an in-vehicle analogue speedometer was between 0.4 s and 0.7 s [143]. Therefore, the mean glance durations to the head-up display in our study were deemed reliable and did not appear to affect driving safety.

Based on the analysis of eye-gaze behaviors, it could be concluded that no significant driver distraction was induced by the usage of in-vehicle traffic signal system.

As a conclusion, the application of in-vehicle traffic signals at intersections could successfully offer positive effects on traffic systems, including the improvement of driving safety and traffic flow, without inducing negative effects, including driver distractions. Moreover, the positive effects provided by the in-vehicle traffic signals would not only exist in full deployment situations, but also in partial deployment scenarios, when the penetration rate changes from 0% to 100%.

6.2. Issues related with the application of in-vehicle traffic signals

6.2.1. Application in partial deployment scenario by monitoring drivers' trust

It was demonstrated that the effectiveness of the in-vehicle traffic signals in a partial deployment scenario was related with drivers' trust on the system. To better apply the system in a partial deployment scenario, it will be a smart choice to monitor drivers' trust state in real time while using the system.

Several previous studies have been performed to try to detect the over trust state of users. Researchers from Nagoya University tried to apply sensors to measure people's behaviors while they were in over trust state, and construct a database of the behaviors related with over trust. A warning system was then proposed to warn the users if an over trust behavior was detected [75]. For the monitoring of drivers, researchers from Tsukuba University proposed a collision avoidance support system based on unconstrained monitoring, and a human machine interface was used to suppress drivers' over trust. If an over trust state was detected from drivers' brain activity and pulse waves, a warning would be provided for the drivers [76]. Another previous research proposed a method to monitor driving operations including the steering, acceleration and brake operations, and compared the observed data of these operations with the predicted data. If a significant difference was found in the comparison, the system would send a warning to the drivers [77].

Therefore, a trust monitoring system may be a choice to cooperate with the in-vehicle traffic signal system in partial deployment scenarios. Driver behaviors including driving operations and eye-gaze behaviors can be monitored in real time and the obtained data can then be used for the estimation of drivers' state. If it is observed that the drivers are over trust on the system, a warning can be provided for the drivers.

6.2.2. Validity of driving simulator experiments

Operation range is one of the essential parameters in the application of in-vehicle traffic signs. It is normally decided, considering the quality of vehicular communications and the speed limit of the road. The operation range was set as 150m in the driving simulator experiments at signalized intersections. In real driving conditions, it is possible that a driver can see the ground traffic lights 150 meters away from an intersection. However, it depends on many external factors including the weather, traffic conditions and time of day. Therefore, the current mode of in-vehicle traffic signals can work as a reference point for drivers. In the driving simulator experiment, drivers could not clearly see the ground traffic lights 150 meters away from an intersection. It was designed based on the policy on geometric design of highways and streets, published by American Association of State Highway and Transportation Officials, considering the design speed and stopping sight distance [144].

For the validity of the results of driving simulator experiments, even though considerable efforts were taken to make the simulation experiments close to a road experience, driving behaviors within a driving simulator cannot be expected to replicate real-world driving behavior precisely. Driving conditions in reality are more complicated, although the traffic flow within the driving simulator was set according to the real traffic conditions. However, the trends observed in the driving simulator were similar to real-world driving in despite of these limitations, while the driving simulator was applied in driver behavior studies [145]. As a driving simulator study, the experiment has an advantage of providing exactly the same experimental condition for every participant. For the experiment which investigated the in-vehicle traffic signals considering waiting time at unsignalized intersections, it was essential to thoroughly manage the major-road traffic flow and gaps during this experiment, which was extremely difficult to be implemented with real vehicles. A driving simulator was therefore considered suitable for performing this kind of experiment. Moreover, for the driving simulator experiments which were performed to analyze the changes of drivers' trust on the system, the influence of drivers' trust state on the changes of trust was not considered. It is difficult to investigate the influences of successful and failed usages on the change of trust while the drivers were in different states of trust, as the drivers' trust changed discontinuously. As the simulations for analyzing the effects of penetration rate on driving behaviors were performed with drivers' initial trust and the changes of trust while using the system, the results might be more realistic if drivers' trust state was taken into consideration. Nevertheless, the results of the simulations in this study were considered reliable, as they were consistent with the results of the driving simulator experiments which were performed for investigating the driving behaviors in different penetration rates.

Chapter 7

Conclusions

Conclusions

Intersections are one of the most common and essential places in transportation systems which will influence the driving safety and traffic flow. To solve traffic problems at intersections, advanced driver assistance systems attracted the interests of many researchers over recent decades. Contributing to this interesting topic, this study tried to apply an in-vehicle traffic signal system to assist drivers in crossing signalized and unsignalized intersections. This dissertation primarily focused on the effects of the in-vehicle traffic signals on driving behaviors based on driver models considering look ahead information and validated the proposed system by performing experiments and simulations for different penetration rates.

In Chapter 1, the background of this research, including the existing traffic problems at intersections and previous studies on providing driver assistances at intersections were introduced. Meanwhile, Chapter 1 also provided a brief introduction of the in-vehicle traffic signals concept.

Chapter 2 introduced the methodology of in-vehicle traffic signals in different penetration rate environment. For the in-vehicle traffic signal system in full deployment scenarios, the driver model was proposed considering the influences of look-ahead information. For the driver model while using the in-vehicle traffic signal system in a partial deployment scenario, the car following behaviors were taken into consideration at signalized intersections. As for the unsignalized intersections, the effects on driving behaviors were analyzed considering drivers' trust on the system.

