DEVELOPMENT OF DRIVING SIMULATION SYSTEM: MOVIC-T4 AND ITS APPLICATION TO TRAFFIC SAFETY ANALYSIS IN UNDERGROUND URBAN EXPRESSWAYS

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Development of Driving Simulation System: MOVIC-T4 and its Application to Traffic Safety Analysis in Underground Urban Expressways

Doctoral Dissertation

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ABSTRACT

In this research, driving simulation system 'MOVIC-T4' based on a new concept was developed for the traffic safety analysis in underground urban expressways which have unknown accident risks. And the deterioration of driver's awareness level was analyzed as the first approach to a traffic safety analysis in underground urban expressways. In the first stage of simulator development, a classical-style driving simulation system using the existing hardware system which consists of CRT monitor for the visual system and the fixed-base cockpit was developed. An original algorithm for controlling subject's vehicle and automated surrounding vehicle were mainly described in this stage. By using this simulator, traffic safety regarding the driver's awareness level in an underground urban expressway was analyzed. The simulator experiments were conducted on elderly drivers and taxi drivers. Driver's awareness level was measured by blinking frequency which correlates with the awareness level. Results of analyses indicated that at basic segment between merging/diverging sections in underground urban expressway, the driver's awareness level could significantly deteriorate, especially for elderly drivers as compared to taxi drivers. It was also shown that an audio information system that gives warning on approaching merging and diverging sections could prevent deterioration of the driver's awareness level. In the second stage of simulator development, a new driving simulation system 'MOVIC-T4' was developed which consists of Head-Mounted-Display (HMD) and 2 degree-of-freedom motion-base. In this stage, the algorithm for duplicating the acceleration cueing and vibration by the motion-base was mainly discussed. And the impacts of using HMD and motion-base on driving data were also investigated. In order to show the reliability of MOVIC-T4, the validity of behavioral and physiological data in the experiments with MOVIC-T4 was analyzed by using the field driving data. From this validity study, the differences of driving data between in a real world and in a simulator were clarified and the several implications to the experiment for traffic safety analysis with MOVIC-T4 were shown.

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平田 輝満

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Chapter1. Introduction

1.1. Background

1.1.1. Emergence of new-type road and necessity of prior assessment of traffic safety in nonexistent roads: underground urban expressway

There are still needs for new roadways such as the ring roads in metropolitan areas. In recent years, underground construction is often considered during planning for such new expressways in high-density urban areas (e.g. Central Artery in Boston, A86 in Paris, Chuo-kanjo and Gaikan Expressway in Tokyo). This is due to the lack of space for construction, the negative impacts on surrounding environment, and the division of the community.

In urban expressways, there may be many conflicts with other vehicles as a result of high traffic volume and the existence of merging or diverging sections. In tunnels, one usually drives under a high mental load because of low visibility and spatial pressure. And also the level of damages in terms of human lives and infrastructure costs in the event of a major accident can be very high. There is also very little change in the visual stimulus caused by a lack of variation in scenery. Consequently, the driver's awareness level can deteriorate (Kato, 1980). Deterioration of the awareness level does not mean drowsiness, but rather a deterioration of the attention level. The driver will tend to follow a certain vehicle inside a tunnel because of the difficulty in gauging a sense of speed. If the front vehicle is large-sized, the driver's visibility becomes even more limited. If this driving pattern is continued, the sense of speed is dulled and the driver can get the illusion that his/her vehicle is slowing down. In this state, one drives in synchrony with the front vehicle and the brain's activity level deteriorates. Awareness level deterioration slows down the driver's response to surrounding traffic (Kato, 1980, Nishimura, 1983), and deteriorates the useful visual field with the prolongation of the monotonous driving task (Roge et al, 2002).

Therefore, in an underground urban expressway, drivers are expected to face even higher risks under the combined pressure of driving inside a tunnel, and driving in an urban expressway. Due to these safety concerns, mitigation countermeasures need to be considered. Because there are no long urban expressway tunnels in existence yet, a driving simulator that can reproduce any kind of virtual roadway is necessary.

1.1.2. Necessity of communication with public in an infrastructure planning process

The transparency and accountability in the infrastructure planning is becoming more and more important. Sharing the information and knowledge with public can enhance the effectiveness and efficiency of infrastructure projects. In recent years, the innovation of information technology is rapidly progressing and we can easily use the technology in order to show the proposed projects. Especially in the roadway planning, the CG animation system and micro traffic simulator are usually used to show the image and effectiveness of proposed roadway. These communication tools are already used practically. And the tools successfully enhance the sharing the information and incorporating the public opinions.

In this study, the driving simulation system for analyzing the traffic safety in underground urban expressway is developed. During planning the new roadway project, the traffic safety must be analyzed with some technical methods such as statistical accident assessment, actual driving test and simulator study. The use of simulator study in traffic safety assessment may be increasing. Then the technical tools such as a driving simulator are considered to be also used as a communication tool with public if the system can be portable and low-cost. In order to use the simulator both as a technical tool and communication tool, the system must have an enough performance regarding traffic engineering and have a small footprint and low-cost.

1.2. Objectives of the study

This study has four main objectives. The first is to develop the driving simulation system using the existing system (hardware) which consists of CRT monitor for the visual system and the fixed-base cockpit. The basic software system including the algorithm for driving vehicle control and surrounding vehicle control are also developed. The second is to analyze the driver's awareness level in underground urban expressway using the above-mentioned driving simulation system. This classical-style driving simulation system has some limitations such as the narrow visual field of view and no duplicating the acceleration cueing, so it can be used in the limited study area. Therefore the new-type driving simulation system is needed to develop, which has better performance. This is the third objective. The fourth is to validate the newly developed driving simulation system "MOVIC-T4" using the field driving data. The validation study especially of an original simulator is indispensable for showing that this apparatus is eliciting similar responses as the normal real life situation.

1.3. Study flowchart

The dissertation is divided into 7 chapters and follows the flowchart shown below.

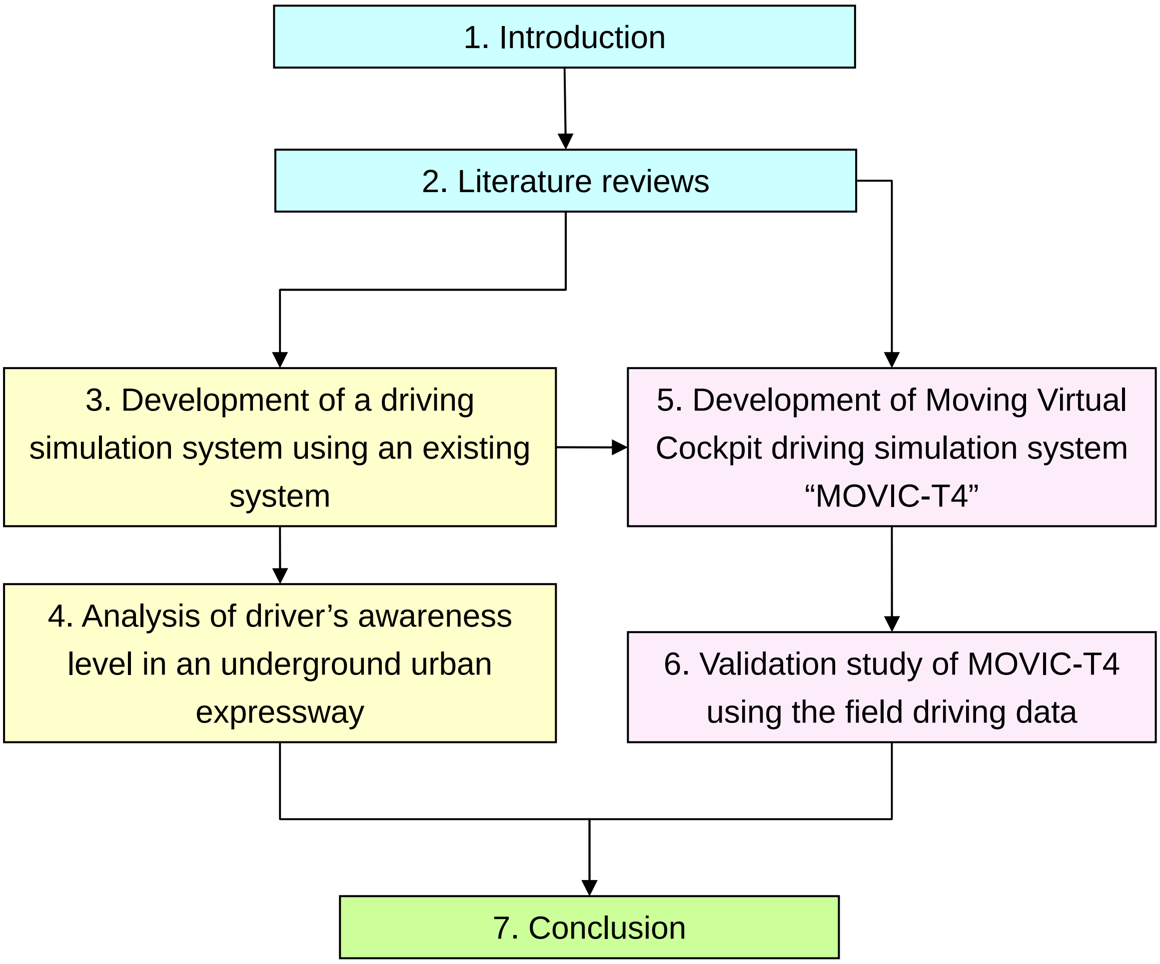


Figure 1-1 Research flow

Chapter 1 establishes the background and the objectives of the study.

Chapter 2 provides a discussion of past studies that are related to the subject of this dissertation. The related areas are: traffic safety issues in highway tunnel, traffic safety assessment methods, simulator development and methods to validate a simulator.

Chapter 3 describes the development of a classical-style driving simulation system using the existing system (hardware) which consists of CRT monitor for the visual system and the fixed-base cockpit. The algorithm for driving vehicle control and surrounding vehicle control are also described in this chapter.

Chapter 4 proceeds with the analysis of traffic safety regarding the driver's awareness level in an underground urban expressway. In this analysis, the relatively monotonous traffic conditions are assumed where the driver's awareness level can deteriorate even in underground urban expressway which may give high mental load to the drivers. After analyzing the possibility of awareness level deterioration, the effectiveness of giving audio information before entering the merging/ diverging sections is analyzed.