The implementations of in-vehicle traffic signals at signalized and unsignalzied intersections were presented in Chapter 3. For the application at signalized intersections, two modes of in-vehicle traffic signals were proposed: current mode and predicted mode. In the current mode, the real time signal of the upcoming ground traffic light was directly displayed to drivers. In the predicted mode, the signal of ground traffic light when drivers arrived at the upcoming intersections were predicted based on the predicted time to intersection and the signal cycle information of ground traffic light. For the application at unsignalized intersections, the in-vehicle traffic signals were proposed for two-way and all-way stop-controlled intersections, respectively. At the two-way stop-controlled intersections, the gap acceptance theory was applied to decide whether a minor-road vehicle could enter the intersections or not. At the all-way stop-controlled intersections, the first-come-first-serve method was applied to decide the order of crossing.

Chapter 4 were focused on providing the details of the experiments for full deployment scenarios. A driving simulator experiment was elaborated at signalized intersections to evaluate the two modes of in-vehicle traffic signals presented by two kinds of in-vehicle displays, respectively. The results indicated that by applying the predicted mode of in-vehicle traffic signals, braking and accelerating operations were significantly reduced. Meanwhile, the mean single glance time for the head-up display was significantly shorter than for the normal 4.3-inch display. It is believed that the predicted mode of in-vehicle traffic signals might prompt driving performances, and the head-up display was deemed suitable for the display of in-vehicle traffic signals without inducing driver distractions. We also tested the effectiveness of the system to assist drivers in passing through unsignalized two-way and all-way stop-controlled intersections. Meanwhile, this study proposed in-vehicle traffic signals with the consideration of waiting time to better assist drivers in crossing unsignalized intersections. Experimental results demonstrated that the in-vehicle traffic signals significantly improved post-encroachment time and decreased maximum brake stroke, which implied that driving safety was enhanced. In terms of eye-gaze behaviors, the percent road center and mean glance duration values indicated that the system did not present an increase in visual distraction. The proposed system was therefore deemed to be reliable in terms of providing driver assistance at unsignalized intersections. Moreover, for minor-road and major-road experiments considering waiting time, in the minor-road case, the application of in-vehicle traffic signal considering waiting time significantly reduced the maximum gas pedal stroke and blink rate, which indicated that the aggressive driving of minor-road vehicles might be successfully avoided. Meanwhile, a significant decrease was observed in the maximum lateral acceleration with the consideration of waiting time, which represented that a better steering stability might be achieved. For the major-road case, it was observed that the post-encroachment time significantly increased and the perception response time was significantly reduced by applying the system while considering waiting time. The results indicated that the in-vehicle traffic signal might enhance drivers' ability to detect the entry of other vehicles, which would contribute to a safe driving. Based on the results of post-encroachment time, it was believed that the driving safety of major-road drivers could be ensured when the in-vehicle traffic signal considering waiting time was applied.

In Chapter 5, the information of the experiments and simulations for partial deployment scenarios were provided. An actual vehicle experiment involving two electric vehicles was conducted at a signalized intersection to investigate the influences of in-vehicle traffic signals on driver behaviors. Different from driving simulator studies, the actual vehicle experiment investigated the driver behaviors of both preceding and following cars, considering the existence of vehicles without in-vehicle traffic signals. It was observed that the maximum deceleration significantly decreased when predicted traffic signal information was displayed to drivers with the in-vehicle traffic signals. Furthermore, for a following car without in-vehicle traffic signals, a significant decrease in maximum deceleration could also be found if its preceding car was in-vehicle traffic signals equipped. Meanwhile, the travel time of a preceding car could be significantly reduced by applying in-vehicle traffic signals. For a following car without in-vehicle traffic signals, its travel time could also be significantly reduced when the preceding car was in-vehicle traffic signals equipped. The results indicated that the driving performances of a following car might be significantly improved if its preceding car was equipped with in-vehicle traffic signals. For the applicability of the in-vehicle traffic signal system in a partial deployment condition at unisgnalized intersections, a driving simulator experiment was conducted to investigate the influences of successful and failed usages on drivers' trust. Traffic simulations and experiments were then performed to analyze the driving safety while applying the system in different penetration rates. It can be observed that the near miss accidents could be reduced in any penetration rate of the system, compared to the condition when no in-vehicle traffic signal system was applied. Moreover, the number of near miss accidents might increase at first with the increase in penetration rate. Afterwards, the numbers of near miss accidents could be reduced with the increase in penetration rate when the penetration rate was larger than 50%.

In Chapter 6, the influences of in-vehicle traffic signals on driving behaviors, including the driving safety and traffic flow were discussed. Afterwards, issues related with the application of in-vehicle traffic signals, especially the application in partial deployment scenarios by monitoring drivers' trust, were discussed.

In Chapter 7, it concludes the details and significances of this research.

The contributions of this dissertation are highlighted as follows:

(1) The effects of in-vehicle traffic signals on driving behaviors were analyzed based on the driver models considering the influences of look ahead information. It was confirmed that the application of in-vehicle traffic signals could produce positive effects, including the improvement of driving performances and the reduction of driver workload, without producing negative effects, including driver distraction and the impairment of driving safety;

(2) For the application of in-vehicle traffic signals in partial deployment conditions, the influences on driving behaviors were investigated based on driver models considering look ahead information, car following behaviors and drivers' trust on the system. It was demonstrated that the in-vehicle traffic signals could still have certain positive influences

on the traffic systems without impairing driving safety, even at the stage when the penetration rate changed from 0% to 100%;

(3) It was revealed that the acceleration and braking operations could be significantly reduced by providing predicted traffic signal to drivers, which might contribute to the ecological driving, when the in-vehicle traffic signals were applied in full deployment scenarios at signalized intersections. For the application of in-vehicle traffic signals within full deployment scenarios at unsignalized intersections, it was demonstrated that the post-encroachment time of vehicles significantly increased, indicating a significant improve in the driving safety. Moreover, a better steering stability might be achieved if the waiting time was considered in the implementation of in-vehicle traffic signals;

(4) It was proved that no visual distraction was induced by the application of in-vehicle traffic signals with the analysis of eye-gaze behaviors;

(5) For the influences of penetration rate on the application of in-vehicle traffic signals, an actual vehicle experiment was performed at a signalized intersection. It was indicated that an in-vehicle traffic signals equipped vehicle might influence the driving behaviors of the following unequipped vehicle, including a significant reduction in maximum deceleration. Meanwhile, the results of traffic simulations revealed that the average travel time at signalized intersections might be reduced with an increase in the penetration rate of in-vehicle traffic signals. As for the unsignalized intersections, it could be observed that the near miss accidents were reduced in any penetration rate of the system, compared to the condition when no in-vehicle traffic signal system was applied. Meanwhile, the number of near miss accidents might increase at first with the increase in penetration rate. Afterwards, the numbers of near miss accidents would be reduced with the increase in penetration rate when the penetration rate was larger than 50%;

(6) This study may offer useful references for the design and evaluation of visual-based driver assistance systems at intersections, and provide useful references for further applications of V2X communications in intelligent transportation systems.

References

[1] Kusano, K. D., and Gabler. H. C., Comprehensive target populations for current active safety systems using national crash databases, Traffic injury prevention, vol. 15, no. 7, pp. 753-761, 2014.
[2] NHTSA, Fatality analysis reporting system: analytical user's manual 1975–2015, U.S Department of Transportation, Washington DC, USA, 2016.
[3] Data Analysis Center for Traffic Accident, http://www.itarda.or.jp/materials/statistical.php, accessed June, 2017.
[4] Federal Highway Administration, U.S. Department of Transportation, https://safety.fhwa.dot.gov/intersection/conventional/unsignalized/, accessed June, 2017.
[5] State highway administration research report, The relationship between congestion levels and accidents. Md-03-sp 208b46 final report, http://roads.maryland.go v/OPR_Research/MD-03-SP308B46-Congestion-Vs-Accidents Report.pdf, accessed June, 2017.
[6] Martina, Z., Preethy, P., Maria, J., and Henning, W., Visual and auditory interfaces of advanced driver assistant systems for older drivers, International Conference on Computers for Handicapped Persons: Computers Helping People with Special Needs, Linz, Austria, pp. 62-69, 2008.
[7] Hounsell, N. B., Shrestha, B. P., Piao, J., and McDonald, M., Review of urban traffic management and the impacts of new vehicle technologies, IET Intelligent Transport Systems, vol. 3, no. 4, pp. 419–426, 2009.
[8] Vashitz, G., Shinar, D., and Blum, Y., In-vehicle information systems to improve traffic safety in road tunnels, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 11, no. 1, pp. 61–74, 2008.
[9] Birrell, S. A., Fowkes, M., and Jennings, P. A., Effect of using an in-vehicle smart driving aid on real-world driver performance, IEEE Transactions on Intelligent Transportation Systems, vol. 15, no. 4, pp. 1801–1810, 2014.
[10] Harvey, C., Stanton, N. A., Pickering, C. A., McDonald, M., and Zheng, P., A usability evaluation toolkit for In-Vehicle Information Systems (IVISs), Applied Ergonomics, vol. 42, no. 4, pp. 563–574, 2011.
[11] Maciej, J., and Vollrath, M., Comparison of manual vs. speech-based interaction with in-vehicle information systems, Accident Analysis & Prevention, vol. 41, no. 5, pp. 924–930, 2009.
[12] Young, M. S., and Birrell, S. A., Ecological IVIS design: using EID to develop a novel in-vehicle information system, Theoretical Issues in Ergonomics Science, vol. 13,

no. 2, pp. 225–239, 2012.
[13] Roya, E. P., Simulation based evaluation of advanced driver assistance systems. Linköping Studies in Science and Technology, Licentiate thesis no. 1735, 2015.
[14] Oliver, C., and Fergus, T., Intelligent speed adaptation: the best collision avoidance system? Institute for Transport Studies, The University of Leeds, https://www-nrd.nhtsa.dot.gov/pdf/esv/esv17/Proceed/00152.pdf, accessed June, 2017.
[15] Jeong, A. J., Hyun, S. K., and Han, B. C., Smart roadside system for driver assistance and safety warnings: framework and applications, Sensors (Basel), vol. 11, no. 8, pp.7420–7436, 2011.
[16] Papaioannou, P., Driver Behavior, Dilemma zone and safety effects at urban signalized intersections in Greece, Accident Analysis and Prevention, vol. 39, Elsevier, Amsterdam, pp. 147-158, 2007.
[17] Zimmerman, K., and Bonneson, J. A., Intersection safety at high-speed signalized intersection: number of vehicles in dilemma zone as potential measure, Transportation Research Record, vol. 1897, Transportation Research Board, Washington, DC, pp. 126-133, 2004.
[18] Gang, L. C., Mark, F., and Yang, L., Design & evaluation of a dynamic dilemma zone system for a high speed rural intersection, Maryland State Highway Administration, pp. 1-65, 2012.
[19] Vadim, A. B., and Petros, I., Personalized driver assistance for signalized intersections using v2i communication, IEEE Transactions on Intelligent Transportation Systems, vol. 17, no. 7, pp. 1910-1919, 2016.
[20] National Highway Traffic Safety Administration, Traffic safety facts 2014, U.S. Department of Transportation, pp. 1–238, 2016.
[21] Federal Highway Administration, The design of a minimal sensor configuration for a cooperative intersection collision avoidance system - stop sign assist: CICAS-SSA report #2, U.S. Department of Transportation, pp. 1–61, 2010.
[22] Moon, Y. J., Jang, B., and Choi, J. D., All way stop controlled collision avoidance system using wireless sensors at unsignalized intersections, Proceeding of 16th ITS World Congress and Exhibition on Intelligent Transportation Systems and Service, Stockholm, Sweden, pp. 1–13, September 2009.
[23] Jang, J. A., Choi, K., and Cho, H., A fixed sensor-based intersection collision warning system in vulnerable line-of-sight and/or traffic-violation-prone environment, IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 4, pp. 1880–1890, 2012.
[24] Liu, M., Lu, G., Wang, Y., and Tian, D., Automatic detection of traffic conflicts at