Chapter 5 describes the development of an original driving simulation system named MOVIC-T4 (Moving Virtual Cockpit) which have higher performance for analyzing the traffic safety on the higher risk traffic conditions and have portability and low-cost for using communication tool with public. The new system consists of Head Mounted Display (HMD) for the visual system and the small-sized motion-base with 2 degree of freedom, pitch and roll. In this chapter, the algorithm to control the motion-base to duplicating the acceleration cueing and vehicle vibration while driving is mainly discussed.

Chapter 6 describes the validation study of newly developed driving simulation system MOVIC-T4. In order to show the performance of this system, the field driving experiment and the simulator experiment are conducted on the same conditions, and the driving behavioral data and the physiological data in both experiments are compared. In addition, the contributions of acceleration cueing by motion-base and HMD are also analyzed in this analysis.

Chapter 7 gives the overall conclusions and future directions.

Chapter2.　Literature reviews

2.1. Traffic safety issues in a road tunnel

Tunnel sections have a lot of risk factors such as cause of traffic jam in entrance and exit, low visibility, and spatial pressure. The typical papers which describe the traffic safety are summarized in the following sections.

Traffic capacity in tunnel sections

Tunnel is usually focused on as the cause of traffic jams. Nagaseki (1992) shows traffic jams occur at pit mouth of tunnel because traffic capacity is diminished by low-velocity at pit mouth of tunnel. It is thought that low-velocity at that point is caused by psychology of drivers, for example, existence of wall surfaces in ceiling and aspects, visually spatial pressure and closure, and concern and tension come up from darkness and visual poorness in tunnel.

In connection with this low-velocity, Iio (1991) sums up Koshi (1984) as follows;
"Low-velocity occurs near the entrance of tunnel, and, as contrasted with speed reduction behavior of first car, follow-on car drivers are tend to reduce more speed than fore car, because drivers react laggardly in comparison with fore car driver. And if ever fore car driver doesn't reduce speed, generally it said that in tunnel distance between two cars is lager than usual distance, so follow-on car drivers reduce speed eventually. "

Oota (2000) purposes to figure out the influence tunnels in highway have on traffic jams, searches at the Yamato tunnel in Tomei highway using video cameras, and analyzes the data from search there. In detail, he analyzes the relations between velocities at each point, cumulative percentage of velocity, and distance between the heads of two cars, which are calculated with the data from video cameras. To conclude, he shows that the probability of traffic jams is very small because the velocities are not too different in the vicinity of entrance and exit of tunnel.

Ishibashi (2000) thinks that difference between brightness outside and inside tunnel, and tests that lights in tunnel has an influence on drivers' behavior. In consideration of the brightness inside and outside tunnel, the data are compared with categorized into 3 types; daytime, evening, and nighttime. The data are velocity, distance between two cars, gate opening of accelerator, flow-rate (inverse of distance between two cars), and coefficient of fluctuation of flow-rate (rate of sectional flow-rate against average flow-rate). But this hypothesis has not yet tested fully.

Nagaseki (1992) tries to observe influence of brightness in tunnel quantitatively with changing the brightness at Tsuburano tunnel. Characteristically, in this study heart rate is used. It is one of the physiological indicators. In addition to it, distance headway between the two cars, and creep from centerline of road are used. The result of analysis shows that velocity is not related with brightness but distance between the heads of two cars is related with it.

Iio (1991) analyzes influences of low-velocity and width of road shoulder in the pit mouth of tunnel. In this study, two experiments are done. One is that two tunnels which are similar except for width of road shoulder are observed and compared, and the anther is that tunnels are observed with varieties of the width of road shoulder. The result of analysis shows that the lager the width of road shoulder is, the nearer the status of driving (velocity, distance headway, and position of driving) inside and out side tunnel is.

Traffic accidents in tunnel sections

Matusura (1999) sums up the characteristics of traffic accidents in tunnel as follows.

- Traffic accidents occur in upper reaches, lower reaches and inside tunnel, in that order.
- Serious accidents are likely to occur.
- Many accidents occur during daytime
- There are a lot of rear-enders

As these causes, physiological and psychological factors are considered, for example, light adaptation, dark adaptation and so on. And below knowledge is summed up.

- Dark adaptation --- the phenomenon that when going out from dark place to light place, first field of view is bad, but little by little it goes well.
  -> It means that traffic accidents are likely to occur near entrance of tunnel, especially in the daytime.
- Light adaptation --- the phenomenon that when going from light place to dark place, first field of view is bad, but little by little it goes well.
  -> It means that traffic accidents are likely to occur near exit of tunnel,

especially in the daytime.

- Scary feeling --- Entrance of tunnel looks like a black hole, and tension goes up from the concern about approach to entrance.
  -> In entrance of tunnel, unconsciously low-velocity occurs, the probability of rear-enders goes up.
- Freedom --- When the exit of tunnel is seen, the psychological constrain is free.
  -> Attention to fore car is diminished.

Sugiyama (1998) experiments using real car in tunnel, and analyzes drivers' behavior to discuss steps to prevent an accident in tunnel. Experimental subjects are nine, and experimental place is Han-na tunnel. Each driver uses automatic car with instruments, and the velocities and accelerations are observed. The result of analysis shows that low-velocity occurs in entrance and exit of the tunnel, and inside the tunnel constant-velocity is observed comparatively.

Matsuura (1999) analyzes the characteristics of traffic accidents in tunnel using accident data from Transportation Authority in Tokyo Police and Institute for Traffic Accident Research and Data Analysis (ITARDA). Accident data show that traffic accidents in tunnel occur in upper reaches, lower reaches and inside tunnel, in that order, serious accidents are likely to occur, and many accidents occur during daytime.

Sugiyama (1999), in order to get basic data for safety measures of Westside road in Sendai, performs analysis of accident case examples about three road includes three tunnels in Westside road in Sendai, consciousness survey by questionnaires, observations of traffic stream, and driving experiments. The result shows that high-accident location is Kawauchi tunnel, and velocity is high in overtaking, so the probability of rear-enders is large.

Renge (1999), to discuss what problems tunnels and subsurface construction in freeway in urban area have, performs two types' driving experiments in Second Han-na road and Han-na tunnel. In the first experiment, driving behaviors' data, for example, velocity, accelerator, distance headway, and so on, are analyzed by zone of tunnel and by driver's age. The result of analysis shows that low-velocity occurs at entrance and exit of the tunnels. And in the second experiment, driving experiments using eye camera and analysis focused on drivers' point of regard are performed. The result shows that inside the tunnel drivers' point of regard tends to sink down short, so the probability that drivers don't get any information for driving safely exists, and near the exit of the tunnel drivers' point of regard tends to outside of tunnel, so the probability that attention to fore car is diminished exists.

And Renge (1999) also performs analysis about speed sense in long tunnel in highway. In this study laboratory experiments that display simulations of video footage from screen, which are consisted of 34 assumptions that are gotten from highway and freeway in Kansai area, are performed. The result shows that velocity is felt fast in light place in tunnel, cross-section area and ambient noise affects the feeling of velocity, in light place wall surface affects the feeling of velocity.

Iida (1999) performs comparison with the shape of pit mouth relatively, and to weigh up, driving experiments using driving simulator. In detail, on driving simulator the shape of pit mouth is changed, in each case driving behavior (velocity, accelerator, usage of brake, and so on) and physiological indicator (heart rate, drivers' point of regard, and so on) are compared. The result shows that though there is data spread widely, some of shapes are assessed by high score. And it's revealed that the shape of tunnel entrance can significantly affect the driving speed change.

Nagatsuka (1999), to purpose to reveal the characteristics and problems of driving in tunnel from drivers' consciousness, performs questionnaire survey. In this study, he performed analyses by students, drivers, professional drivers, age, and sex. The result shows that totally there is consciousness of going out of tunnel as soon as possible, and as the factors of this consciousness, concern about traffic jams, darkness, and visual poorness are considered.

Hatano (1999) analyzes influence that the changes of brightness and color in tunnel have on comfort during driving in tunnel, and discuss about it. The way of experiment is that varieties of color and brightness are displayed to screen, and in each case experimental subjects assess about 9 items of psychological measure by 5 points scale. The result shows that brightness of tunnel affects velocity, and color affects comfort, and tunnel in case of using high-pressure sodium vapor lamp or fluorescent lamp gets better assessment than tunnel in case of using low-pressure sodium vapor lamp.

Ohashi et al (2000) investigates the driver's mental load in Tokyo metropolitan expressway by using RR-interval measurement. They considers the several kinds of mental load index using RR-interval, and analyze the mental load with the viewpoint of roadway structure difference. The results show that the driver's mental load tends to increase at merging points, curved sections and tunnel sections.

Awareness level deterioration in tunnel

In tunnel, drivers usually drive under higher mental load due to its low visibility and spatial pressure. Therefore it's somewhat unimaginable that driver's awareness level can deteriorate in tunnel. However the visual scene inside tunnel can be considered to be more monotonous because of its monotonous wall surface design and darkness. This monotonous visual stimulus can cause the deterioration of driver's awareness level (Kato, 1980 and Nishimura, 1993). In this study, the driver's awareness level in underground urban expressway is analyzed for the first approach to analyze the traffic safety in an underground urban expressway. Therefore in this section, the previous researches related human's awareness level are summarized.

Yamamoto (1992) performs a series of driving experiments, and searches relation between eye movement during driving and arousal level. The result shows that arousal level can be assessed by duration of eye movement, travel time, and travel velocity. But he mentions that there aren't comfortable data about individual difference and intra-individual variation, and the other indicators are tried to assess arousal level with maximum accuracy.

Kishi (1992) introduces the way to assess arousal level with brain wave, and mentions the efficiency to use this method as background that development of expressway network makes long time travel, and there are a lot of particular traffic accidents caused by reduction of arousal level in express highway. And he introduces the rhythm of arousal level during long mindless job.

Hukui (1995) discusses the way to measure the reductive state of driver's steering function during continuative driving. In detail, the way to estimate process holdup time of steering and horizontal amount of displacement from performance of steering, and from these variations functional reduction is revealed.

Seko (1984) mentions that a lot of methods and devices to detect drive dozing have been produced from danger that reduction of arousal level caused by long time travel, mindless drive and driving nighttime occurs, and introduces explanation about phenomena caused by reduction of arousal level, and the ways to detect drive dozing. As physiological changes caused by reduction of arousal level, he introduces brain wave, eye movement, electro-dermal activity level, and heart rate.

Kawakami (1992) performs experiment using simple driving simulator about variation of heart rate from mental state before driving to driving state, reductive state of arousal level, and state of drive dozing, and researches the possibility of indicator of driving subservience.

As relation between arousal level and heart rate, he mentions,
1) Reduction of muscle activity and mental concentration causes reduction of absolute level or variation of heart rate.
2) Yawn and motion against sleepiness that go up heart rate can be considered as conflict between awakening and sleepiness.
3) In conflict, snooze occurs in the process of reduction of absolute level of heart rate. That is to say, when the will to awaken loses to sleepiness, it is considered that drivers fall asleep, and absolute level of heart rate is low in comparison with stable state of arousal level.
4) Individual differences of absolute level of heart rate are different in each case.

Akutsu (1995) pays attention to the way of information from vehicle, using estimated methods, for example, reduction of conscious level, detective and recognition of snooze, and so on, especially the way of using signal out of steering, signal of heart rate, and signal of eyewink in the process of information of living body, and discusses distinguishing items of the developing technologies that estimate reduction of conscious level.

Sugiyama (1996) mentions, as the way to measure reduction of driver's conscious level, the way to measure eyewink is taken a hopeful view on because it has possibility that it measures reduction of conscious level earlier. And the way to estimate reduction of conscious level from switching time of eyewink that is gotten from video camera that records driver's face.

Roge et al (2002) investigated the relationship between driver's useful visual fields and deterioration of awareness level induced by the prolongation of the monotonous driving task. The results indicated the monotonous driving task caused the deterioration the useful visual field.

Mochiduki (2002) introduces physiological indicators applied on assessment of driving, and reviews about these indicators. In these indicators, he pays attention on driver's tiredness, tension, and arousal level, and mentions that as indicators of assessment related them, HRV, adrenalin, and brain wave are produced, and the advancement of each method for analyzing is outstanding.

Nishio (2000) first checks the variation of indicators of assessment that is available to assessment of arousal level in laboratory experiments, and second checks them in case of driving outside to check whether these indicators are available outside too. The result shows that in outside driving electro-dermal activity and variation of eyewink is available to assess, but brain wave is not available to assess outside, and last he mentions there is difference during sensitivity of physiological indicators from differences the degree of reduction of arousal level.

Nishimura (1987) tries to assess driver's arousal level using the reflection of arousal level by electro-dermal activity. In detail, on freeway, the comparison between usual driving and the driving burdened by another task is discussed, and on testing ground the data of driver's brain wave, electrocardiogram, eye movement, and electro-dermal activity are gotten, the data also compared with the data on freeway. The result shows that the electro-dermal activity is similar to conscious level and subjectivity of experimental subjects, the variation of α-component of brain wave is not seen during driving, so relation with arousal level is not seen, there is relation between arousal level and frequency of eyewink, and about heart rate the relation is not seen.

Nishimura (1993), relative to transportation safety, treats phenomena that, through physical condition goes well, physiological and psychological influence caused by tasks causes reduction of arousal level, and finally snooze occurs. And he points out that the structures like a long tunnel cause the reduction of arousal level of drivers.

Hosaka (1983) produces the way to measure the reduction of arousal level using indicator of frequency of eyewink. As vegetative work, distinction of Morse code is used for 30~40 minutes, and indicators are eyewink, brain wave, and performance. The result shows that from this experiment it is considered that increase of frequency of eyewink is used as the base information to alarm to workers in asleep.

Kuramata (1993,1994), in his experiments, makes the vegetative condition (just sit on the chair, seeing the wall), observes on video camera the face of experimental subjects, burdens them when reduction of arousal level is checked, and observes the variation of arousal level between before and after burdening. As indicators of assessments, eyewink and SPL are chosen and as impulsions, music, exercise, communication, and gum are chosen.

Pierre et al (2003) investigated the effect of the degree of monotony of road surroundings, and the driving behavioral index to evaluate the awareness level. The simulator experiments indicated that the driver's steering amplitude data can be used for good indicator of awareness level, especially the frequency of large steering amplitude. And the degree of monotony of road surroundings (constantly positioned trees only vs. randomly positioned trees, houses, factories and pedestrians) can change the degree of deterioration of driver's awareness level.

2.2. Driving simulator issues

2.2.1. Advantages and disadvantages of simulator research

2.2.1.1 Advantages of simulator research

Coinciding with virtual reality technologies improvement, driving simulation system where one can drive virtually in any kind of a roadway was used as the main research tool in the current transportation engineering studies because of its many advantages offering over on-road experiments mainly conducted in the classical transportation studies. Discussed below are the advantages of using a driving simulator for the research area in the transportation engineering (and planning). The main advantages, some of which have been described by Nilsson (1993) in S. T. Godley (1999), concern experimental control, efficiency and expense, safety, conceptual solutions, and data collection.

1) Experimental control

Experimental control is perhaps the greatest asset of simulator based road research for a number of reasons. Firstly, many extraneous variables that can affect driver behavior can be controlled using a simulator. However, in on-road experiments, features such as pedestrians and animals, passing vehicles, objects on the road, and parked cars, can all lead to the exclusion of data for individual participants. In addition, weather can vary between participants or can delay experiments. Secondly, for research that manipulates the road environment, control roads can be precisely replicated so they are identical to the experimental roads except for the removal of the particular treatment variable of interest. By comparison, on-road experiments often use the same site before and after a road treatment has been introduced. This design introduces extraneous factors such as traffic flow, time of the year, weather, and seasonal differences. Such a method also does not counterbalance the order of presentation across participants between the control and treatment sites. Furthermore, a considerable duration in time is needed to complete experiments in this way. As an alternative to using the same location for on-road comparisons, control and experimental sites can be evaluated concurrently by matching different roads with and without the treatment of interest. This strategy raises the problem that no two real life road sites are exactly the same. Thus, this method introduces additional extraneous variables. Similar issues arise for studies that manipulate properties of the driver or vehicle rather than the road environment. In summary, simulator research allows the manipulation of independent variables while enabling all extraneous variables to be held constant.

2) Efficiency & expense

Simulator research is generally more efficient than on-road studies. Firstly, experiments require fewer participants as a consequence of the experimental control issues discussed above. In addition, relative to a laboratory approach, the proportion of the experimental session in which a participant's performance is not being measured is usually considerably higher in studies that involve an instrumented vehicle. Test routes are often situated away from the participant population, such as on rural roads. Moreover, each participant is usually required to drive on several test and control roads. These roads are not always adjacent to each other, prolonging the time each participant has to spend in the instrumented vehicle while not being measured. In comparison, simulator experiments can test each participant for a much shorter time, and have minimal driving while performance is not measured. Consequently, this allows for more treatments to be presented to each participant (assuming that the overall experiment session time remains constant). As such, simulators are more conducive to conducting experiments with repeated measures designs. Furthermore, when using a repeated measures design in a simulator experiment, all drivers can be exposed to identical environmental and experimental circumstances. This approach leads to less between-participant variation. Thus, a smaller number of participants are needed to obtain the same level of statistical power that would occur with larger number of participants in an on-road experiment (Nilsson, 1993). On-road investigations of driver behavior that modify the road or road environment are expensive, especially when a large range of treatments are evaluated. In contrast, the cost of implementing each treatment using a simulator is less expensive. Consequently, a larger number of sites may be evaluated using a simulator experiment. Altering road treatments for paint color, layout, or size, is also very rapid and inexpensive using a simulator compared to road trials, where even simple adjustments may require new sites.

3) Safety

Safety is another advantage of simulator research, allowing experimenters flexibility in what they can examine, while avoiding potential injury to participants. Driver behavior during critical decision times can also be studied using a simulator, such as when avoiding an accident and during an accident (Nilsson, 1993). Obviously, such studies are not feasible on the real road. Evaluating road treatments only after they are installed on public roads can waste public money by putting in place what later may be found to be ineffective safety devices. Many road safety studies examine ways to avoid accidents in certain situations or locations that either have high accident rates or are conducive to unsafe driving practices such as speeding. Others examine the performance of drivers impaired from alcohol, fatigue, and mental overload. Such circumstances, where accidents are known to be more common than usual, can be so dangerous that they are impossible to investigate with experimental participants in real vehicles due to the chance of accident involvement. However, all of these situations can be investigated safely using an appropriate simulator (Nilsson, 1993).

4) New developments and concepts

New developments in technology can be evaluated using a simulator while they are still in a stage of development or even while still in a conceptual stage. Examples of these developments are intelligent vehicle systems, such as anti-collision devises and future automated highway systems. New technology can be evaluated for its acceptance, usability and safety influences before it is ever installed in a real vehicle on the road (Nilsson, 1993). In addition, Assessment of traffic safety in roadway still in planning can be conducted with simulator. The target roadway of this research is also nonexistent one which might well increase in the future urban places.

5) Ease of data collection

Modern simulators can measure most, if not all, aspects of driver responses with relative ease. Although many measurements are also possible using an instrumented vehicle, they are not always as accessible or reliable. When measuring public traffic, the range of dependent variables that can be recorded is usually very limited, often incorporating only driving speed. Thus, the way a driver reacts to a particular experimental manipulation, such as by using the brake pedal or moving laterally to the edge of the lane, often cannot be measured. This constraint severely limits what can be learnt about driver behavior. Nilsson (1993) also comments that other monitoring equipment, such as video (of the scene and the driver), eye and head tracking equipment, and equipment for measuring physiological responses, are easy to arrange for a simulator. Again, these are not impossible in instrumented vehicle studies, but are much simpler using a simulator, as simulators are not limited to using portable equipment. However, the quality of the data gathered from such monitoring devices can be limited when used in a simulator. Visual scenes of simulators can be limited, sometimes including only the forward lateral 60 degrees (or less) of visual arc, or an oversimplified representation of the visual road environment, or both. Current developments in simulator technology, however, have overcome some of these concerns. Modern advanced simulators usually include larger visual scenes and realistic road environment characteristics and dynamics.