unsignalized intersections using image sequences, Proceeding of COTA International Conference of Transportation Professionals, Beijing, China, pp. 2452–2459, August 2012.
[25] Qiao, F. X., Wang, X. B., Yu, L., and Jia, J., Using radio frequency identification to improve drivers' awareness of stop sign at unsignalized intersections, Transportation Research Board, pp. 1–20, 2013.
[26] Max, D., Craig, S., Nicolas, J. W., and Janet, C., Intersection decision support: an overview report #6 in the series: developing intersection decision support solutions, University of Minnesota, 2007.
[27] David, R., Sofia, A., Steven, E. S., James, A. M., and Ching, Y. C., Gap acceptance for vehicles turning left across on-coming traffic: implications for intersection decision support design, Transportation Research Board 85th Annual Meeting, pp. 1–25, Washington, D. C., USA, 2006.
[28] National Highway Traffic Safety Administration, Traffic safety facts 2010, U.S. Department of Transportation, Washington, D. C., USA, 2012.
[29] National Cooperative Highway Research Program, NCHRP report 500, vol. 5: a guide for addressing unsignalized intersection collisions, Transportation Research Board, 2003.
[30] Jacob, F., Arvind, M., Alec, G., Craig, S., and Max, D., Range sensor evaluation for use in cooperative intersection collision avoidance systems, IEEE Vehicular Networking Conference, pp. 1–8, Tokyo, Japan, 2009.
[31] Van, M. P., Correlation of design and control characteristics with accidents at rural multi-lane highway intersections in Indiana: interim report, FHWA/IN/JHRP-77/22, Indiana, USA, 1977.
[32] Streubel, T., and Hoffmann, K. H., Prediction of driver intended path at intersections, Proceedings of the IEEE Intelligent Vehicles Symposium, pp. 134–139, Dearborn, USA, 2014.
[33] Burchett, G., and Maze, T., Rural expressway intersections that contribute to reduced safety performance, The 2005 Mid-Continent Transportation Research Symposium, pp. 1-14, Iowa, USA, 2005.
[34] Cabrera, M. D., Cerri, P., and Medici, P., Robust real-time traffic light detection and distance estimation using a single camera. Expert Systems with Applications, vol. 42, no. 8, pp. 3911-3923, 2015.
[35] Vehicle Information and Communication System Center, Traffic signal prediction systems, http://www.vics.or.jp/know/service/tsps.html, accessed December, 2018.
[36] Toyota Motor Corporation, ITS Connect, http://toyota.jp/technology/safety/itsconnect/, accessed December, 2018.

[37] Judy, A., Washington auto show displays the latest in automated safety features, https://www.techlicious.com/blog/washington-auto-show-latest-automated-safety-features/, accessed December, 2018.
[38] National Highway Traffic Safety Administration, Traffic Safety Facts 2009, U.S. Department of Transportation, pp. 1–232, 2010.
[39] Owsley, C., Driver capabilities, in Clarke A.J. (Ed.), Transportation in an Aging Society: A Decade of Experience, Transportation Research Board, 1st edition, pp. 44–55, 2004.
[40] Owsley, C., and McGwin, G., Vision and driving, Vision Research, vol. 50, no. 23, pp. 2348–2361, 2010.
[41] Tonguz, O. K., Biologically inspired solutions to fundamental transportation problems, IEEE Communications Magazine, vol. 49, no. 11, pp. 106–115, 2011.
[42] Hagenauer, F., Baldemaier, P., Dressler, F., and Sommer, C., Advanced Leader Election for Virtual Traffic Signals, ZTE Communications, Special Issue on VANET, vol. 12, no. 1, pp.11–16, 2014.
[43] Ferreira, M., and Orey, P. M., On the impact of virtual traffic signals on carbon emissions mitigation, IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 1, pp. 284–295, 2012.
[44] Ferreira, M., Fernandes, R., Conceição, H., Viriyasitavat, W., and Tonguz, O. K., Self-organized traffic control, ACM International Workshop on VehiculAr InterNETworking, pp. 85–90, New York, USA, 2010.
[45] Monreal, C. O., Gomes, P., Silvéria, M. K., and Ferreira, M., In-vehicle virtual traffic signals, a graphical user interface, 7th Iberian Conference on Information Systems and Technologies, Madrid, Spain, pp. 1–6, 2012.
[46] Conceição, H., Ferreira, M., and Peter S., Virtual traffic signals in partial deployment scenarios, Proceedings of the IEEE Intelligent Vehicles Symposium, Gold Coast, Australia, pp. 988–993, 2013.
[47] John, M. S., Michael, J. F., Anuj, K. P., and Shan, B., Literature review of behavioral adaptation to advanced driver assistance systems, Transportation Research Institute, The University of Michigan, pp. 1-55, 2016.
[48] Lundgren, J., and Tapani, A., Evaluation of safety effects of driver assistance systems through traffic simulation, Transportation Research Record, vol. 1953, 2006.
[49] Vaa, T., Penttinen, M., and Spyropoulou, I., Intelligent transport systems and effects on road traffic accidents: state of the art, IET Intelligent Transport Systems, vol. 1, no. 2, pp. 81–88, 2007.
[50] Chorltona, K., and Conner, M., Can enforced behavior change attitudes: Exploring