2.2.1.2 Disadvantages of simulator research

There are several advantages of driving simulation research as mentioning above. However, there are also several disadvantages (limitations) of driving simulator research such as the replication of the laws of physics and the realism of scenarios, simulator sickness, and the validity of results from simulator research.

1) Physical limitations & realism

Fixed-base simulators with a motion platform have a limited range of pitch and roll replicating vehicular movements whilst accelerating/decelerating and cornering, respectively. Therefore, there is a limit to how quickly drivers can perform these actions before they start to feel unrealistic (Nilsson, 1993). If this threshold is surpassed, drivers will notice the lack of G-force sensations. In turn, these actions can then become confusing to the driver. Rapid maneuvers that are not physically matched by simulator dynamics can also be conducive to simulator sickness, as will be discussed below. When braking, for example, an experienced driver may notice that the usual G-force associated with decelerating in a real vehicle is missing. This may then cause the driver to press the brake pedal harder, resulting in the simulator's motion stopping before they intended it to. If accurate and realistic deceleration is an important dependent variable for a simulator experiment, this issue can be serious. Therefore, drivers of the simulator need sufficient practice performing these actions so they will know how the simulator will react, and feel comfortable with any incomplete replication of these driving actions. That is, drivers may need to learn to drive the simulator based on visual and auditory senses more, and based on the sensation of horizontal movement less. In real vehicles, a temporal delay of approximately 100 msec usually exists between a pedal or steering action by the driver and the vehicle's response. Simulators can also have a delay additional to this to enable the visual scene to be drawn by the operating computer. This delay can be a problem for studies evaluating pure vehicle handling, but it should be much less of an issue for investigations of normal driving situations. This delay may, however, influence the occurrence of simulator sickness (discussed below) and the subjective realism experienced (Nilsson, 1993). For complex traffic situations, which are common in real life, complete replication in a simulator is very difficult or even impossible to achieve. This is because there are a large number of traffic situations that can occur, and because many of these situations occur in real life with uncertainty. Simulator experiments can also be restricted by the number of vehicles involved in a scenario due to issues of computer overload. Therefore, research involving large numbers of traffic interactions tends to be simplified on simulators, reducing the level of realism experienced by the drivers. As such, the results found need to be interpreted with caution. Realism is not a problem when the simulated driving task does not involve traffic situations, such as when investigating how drivers interact with road or environment conditions. As these circumstances do not require a large number of components, they can be fully represented, or represented without complete replication without changing the way drivers react to the environment (Nilsson, 1993).

2) Simulator sickness (main discussion from S. T. Godley (1999) or Michael A. Mollenhauer (2004))

An important limitation of simulator research is simulator sickness (also euphemistically known as simulator discomfort). Motion is essential for motion sickness, but simulator sickness can occur without motion. In addition, although simulator sickness is composed of a constellation of signs and symptoms similar to those occurring with motion sickness, it exhibits a different profile to motion sickness. Simulator sickness tends to be less severe, and has a lower rate of incidence. It also originates from elements of the visual display and visualvestibular interaction, as discussed below, which are atypical of the conditions that induce motion sickness. Symptoms of simulator sickness usually arise when the person is using the simulator, and may persist or even start to occur after usage. They can even last for more than six hours after the simulator session. Kennedy and Fowlkes (1992) have shown that simulator sickness is polysymtomatic, with some sufferers displaying all of the symptoms, whilst others only display a few. No single symptom predominates across sufferers, although visual epiphenomenona (eyestrain and dizziness) are particularly prevalent. Major reported symptoms for flight simulators at the time of use are nausea, drowsiness, general discomfort, pallor, headache, stomach awareness, disorientation, fatigue, and incapacitation. Vomiting, however, is rare. The most widely believed theory regarding the cause of simulator sickness involves cue conflicts, that is, from a disparity between a person's senses or within a single sense. Two senses are primarily involved, the visual sense and the vestibular (inner ear) sense, although the proprioceptive (body movements) sense may also contribute to cue conflicts. In fixed-base simulators, cue conflict occurs when a person's visual system senses motion, but their vestibular sense does not. In moving-base simulators, cue conflict occurs when the visual stimuli do not exactly match the motion that the vestibular system senses. An alternative, but less widely accepted theory on the aetiology of simulator sickness was proposed by Riccio and Stoffregen (1991). They argue that simulator sickness is caused by postural instability, or ataxia, which is a person's loss of full control of movements in their perception and action systems. They claim that ataxia both precedes symptoms of sickness, and is necessary to produce the symptoms. Kennedy and Fowlkes (1992) argue that simulator sickness is polygenic. That is, no single specific factor can be identified as its cause, but rather, many factors are involved. The rate of simulator sickness is, however, highly dependent on three aspects: the simulator used, the driving scenario presented, and the driver of the simulator. The detail of these elements can be seen in S. T. Godley (1999) or Michael A. Mollenhauer (2004).

3) Validity

Simulators must have real world validity to be useful human factors research tools. Two levels of validity associated with simulators have been proposed by Blaauw (1982). The first concerns correspondence between the simulator and the real world in the way the human operator behaves. He calls this behavioral validity, although it is commonly referred to as predictive validity. The second level is the physical correspondence between the simulator and its real world counterpart. This deals with issues such as the simulator's components, layout, and dynamic characteristics. Blaauw called this physical validity, but it is often simply referred to as a simulator's fidelity. It is often presumed that validity at this second level incorporates validity at the first level. Thus, simulator studies often report the physical correspondence, and usually do not mention, let alone analyze, the behavioral correspondence. In reality, however, the two levels are not always related (Blaauw, 1982). Researchers often account for physical validity through a description of their driving simulator, citing its many aspects that reproduce real life driving. The closer a simulator is to real driving in the way it is used, in the way stimuli are presented, and in the way it physically reacts to that stimuli, the greater the fidelity it is considered to have. Therefore, a moving-base driving simulator is often assumed to have greater physical validity than a fixed-base simulator. Although fidelity of a driving simulator is attractive, often too much importance is placed on it. In the search for simulators with ever greater fidelity, it should be remembered that, ultimately, no level of physical validity is useful to human factors research if behavioral validity cannot be established. Accordingly, a more sophisticated (and therefore greater physically valid) simulator may not have more behavioral validity than a less sophisticated and expensive one.

2.2.2. Validation study of driving simulator

As I mentioned in the previous section, the validity of the simulator is important in order to show that the analysis results are reliable. In the transportation engineering research area, the behavioral validity is necessary, however the physical validity is not always necessary. This is because the driving data in the experiments for the assessment of traffic safety or efficiency is usually used. Accordingly only validating the behavioral validity is necessary.

Behavioral validity has two level of validity as follows (Blaauw (1982)):
i) Absolute validity: Absolute validity is achieved if the numerical values between the two systems are the same,
ii) Relative validity: Relative validity is achieved if the differences found between experimental conditions are in the same direction, and have a similar or identical magnitude on both systems.

Tornoros (1998) observed that relative validity is necessary for a simulator, but absolute validity is not essential. This is because research questions usually deal with matters relating to the effects of independent variables, with experiments investigating the difference between a control and treatments, rather than aiming to determine numerical measurements. Some of the typical validation studies are introduced below.

Tornoros (1998) validated driving behavior in a simulated road tunnel. Speed and lateral position of 20 subjects were measured in a real tunnel and in the same tunnel implemented in the VTI driving simulator. In both situations a left-hand steered and manually geared passenger car was used. Driving speed was higher in the simulated tunnel than in the real tunnel. Elimination of speed information from the speedometer caused a similar small speed increase in both situations. Also, the difference in speed between driving lanes was similar in both cases. The effects on speed variation were similar to that for speed level. Regarding lateral position, subjects positioned the car somewhat further away from the nearest tunnel wall in the real tunnel than in the simulated tunnel. In both situations the distance to the nearest wall was greater when it was located to the left of the driver than on the opposite side. Lateral position deviation was about the same when the road was straight, but in a curved section it was somewhat greater for the simulated tunnel. It is concluded that behavioral validity in absolute terms was not quite satisfactory, especially regarding choice of speed, whereas relative validity was good for both speed and lateral position.

Iida et al (1999) investigated the validity of reliance on drivers' behavior from the driving simulator and the method of experiment using it. The validated driving data were speed, accelerator, the point of vision and slow-down at the entrance of tunnel. The results indicated that the trend of speed change and the point of view had no difference between in real world and in simulator. By using this simulator, the tunnel entrance design was assessed which aimed to prevent the speed decrease at the entrance.

S. T. Godley (2002) performed the behavioral validation of an advanced driving simulator for its use in evaluating speeding countermeasures for mean speed. Using mature drivers, 24 participants drove an instrumented car and 20 participants drove the simulator in two separate experiments. Participants drove on roads which contained transverse rumble strips at three sites, as well as three equivalent control sites. The three pairs of sites involved deceleration, and were the approaches to stop sign intersections, right curves, and left curves. Numerical correspondence (absolute validity), relative correspondence (or validity), and interactive (or dynamic) relative validity were analyzed, the latter using correlations developed from canonical correlation. Participants reacted to the rumble strips, in relation to their deceleration pattern on the control road, in very similar ways in both the instrumented car and simulator experiments, establishing the relative validities. However, participants generally drove faster in the instrumented car than the simulator, resulting in absolute validity not being established.

2.2.3. Driving simulator design

In recent years, the driving simulator is widely used for several research areas. And there are many types of simulator in the world. Main components of simulator might be the visual system and motion system. Visual systems have mainly 3 types including CRT monitor, Projection system (projector and wide screen) and Head mounted display (HMD). Most commonly used system is projection system because the wide field of view (FOV) can be relatively easily produced. HMD is not widely used, but the FOV can expand with the head-tracking sensor (however instant FOV is still narrow). And another advantage of HMD is considered to be its small-sized system while the projection system usually needs large space.

Regarding the motion system, there are several motion systems which have different degree of freedom (DOF) movement depend on the research purpose. Most of motion-system is 6-DOF simulator which have the movement: heave, pitch, roll, surge, sway and yaw. Some of the motion-system have extra movements: longitudinal or lateral long-distance movement using the rail system. And 2- or 3-DOF simulator is also sometimes used which has the movement: pitch and roll (and heave). Due to the limitation of movement, 2- or 3-DOF motion-base can be used in limited area.

Some of typical driving simulators are introduced below.