the influence of Intelligent Speed Adaptation, Accident Analysis & Prevention, vol. 48, pp. 49–56, 2012.
[51] Zheng, R. C., Nakano, K., Yamabe, S., Aki, M., Nakamura, H., and Suda, Y., Study on emergency-avoidance braking for the automatic platooning of trucks, IEEE Transactions on Intelligent Transportation Systems, vol. 15, no. 4, pp. 1748–1757, 2014.
[52] Zheng, R. C., Yamabe, S., Nakano, K., and Suda, Y., Biosignal analysis to assess mental stress in automatic driving of trucks: palmar perspiration and masseter electromyography, Sensors, vol. 15, no. 3, pp. 5136–5150, 2015.
[53] Yang, B., Zheng, R. C., and Nakano, K., Application of in-vehicle traffic lights for improvement of driving safety at unsignalized intersections, IEEE Intelligent Vehicles Symposium, Seoul, pp. 628-633, 2015.
[54] Yang, B., Zheng, R. C., Kaizuka, T., and Nakano, K., Influences of waiting time on driver behaviors while implementing in-Vehicle traffic light for priority-controlled unsignalized intersections, Journal of Advanced Transportation, Article ID 7871561, pp. 1-12, 2017.
[55] Yang, B., Zheng, R. C., Kaizuka, T., Nakano, K., Analysis of driver behaviors while using in-vehicle traffic light with partial deployment of V2I communication, IEEE Intelligent Vehicles Symposium, Changshu, China, pp. 19-24, 2018.
[56] Maria, S., Factors correlated with traffic accidents as a basis for evaluating advanced driver assistance systems, Accident Analysis & Prevention, vol. 41, no. 5, pp. 1025–1033, 2009.
[57] Pettitt, M. A., Burnett, G. E., Bayer, S., and Stevens, A., Assessment of the occlusion technique as a means for evaluating the distraction potential of driver support systems, IET Intelligent Transport Systems, vol. 153, no. 4, pp. 259–266, 2006.
[58] Ranney, T. A., Garrott, R., and Michael J. G., NHTSA driver distraction research: past, present, and future, NHTSA, Washington, DC, pp. 1-9, 2000.
[59] Yang, B., Zheng, R. C., Yin, Y. D., Yamabe, S., and Nakano, K., Analysis of influence on driver behavior while using in-vehicle traffic signals with application of head-up display, IET Intelligent Transport Systems, vol. 10, no. 5, pp. 347-353, 2016.
[60] Doshi, A., Cheng, S.Y., and Trivedi, M. M., A novel active heads-up display for driver assistance, IEEE Transactions on Systems, Man, and Cybernetics—Part B: Cybernetics, vol. 39, no. 1, pp. 85–93, 2009.
[61] Yang, B., Zheng, R. C., Shimono, K., Kaizuka, T., and Nakano, K., Evaluation of the effects of in-vehicle traffic signals on driving performances for unsignalized intersections, IET Intelligent Transport Systems, vol. 11, no. 2, pp. 76–83, 2017.
[62] Zheng, R. C., Nakano, K., Ishiko, H., Hagita, K., Kihira, M., and Yokozeki, T., Eye-

gaze tracking analysis of driver behavior while interacting with navigation systems in an urban area, IEEE Transactions on Human-Machine Systems, vol. 46, no. 4, pp. 546–556, 2016.
[63] Allen, B. L., Shin, B. T., and Cooper, P. J., Analysis of traffic conflicts and collisions, Transportation Research Board, pp. 67–74, 1979.
[64] Gettman, D., Pu, L., Sayed, T., and Shelby, T., Surrogate safety assessment model and validation, final report, National Academy Press, Washington, D.C., 2008.
[65] Ragnhild, J. D., Marjan, P. H., Peter, C. W., and Wiebo H. B., Effects of in-car support on mental workload and driving performance of older drivers, Human Factors: The Journal of the Human Factors and Ergonomics Society, vol. 51, no. 4, pp. 463-476, 2009.
[66] Haitao, X., Kanok, B., and Matthew, B., Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits, Journal of Intelligent Transportation Systems, Technology, Planning, and Operations, vol. 17, no. 1, pp. 31-41, 2012.
[67] Saboohia, Y., and Farzaneh, H., Model for developing an eco-driving strategy of a passenger vehicle based on the least fuel consumption, Applied Energy, vol. 86, no. 10, pp. 1925-1932, 2009.
[68] Anargiros, I. D., Ioannis, K. N., and Markos, P., Simulation of the penetration rate effects of ACC and CACC on macroscopic traffic dynamics, IEEE 19th International Conference on Intelligent Transportation Systems, Rio de Janeiro, Brazil, pp. 336-341, 2016.
[69] Highway Safety Manual, American Association of State Highway and Transportation Officials, Washington, DC, 2010.
[70] Treiber, M., and Kesting, A., Traffic Flow Dynamics: Data, Models and Simulation, Springer-Verlag, Berlin, Heidelberg, pp. 1-506, 2013.
[71] Hao, L., Heng, W., Ting, Z., Li, Z., and Jeffrey, Y., Fine-tuning ADAS algorithm parameters for optimizing traffic safety and mobility in connected vehicle environment, Transportation Research Part C: Emerging Technologies, vol. 76, pp. 132-149, 2017.
[72] Mark, B., and Mike, M., Car-following: a historical review, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 2, no. 4, pp. 181-196, 1999.
[73] Ministry of Land, Infrastructure and Transport, Guidelines of communication based driving assistance systems, http://www.soumu.go.jp/main_content/000288894.pdf, accessed December, 2018.
[74] Sayed, T., Brown, G., and Navin, F., Simulation of traffic conflicts at unsignalized intersections with TSC-Sim, Accident Analysis & Prevention. vol. 26, no. 5, pp. 593-607, 1994.

[75] Miwa, K., Importance of over trust research, http://kashin-free.jp/introduction/2009/11/post.html, accessed December, 2018.
[76] Itoh, M., Contributing factors to driver’s over-trust in a driving support system for workload reduction, Transactions of the Society of Instrument and Control Engineers, vol. 45, no. 11, pp. 555-561, 2009.
[77] Inagaki, T., The design of automated driving system and legal system that consider the characteristics and limits of human perception and judgment, https://kaken.nii.ac.jp/ja/grant/KAKENHI-PROJECT-15H05716/, accessed December, 2018.
[78] National Research Council, Highway Capacity Manual, Transportation Research Board, Washington, D. C, 2000.
[79] Fitzpatrick, K., Gaps accepted at stop-controlled intersections, Transportation Research Record, pp. 103–112, 1991.
[80] Steven, M. T., Michael, A. K. J., and David, S. H., Connecting gap acceptance behavior with crash experience, Transportation Research Board, 2011.
[81] Abishai, P., Yoram, S., and Sitvanit, S. L., Evaluation of the waiting-time effect on critical gaps at roundabouts by a logit model, EJTIR, vol. 5, no. 1, pp. 1-12, 2005.
[82] Pollatschek, M. A., Polus, A., and Livneh, M., A decision model for gap acceptance and capacity at intersections. Transportation Research Part B, vol. 36, pp. 649–663, 2002.
[83] Thakonlaphat, J., and Kazushi, S., Effect of waiting time on the gap acceptance behavior of u-turning vehicles at midblock median openings, Journal of the Eastern Asia Society for Transportation Studies, vol. 9, pp. 1601–1613, 2011.
[84] Turki, I. A. O. and Mohammad, S. E., Gap acceptance behavior at u-turn median openings – case study in Jordan, Jordan Journal of Civil Engineering, vol. 7, no. 3, pp. 332–341, 2013.
[85] Nabaee, S., An evaluation of gap acceptance behavior at unsignalized intersections, Oregon State University, 2011.
[86] Tupper, S. M., Safety and operational assessment of gap acceptance through large-scale field evaluation, University of Massachusetts Amherst, 2014.
[87] Devarasetty, P. C., Zhang, Y. L., and Fitzpatrick, K., Differentiating between left-turn gap and lag acceptance at unsignalized intersections as a function of the site characteristics, Journal of Transportation Engineering, vol. 138, no. 5, 2012.
[88] Japan Automobile Manufacturers Association, Guidelines for in-vehicle display systems–version 3.0, JAMA, pp. 1–15, 2004.
[89] Smart Eye AB., User manual for Smart Eye Pro 5.9, Smart Eye AB, Sweden, 2012.
[90] Takegami, T., and Gotoh, T., Vision-based algorithm for eye movement detecting

using corneal reflection and iris contour, Institute of Electronics, Information, and Communication Engineers, vol. J82-D-I, no. 10, pp. 1295–1303, 1999.
[91] Wu, H., Palekar, M., Fujimoto, R., et al., An empirical study of short range communications for vehicles, 2nd ACM Int. workshop on Vehicular ad hoc networks, Cologne, Germany, pp. 83–84, September 2005.
[92] Garmin Nuvi 40LM Navigator, http://www.amazon.com/Garmin-Nuvi-40LM-Navigator/dp/B00TAEUMSM, accessed July 2015.
[93] National Highway Traffic Safety Administration, Visual-Manual NHTSA Driver Distraction Guidelines for in-Vehicle Electronic Devices, U.S. Department of Transportation, pp. 1–281, 2013.
[94] American Association of State Highway and Transportation Officials, A policy on geometric design of highways and streets, AASHTO, pp. 1–905, 2001.
[95] Ahmed, A., Sadullah, A. F. M., and Yahya, A. S., Field study on the behavior of right-turning vehicles in Malaysia and their contribution on the safety of unsignalized intersections, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 42, no. 3, pp. 433-446, 2016.
[96] Ahlstrom, C., Kircher, K., and Kircher. A., Considerations when calculating percent road center from eye movement data in driver distraction monitoring, 5th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, Iowa City, United States, pp. 132–139, June 2009.
[97] Department of Transportation, Guidelines for reducing visual-manual driver distraction during interactions with integrated, in-vehicle, electronic devices, NHTSA, pp. 1–46, 2010.
[98] Victor, T. W., Keeping eye and mind on the road, PhD thesis, Uppsala University, 2005.
[99] Roidl, E., Frehse, B., and Höger, R., Emotional states of drivers and the impact on speed, acceleration and traffic violations - a simulator study, Accident Analysis & Prevention, vol. 70, pp. 282–292, 2014.
[100] Amanda, N. S., and John, A. G., Situational specificity of trait influences on drivers' evaluations and driving behaviour, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 12, no. 1, pp. 29–39, 2009.
[101] Ramachandran, B. R. N., Romero, P. S. A., Born, J., Winkler, S., and Ratnam, R., Measuring neural, physiological and behavioral effects of frustration, 17th International Conference on Biomedical Engineering. vol. 61. Springer, Singapore, 2017.
[102] Fukuda, K., Eye blinks: New indices for the detection of deception, International Journal of Psychophysiology, vol. 40, no. 3, pp. 239–245, 2001.