1) NADS in university of IOWA (http://www.nads-sc.uiowa.edu/)

NADS (National Advanced Driving Simulator) is the most advanced and largest driving simulator in the world. NADS has 360 FOV and 6-DOF and more bi-lateral travel movement.

4) VTI simulator (VTI: the Swedish National Road and Transport Research Institute)

6-DOF motion-base and lateral motion rail with multi screen and projector

2) DS of Mitsubishi Precision, Co. Ltd.

6-DOF motion-base with multi screen and projector (right figure: using real cab)

3) LADS at University of Leeds

Real cab and multi screen and projector without motion-base

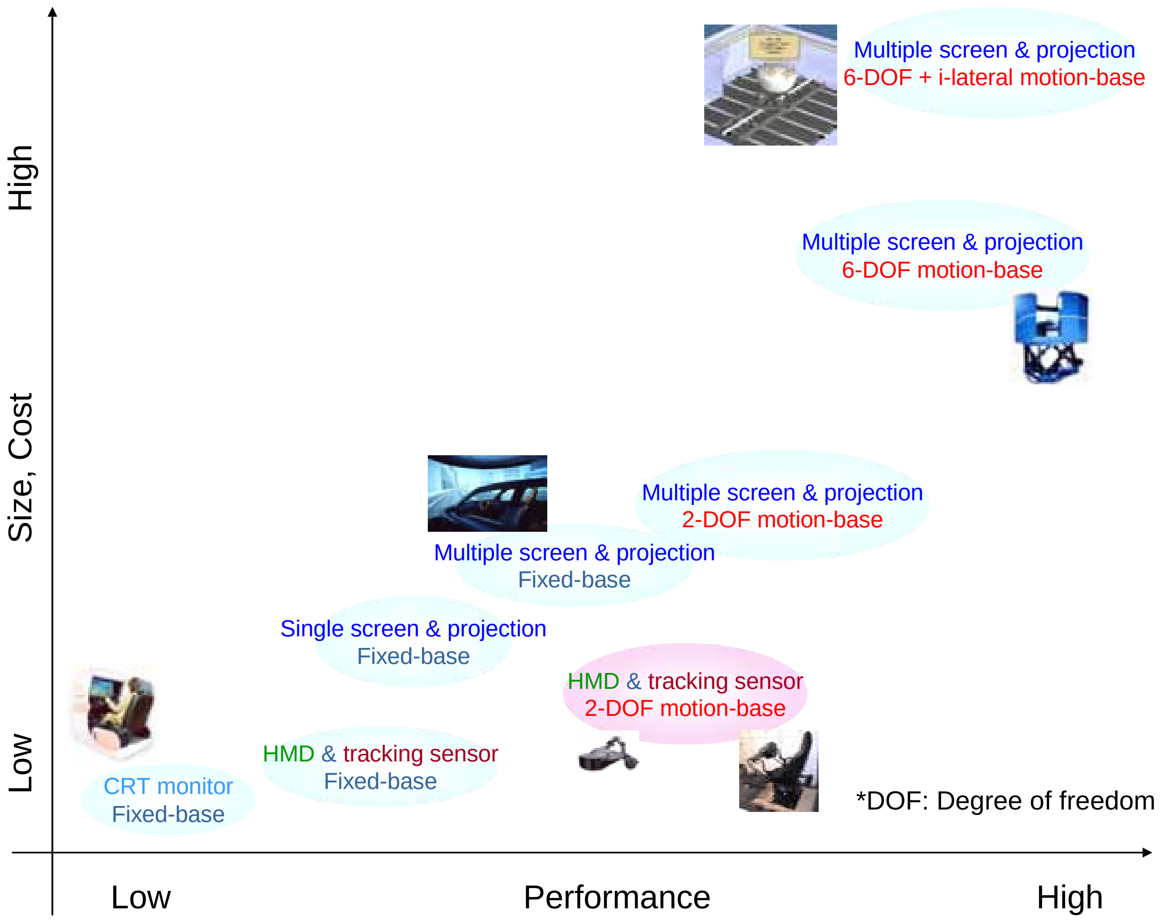


Figure 2-1 Performance, size and cost of several types of driving simulator

2.3. Direction of simulator development in this study

The objective of this study is to analyze the traffic safety in an underground urban expressway where one might drive under high mental load due to the low visibility and spatial pressure in tunnel and high frequent conflict with surrounding vehicles induced by high traffic volume and merging-diverging vehicles. Accordingly, drivers expect to run with frequent change of acceleration or deceleration, and look at side and rear view to check the traffic conditions there. It is therefore important to add a motion system to a simulator in order to duplicate the acceleration and turning of a vehicle. Moreover, the wider field of view is also needed when changing lane or merging. In this manner, more realistic driving behavioral and physiological data can be obtained. In addition, a small portable simulator can be used as a demonstration tool in addition to a safety analysis tool. Proposed new roadway projects can be shown to the public using this simulator. Then, the small-sized driving simulation system with high performance for the safety analysis is tried to develop in this study.

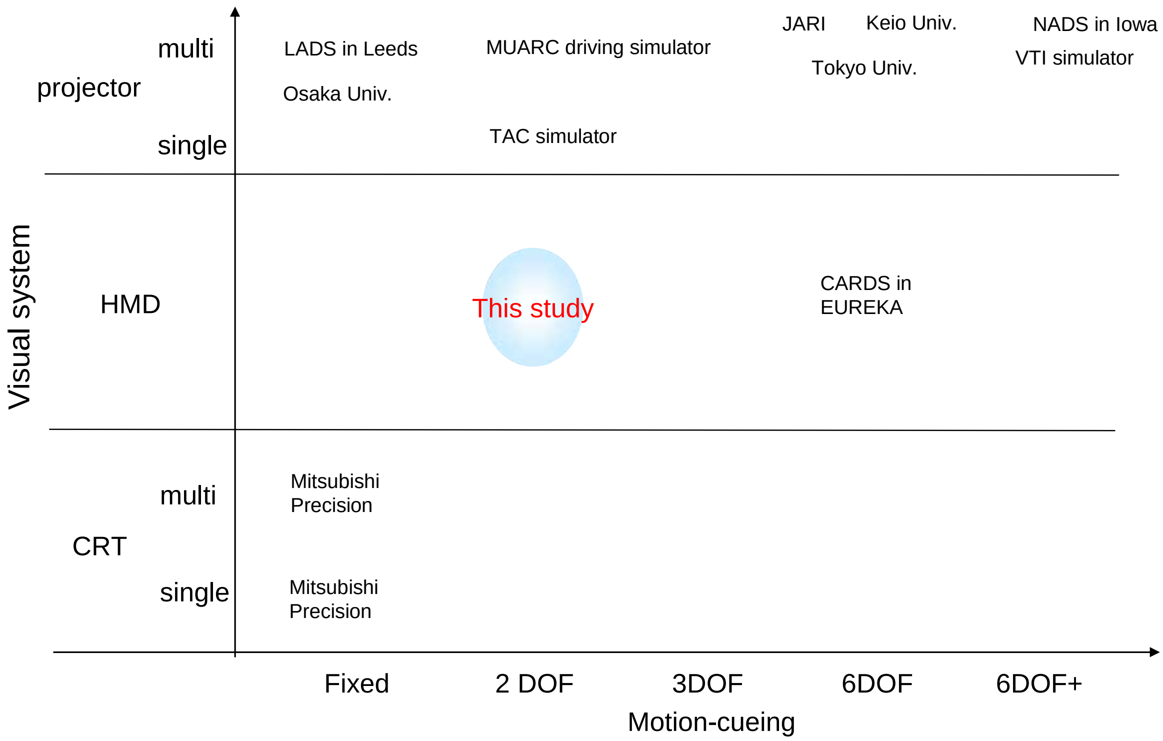


Figure 2-2 Variety of driving simulation system (Hardware components)

2.4. Summary

There are many researches describing the traffic safety issues in roadway tunnel. However, almost all researches deal with the traffic safety in the existing mountain tunnels. There are few researches which discuss the traffic safety in an underground urban expressway. This is because such kind of expressway has not been existed. Therefore the simulator study is needed to analyze the nonexistent road. And the additional utilization of simulator for a communication tool with public might be new point of view after the utilization of simulator as a technical tool including a traffic safety assessment.

		Mountain tunnel	Urban tunnel: short	Urban tunnel: long
Driving experiments	Simulator study	Lidstrom,M(1998) Akamatsu(2003) Jan Tornros(1998)		This study
	On-road study	Kato(1980) Nishimura(1993) Aso et al(1988) Lemke,K(2000) Iida et al (2003)	Ohashi et al (2000)	
Camera or detector survey		Koshi(1984) Nagaseki et al(1992) Sugiyama(1998)		
Statistical data analysis of safety in tunnel		Matsubara(1984) Hanshin Exp. Public Corporation (1999) Tecnosistemi group(2002)	Ogawa(1999)	

Figure 2-3 Related studies regarding the traffic safety in tunnel

Chapter3. Development of a driving simulation system using an existing system

3.1. Introduction

In this chapter, the development of the software to control the driving vehicle and the automated surrounding vehicle is mainly discussed as the 1st stage development of the driving simulation system using an existing hardware system (DS1). The developed software here is the basis of the new-type original driving simulation system: MOVIC-T4 described in chapter 5 (see Figure 3-1).