[103] Mosa. A., and Stella. T. B., Spontaneous blink rate of a normal population sample, International Contact Lens Clinic, vol. 26, no. 2, pp. 29–32, 1999.
[104] Classen, S., Shechtman, O., Stephens, B. et al., The impact of roadway intersection design on driving performance of young and senior adults, Traffic Injury Prevention, vol. 8, no. 1, pp. 69–77, 2007.
[105] Transport Research Laboratory, UK, http://www.rulesoftheroad.ie/rules-for-driving/speed-limits/speed-limits_stopping-distances-cars.html, accessed December, 2018.
[106] Open Street Map, https://www.openstreetmap.org/, accessed 10 July 2017.
[107] Osakada, Y., Development of a program simulating behavior of a driver without right of way when crossing a non-signalized intersection, Naist-DD0661006, pp. 1-102.
[108] Road Traffic Act, http://elaws.e-gov.go.jp/search/elawsSearch/elaws_search/lsg0500/detail?lawId=335AC0000000105_20180401_429AC0000000052&openerCode=1, accessed December, 2018.
[109] Troutbeck, R., Unsignalized intersection theory, Queensland University of Technology, 1997.
[110] Takuya, H., Analysis of passing behavior of non-priority side at non-signalized intersections using time series measurement of vehicles' position, JSAE autumn conference, pp. 17-20, 2007.
[111] Sayed, T., Brown, G., and Navin, F., Simulation of traffic conflicts at unsignalized intersections with TSC-Sim, Accident Analysis & Prevention. vol. 26, no. 5, pp. 593-607, 1994.
[112] Troutbeck, R. J., Estimating the critical acceptance gap from traffic movements, research report 92-5, Queensland University of Technology, 1992.
[113] Chang, S., Lin, C., and Hsu, C., The effect of a collision warning system on the driving performance of young drivers at intersections, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 12, no. 5, pp. 371–380, 2009.
[114] Roberts, S., and Day, T., Integrating design and virtual test environments for brake component design and material selection, SAE Technical Paper, pp. 1–11, 2000.
[115] Waard, D., Brookhuis, K., and Toffetti A., Developments in human factors in transportation, design, and evaluation, Shaker Publishing, the Netherlands, pp. 1–363, 2006.
[116] Lee, Y. C., and Winston, F. K., Stress induction techniques in a driving simulator and reactions from newly licensed drivers, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 42, no. 1, pp. 44–55, 2016.
[117] Friedman, H. S., and Schustack, M. W., Personality: classic theories and modern

research (5th Edition), Pearson, UK, pp. 1–576, 2010.
[118] Björklund, G. M., Driver irritation and aggressive behaviour, Accident Analysis & Prevention, vol. 40, no. 3, pp. 1069–1077, 2008.
[119] Doughty M. J., and Naase T., Further analysis of the human spontaneous eye blink rate by a cluster analysis-based approach to categorize individuals with 'normal' versus 'frequent' eye blink activity, Eye Contact Lens, vol. 32, no. 6, pp. 294–299, 2006.
[120] Oh J., Jeong S. Y., and Jeong J., The timing and temporal patterns of eye blinking are dynamically modulated by attention, Human Movement Science, vol. 31, pp. 1353–65, 2012.
[121] Caird, J. K., Chisholm, S. L., Edwards, C. J., and Creaser, J. I., The effect of yellow light onset time on older and younger drivers' perception response time (PRT) and intersection behavior, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 10, no. 5, pp.383–396, 2007.
[122] McGehee, D. V., Mazzae, E. N., Baldwin, G. H. S. et al., Examination of drivers' collision avoidance behavior using conventional and antilock brake systems on the Iowa driving simulator, National Highway Traffic Safety Administration, pp.1–102, 1999.
[123] Mazzae, E. N., Barickman, F. S., Forkenbrock, G., and Baldwin, G. H. S, NHTSA light vehicle antilock brake system research program task 5.2/5.3: test track examination of drivers' collision avoidance behavior using conventional and antilock brakes, National Highway Traffic Safety Administration, pp.1–161, 2003.
[124] Shawarby, I.E., Ahn, K., and Rakh, H., Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions, Transportation Research Part D: Transport and Environment, vol. 10, no. 1, pp. 13–30, 2005.
[125] Younga, M. S., Birrella, S. A., and Stantonb, N. A., Safe driving in a green world: A review of driver performance benchmarks and technologies to support 'smart' driving, Applied Ergonomics, vol. 42, no. 4, pp. 533–539, 2011.
[126] Kamal, M., Mukai, M., Murata, J., and Kawabe, T., Ecological driver assistance system using model-based anticipation of vehicle–road–traffic information, IET Intelligent Transport Systems, vol. 4, no. 4, pp. 244–251, 2010.
[127] Gonder, J., Earleywine, M., and Sparks. W., Final report on the fuel saving effectiveness of various driver feedback approaches, National Renewable Energy Laboratory, 2011.
[128] Smart Driving, http://www.ucl.ac.uk/archaeology/about/facilities/green/tips/toptips1, accessed 20 July 2015.
[129] Bandivadekar A., Bodek, K., Cheah, L., Evans, C., Groode, T., Heywood, J., Kasseris, E., Kromer, M., and Weiss, M., On the road in 2035: Reducing transportation's