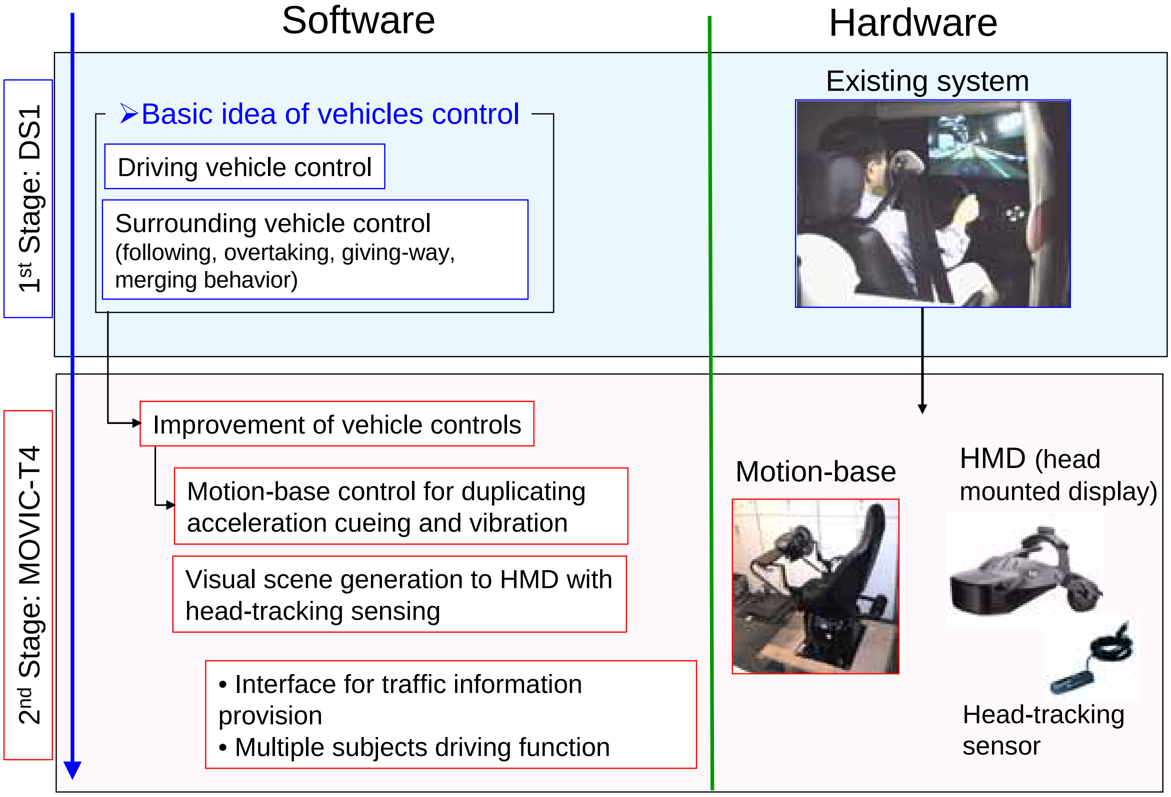


Figure 3-1 Two stages of driving simulation system development

3.2. General information of DS1

3.2.1. Hardware layout

The classical-style driving simulation system (called "DS1" in this study) uses the existing hardware including the display system, control devices and cockpit made by MITSUBISHI PRECISION CO. Ltd in Japan (http://www.mpcnet.co.jp/). The system components of DS1 are shown below.

Overall system components of hardware

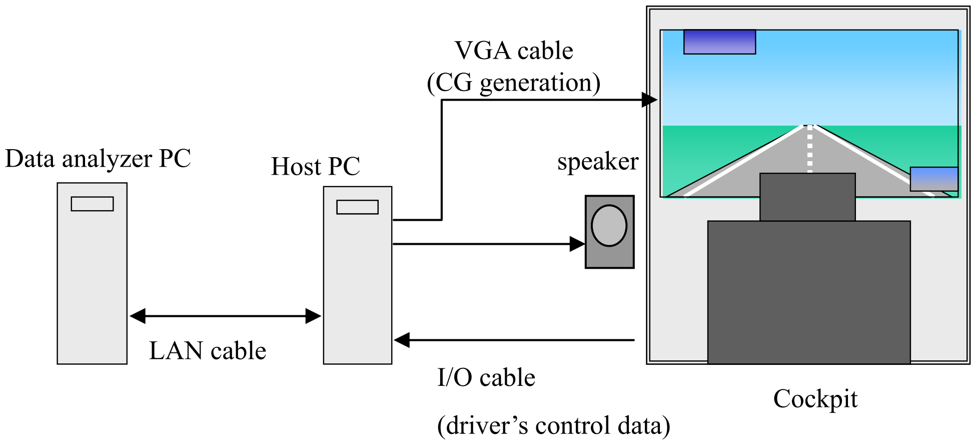


Figure 3-2 Hardware components

Figure 3-3 Photograph of DS1

Visual system
Type: CRT monitor (27 inch)
Resolution: 800 * 600 pixels
Frame rate: 30Hz (MAX 60Hz)

OS & language
Windows 2000
Microsoft Visual C++
WorldToolKit by SENSE8 (real-time 3D development tool, http://sense8.sierraweb.net/)

Control devices
Steering, Accelerator pedal, Brake pedal (Real vehicle devices)

3.2.2. Software layout

Overall system components of software

The state of subject's control vehicle is computed depend on the use of control devices. Surrounding vehicles run automatically according to the surrounding traffic conditions.

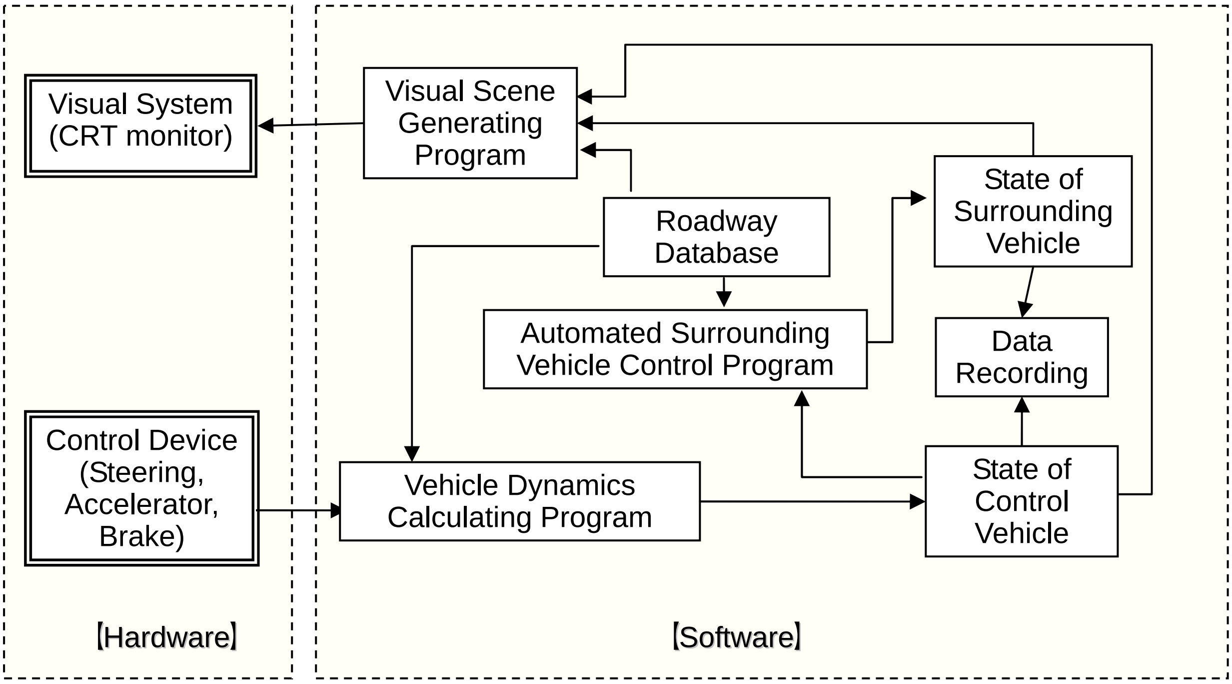


Figure 3-4 Software components of DS1

Recordable data

Subject vehicle: driving position, speed, accelerator amount, braking amount

Surrounding vehicles: driving position, speed

3.3. Driving vehicle control

The acceleration performance is the most important factor of driving vehicle performance. In the simulator, the simplified acceleration performance is applied. Figure 3-5 shows the acceleration performance of real vehicle which is normal passenger vehicle (AT). In real vehicle, the acceleration is changed according to the change of speed and gear position. However the change of acceleration is small especially in relatively higher speed. Therefore the simplified acceleration performance is applied to DS1 in order to lessen the computational amount (Figure 3-6).

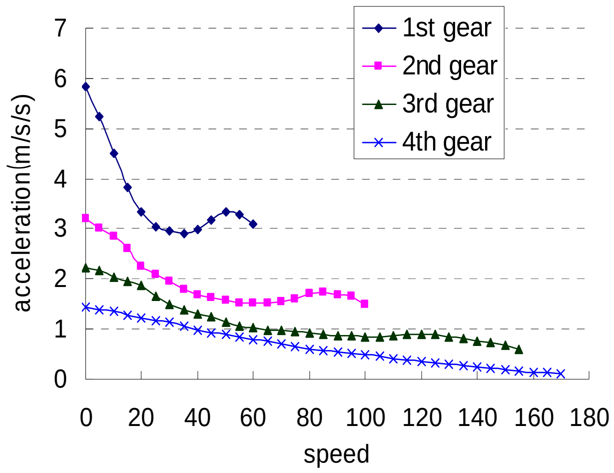


Figure 3-5 Acceleration performance of real vehicle (AT, 1500cc)

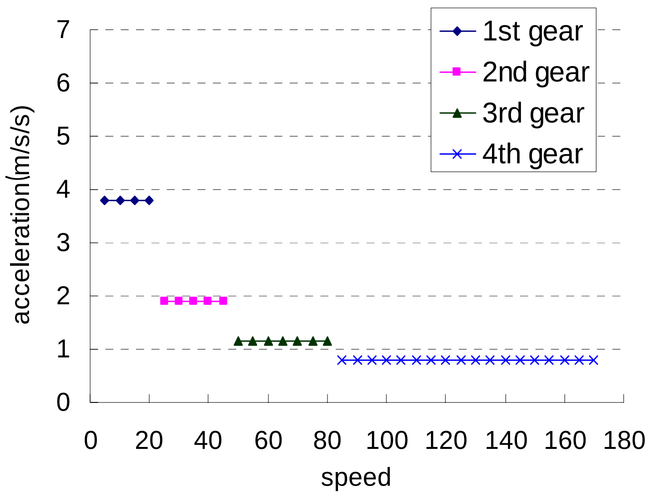


Figure 3-6 Acceleration performance of DS1

3.4. Surrounding vehicle control

3.4.1. Requirements of control algorithm of surrounding vehicles in DS

It is considered that surrounding vehicles control that occurs in DS also is the same as the control algorithm used in the studies of traffic simulation. But the study which discusses surrounding vehicles control deeply has not ever been seen, because in the studies in DS the main purpose is to analyze drivers' behavior at the particular points for example at pit mouth in tunnel. Partly some studies that use DS discuss surrounding vehicles control, but these studies just say "surrounding vehicles follow the fore cars by control logic of the system, but in the range that surrounding vehicles don't give any influence to fore cars, their speed changes in a circle in the range of 50km/h±5km/h that is regulatory speed in fog (Akita et al, 2001)", and "moving these surrounding vehicles in regular logic" (Oguchi et al, 2001).

And Nishi and Majid (2000) install the traffic flow simulation established as basic on the observation on the scene and, considering surrounding vehicles and interactions, establish the system that measures driver's behavior in merging section, and discuss the possibility of its availability. Experimental site is Ichinohashi JCT in Metropolitan expressways, and the experiment deals with driver's behavior only at merging section in heavy traffic. In traffic flow simulation, vehicle behavior model that gives surrounding vehicles good distance headway by its speed (S-V relation), and calculates the acceleration for the good distance is used. In the merging sections the car that merges onto the main line has the S-V relation with the fore car that runs on the main line, and the car that runs on the main line also has the S-V relation with the fore car that merges onto the main line. In upper reaches and zone of merging section, run-away phenomena are recreated.

In this study, driving algorithm of surrounding vehicles control is discussed in the expressway that consists of three main lines and one line of merging section (two lines structurally).

There are two differences between surrounding vehicles control algorithm in DS and traffic simulation, as follows.

- In DS, experimental subjects drive actually, so repeatability of DS is requested. In

DS there is threat that the repeatability is recreated because amount of calculations are used to create 3DCG images, and if surrounding vehicles algorithm needs more calculations to create images, the capacity of calculator may be over.

- In traffic simulation the main purpose is to analyze traffic flow, so there is not very serious influence if car stops suddenly and the collapse occurs suddenly. But in DS, if those cases occur, they may cause serious influences to driver ’ s behavior, so the algorithm that completes the smooth driving is requested.

In these constraints, it is discussed to recreate the maximum performance in comparison with the characteristics of real driving.

3.4.2. Control algorithm of surrounding vehicles at basic segment

In car following model, in almost all studies the algorithm as follows is produced.

*Moderate speed is given to each surrounding vehicles. In free drive, they drive at moderate speed, and when the distance between two cars is under the good distance (S-V relation), they begin to reduce their speed.

The thesis that discusses the decision model of acceleration in detail has ever been seen, so the process to calculate acceleration is not clear.
<Examples>
“ If actual distance headway between the two cars is smaller than the desired distance headway between them, rear car is considered as following vehicle, and it is ordered to reduce the speed (Nakamura et al, 1992).”
“Just when time headway between the two cars is the same as the time between them in following vehicles that each car has with a distribution, rear car is ordered to do following vehicles model (Matsumoto et al, 1992).”

Oguchi (2000) sums up literature reviews about the decision model of acceleration in tracing behavior model, but he mentions, “General characteristics of the structure of the model that occurs traffic jams without rear-enders are not clear.” From this mention, it is considered to use restraint in discussing the structure of the decision of acceleration in the thesis. In this study, the main purpose is not to analyze traffic flow, so it is not necessary to recreate constitution of traffic jams, speed reduction wave, and amplification transmission to upper reaches in detail, the model that the frequency of rear-enders is small minimally is discussed.

In this point of view, in this study the decision model of acceleration that Gazis and Herman suggest and that is well known all over the world is used. And in this study it is necessary to change accelerations in case by case, so the formula as follow is used.

$$a_{n+1} = \lambda \frac{\{v_{n+1}(t)\}^m}{\{x_n(t) - x_{n+1}(t)\}^l}[v_n(t) - v_{n+1}(t)]$$

a : *acceleration*, x : *location*, v : *velocity*, λ, m, l : *parameters*
n : *number of vehicles, in this case, n means fore vehicle, and* $n+1$ *means tracing vehicle*

But if this formula is only used, driving of constant speed occurs when relative speed between two cars is 0km/h, and in the case of narrow distance between two cars rear car is not ordered to reduce the speed. So the algorithm that orders to continue to reduce speed for rear car when the distance between two cars is under the moderate distance is used in this study.

In the parameters of m, l in this formula, from the points of the consistency of macroscopic curve of velocity vs. density some combinations are introduced, but the theses that discuss parameter of λ in detail are not found. In this study if the parameter of λ is defined by myself, from the various distances between two cars and combinations of relative speeds it must be decided seriously.

Driving characteristics that recreate in single line

Table 3-1 shows that driving characteristics in express highways that recreate in this study.

Table 3-1 Driving characteristics in express highway (single line)

	Driving characteristics
1	Moderate velocity in free driving
2	Moderate distance between two cars is the function of velocity
3	Reducing speed if the distance between two cars is under the moderate distance (acceleration is the function of large when velocity, relative velocity, and the distance)
4	When the relative speed is plus if the distance is narrow, there is only reducing speed just a bit, and there is no braking
5	When the distance is narrow, if fore car's velocity is very lower than moderate speed, overtaking occurs. If there is not remarkable difference of velocity, rear car remains to trace fore car.
6	In overtaking, in lateral gap of overtaking lane, if TTC between two cars is over ○○seconds or minus, and the distance is over □□m, lane change to next lane occurs. Before that, tracing fore car
7	Acceleration in overtaking is different by type of vehicle and velocity at that time (heavy traffic' acceleration is small, and load capacity influences to acceleration)
8	When overtaking is finished, go back to the first lane. If don't go back to the lane, remain to drive with moderate speed until going back
9	In overtaking lane, change lane if fast tracing car appears. On the other hand, tracing car in overtaking lane remains tracing the fore car until the fore car changes lane.

* the parts of hatching□□□Originalities in this study

Desired distance headway

Fundamentally, the lager velocity is, the lager distance between two cars is.

In this study, the relation is expressed the linear formulas as Figure 3-7. The parameters of the formulas can be changed for adjustment of traffic flow of surrounding vehicles, and for fitting on experimental conditions.

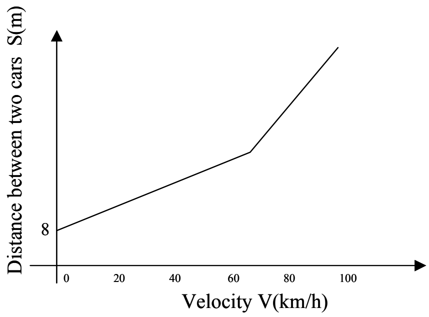


Figure 3-7 The relationship between desired distance headway and velocity

Decision model of acceleration (in reducing speed in narrow distance headway))

Already mentioned, the model that Gazis and Herman suggest, and that is well known all over the world is used.

$$a_{n+1} = \lambda \frac{\{v_{n+1}(t)\}^m}{\{x_n(t) - x_{n+1}(t)\}^l}[v_n(t) - v_{n+1}(t)]$$ a：acceleration, x：location, v：velocity
In this case, n means fore car, and n+1 means tracing car

⇒ Each parameter can be installed.

Algorithm

Figure 3-8 shows general flow and algorithm in detail of surrounding vehicles control algorithm in basic segment.