petroleum consumption and GHG emissions, MIT Laboratory for Energy and the Environment, Report No. LFEE 2008-05 RP, 2008.
[130] Servin, O., Boriboonsomsin, K., and Barth, M., 2006. An energy and emissions impact evaluation of intelligent speed adaptation, 2006 IEEE Intelligent Transportation Systems Conference, pp. 1257-1262, 2006.
[131] U. S. Department of Agriculture, http://www.fs.fed.us/sustainableoperations/greenteamtoolkit/documents/EcoDriving.pdf, 2016, accessed December, 2018.
[132] Kamal, M. A. S., Mukai, M., Murata, J., and Kawabe, T., Ecological driver assistance system using model-based anticipation of vehicle–road–traffic information, IET Intelligent Transport Systems, vol. 4, no. 4, pp. 244 – 251, 2010.
[133] Pettitt, M. A., Burnett, G. E., and Bayer, S., Stevens, A., Assessment of the occlusion technique as a means for evaluating the distraction potential of driver support systems, IET Intelligent Transport Systems, vol. 153, no. 4, pp. 259–266, 2006.
[134] Liu, Y. C., and Wen, M. H., Comparison of head-up display (HUD) vs.head-down display (HDD): Driving performance of commercial vehicle operators in Taiwan, International Journal of Human-Computer Studies, vol. 61, no. 5, pp. 679–697, 2004.
[135] Caird, J. K., Chisholm, S. L., and Lockhart, J., Do in-vehicle advanced signs enhance older and younger drivers' intersection performance? Driving simulation and eye movement results, International Journal of Human-Computer Studies, vol. 66, no. 3, pp. 132–144, 2008.
[136] Stanton, N. A., Advances in Human Aspects of Road and Rail Transportation, CRC Press, 1st edn, 2012.
[137] Dopart, C., Häggman, A., Thornberry, C., Mehler, B., Dobres, J., and Reimer, B., A driving simulation study examining destination entry with iOS 5 Google Maps and a Garmin portable GPS system, Human Factors and Ergonomics Society Annual Meeting, San Diego, United States, pp. 1889-1893, September 2013.
[138] Transportation Research Institute, Glance strategies for using an in-vehicle touch-screen monitor, The University of Michigan, pp. 1–27, 2009.
[139] Federal Highway Administration, Driver visual behavior in the presence of commercial electronic variable message signs, U.S. Department of Transportation, pp. 1–64, 2011.
[140] Birrell, S. A., and Fowkes, M., Glance behaviors when using an in-vehicle smart driving aid: A real-world, on-road driving study, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 22, pp. 113–125, 2014.
[141] Victor, T. W., Harbluk, J. L., and Engström, J. A., Sensitivity of eye-movement measures to in-vehicle task difficulty, Transportation Research Part F: Traffic Psychology

and Behaviour, vol. 8, no. 2, pp. 167–190, 2005.
[142] Jiménez, P., Bergasa, L. M., Nuevo, J., Hernández, N., and Daza, I. G., Gaze fixation system for the evaluation of driver distractions induced by IVIS, IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 3, pp. 1167–1178, 2012.
[143] Wierwille, W., and Tijerina, L., Modelling the relationship between driver in-vehicle visual demands and accident occurrence, Elsevier, pp. 233–243, 1998.
[144] American Association of State Highway and Transportation Officials, A policy on geometric design of highways and streets, AASHTO, pp. 1–905, 2001.
[145] Helland, A., Jenssenc, G.D., Lervågc, L.E., et al., Comparison of driving simulator performance with real driving after alcohol intake: A randomised, single blind, placebo-controlled, cross-over trial, Accident Analysis & Prevention, vol. 53, no. 1, pp. 9–16, 2013.

List of Publications

Academic Journals (With Reviewing)

[1] Bo Yang, Rencheng Zheng, Yuandong Yin, Shigeyuki Yamabe, Kimihiko Nakano, Analysis of influence on driver behavior while using in-vehicle traffic lights with application of head-up display, IET Intelligent Transport Systems, vol. 10, no. 5, pp. 347-353, 2016, DOI: 10.1049/iet-its.2015.0179 (Copyright @2016 The Institution of Engineering and Technology).

[2] Bo Yang, Rencheng Zheng, Keisuke Shimono, Tsutomu Kaizuka, Kimihiko Nakano, Evaluation of the effects of in-vehicle traffic lights on driving performances for unsignalised intersections, IET Intelligent Transport Systems, vol. 11, no. 2, pp. 76-83, 2017, DOI: 10.1049/iet-its.2016.0084 (Copyright @2017 The Institution of Engineering and Technology).

[3] Bo Yang, Rencheng Zheng, Tsutomu Kaizuka, Kimihiko Nakano, Influences of waiting time on driver behaviors while implementing in-vehicle traffic light for priority-controlled unsignalized intersections, Journal of Advanced Transportation, Article ID 7871561, pp. 1-12, 2017, https://doi.org/10.1155/2017/7871561 (Copyright @2017 Bo Yang et al.).

Proceeding of Academic Conferences (With Reviewing)

[1] Bo Yang, Rencheng Zheng, Kimihiko Nakano, Application of in-vehicle traffic lights for improvement of driving safety at unsignalized intersections, IEEE Intelligent Vehicles Symposium, Seoul, Korea, pp. 628-633, 2015, DOI: 10.1109/IVS.2015.7225755 (Copyright @2015 IEEE).

[2] Bo Yang, Rencheng Zheng, Tsutomu Kaizuka, Kimihiko Nakano, Implementation of in-vehicle traffic light with a real car based on vehicle-to-infrastructure communication, ITS World Congress, Montréal, Canada, pp. 1-6, 2017.

[3] Bo Yang, Rencheng Zheng, Tsutomu Kaizuka, Kimihiko Nakano, Analysis of driver behaviors while using in-vehicle traffic light with partial deployment of V2I communication, IEEE Intelligent Vehicles Symposium, Changshu, China, pp. 19-24, 2018, DOI: 10.1109/IVS.2018.8500424 (Copyright @2018 IEEE).

Proceeding of Academic Conferences (Without Reviewing)

[1] Bo Yang, Kimihiko Nakano, Rencheng Zheng, Yuandong Yin, Antonin Joly, Evaluation of effectiveness of in-vehicle traffic light assisting a driver to pass an intersection using a driving simulator, 12th ITS Symposium, Sendai, Japan, 1-2B-06, 2014.

[2] Bo Yang, Rencheng Zheng, Keisuke Shimono, Kimihiko Nakano, Evaluation of the method to assist a driver by displaying traffic signal in the vehicle, Spring annual conference of JSAE, Yokohama, Japan, no. 1248, 2015. (In Japanese)

[3] Bo Yang, Rencheng Zheng, Tsutomu Kaizuka, Kimihiko Nakano, Evaluation of in-vehicle traffic lights in assisting drivers to pass intersections considering waiting time, 13th ITS Symposium, Tokyo, Japan, 1-2A-09, 2015.