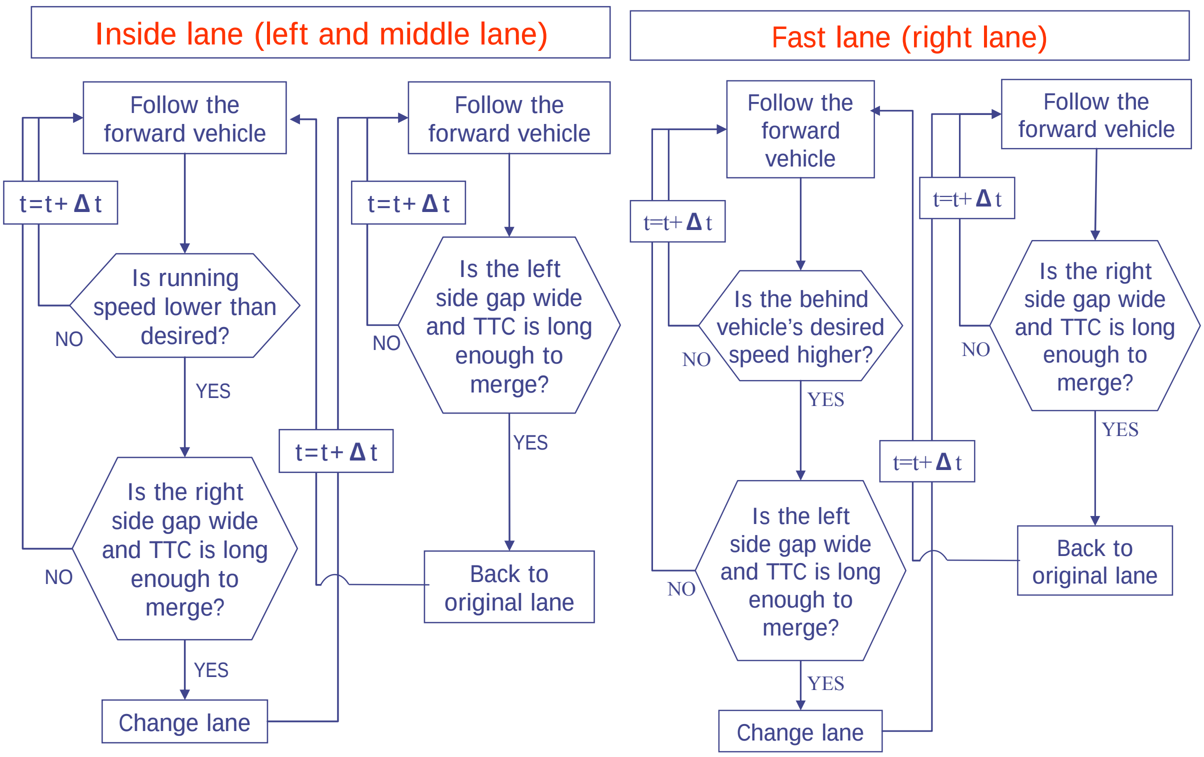


Figure 3-8 General flow of driving model in basic segment

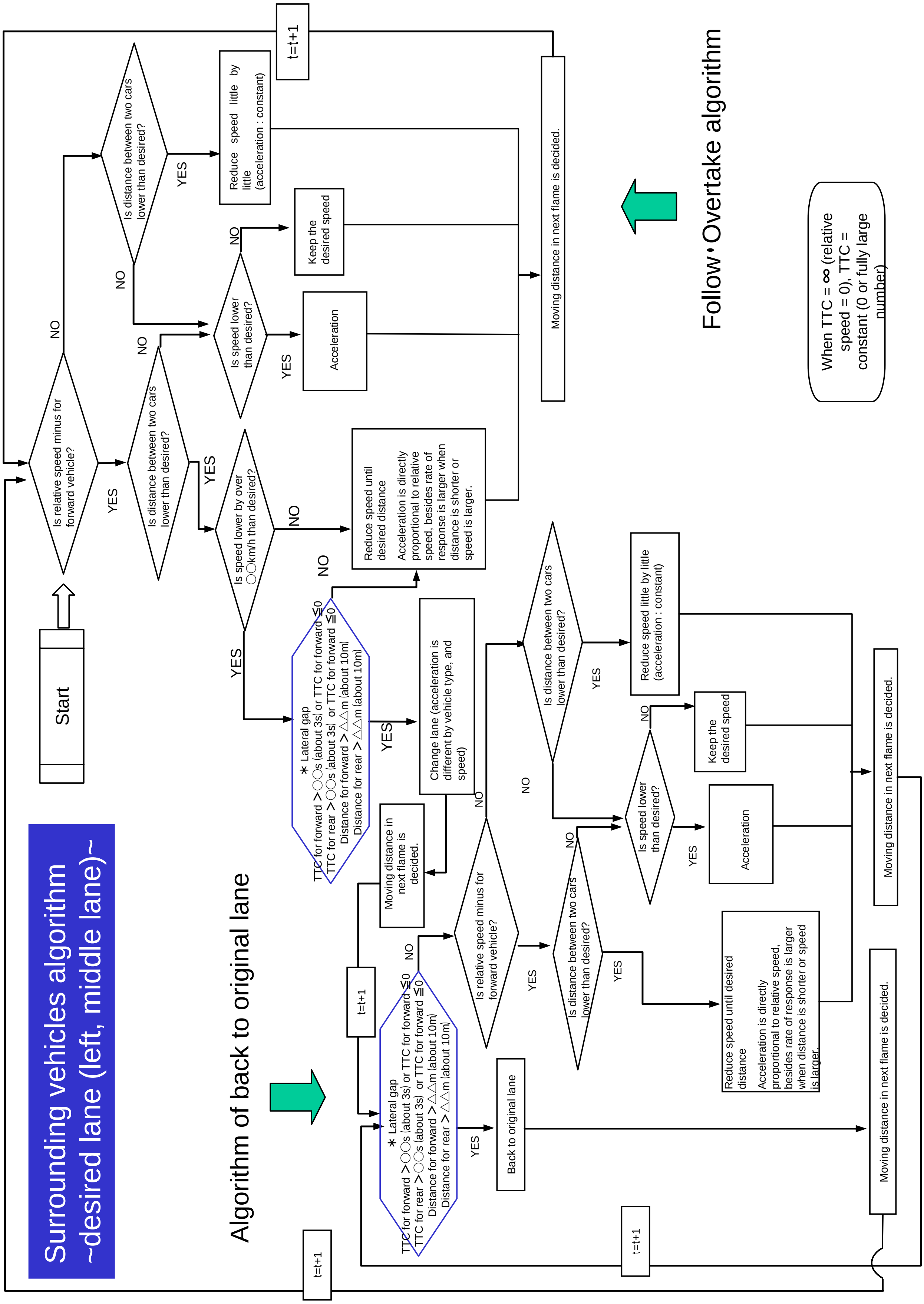


Figure 3-9 Algorithm of surrounding vehicles control (basic segment: left and center line)

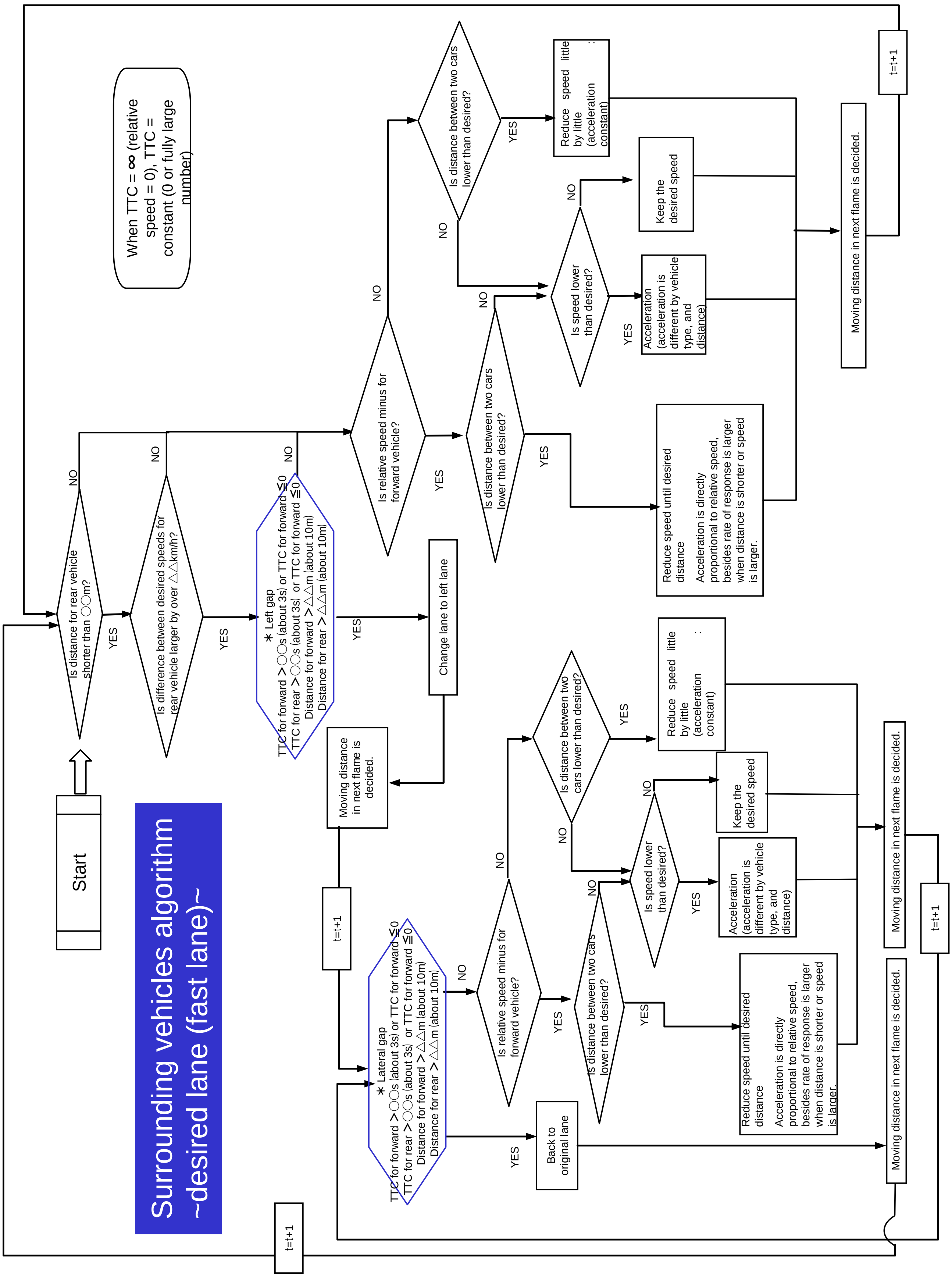


Figure 3-10 Algorithm of surrounding vehicles control (basic segment: overtaking lane)

3.4.3. Control algorithm of surrounding vehicles at merging section

In the study that analyzes the driving behavior in merging section zone, nowadays with the development of computing power in calculator, most of all studies produce micro-simulation model that recreates driving behavior of each vehicle.

Micro-simulation models in merging section that past studies produce are divided into gap searching model and gap acceptance model.

＜Gap searching model＞

Gap to approach merging section is assessed by the utilities, and so on that consist of gap length, relative speed, and needful acceleration, and it is decided before the time to approach merging section. Thus, many studies apply disaggregative approach model to the decision-making.

＜Gap acceptance model＞

Each vehicle has the border of gap, and if a longer gap than the border one is found, the vehicle follows it. Some studies set the variation of border of gap depending on driving conditions.

As the studies that use gap searching model, there are Morikawa (1987), Nakamura (1992), Kita (1995), Uchiyama (1999), Shimizu(2001), and so on. Morikawa (1987) structures simulation model to get base resources to design geometric structure in merging sections. The judgment of whether the vehicles approach merging sections or not is decided by the comparison the distance between the heads of two cars with the gap between two cars in main line, and the lag between two cars. Nakamura (1992)[40)] use simulation to estimate traffic volume in weaving sections, and the judgment of merging section approach is gotten in the process that the maximum gap of summary of the value that relative speed between a car and the fore car in the next line is divided by the distance of between two cars (relative rate of distance between two cars ; TTC) is selected in the gaps within ±100m, and the decision of moderate acceleration in lane change is calculated. Kita (1995) , to judge whether a car runs to merging section or not, expresses the utility function that has explaining variables of rest acceleration lane length normalized the velocity of approaching car and TTC that structures gap of a car on main line, and makes the program that in both cases the cars chose the behavior of high utility. Uchiyama (1999) studies about the behavior in merging sections under construction, and applies disaggregative approach model that is used in Nakamura's study to the alternative problems whether to approach merging section nor not. Shimizu(2001) structures traffic simulation model to analyze the effect of driving support system in merging sections. As the norm of gap alternative behavior in approaching merging sections, cars that approach merging sections decide whether they run to lateral gap or the other gap by regularly selecting the larger utility for cars that approach merging sections. The utility function consists of TTC against cars on main line and absolute figure of accelerative variables.

As the studies that use gap acceptance model, there are Matsumoto (1992), Nakamura (1994). Matsumoto (1992) produces simulation model in weaving sections to assess the length of weaving sections, defines that it is possible to do lane change when the gap against nearby lane and the lag between two cars is over a border. Nakamura (1994) installs time of perceptional reaction, and recreates the delay of reaction, and produces the simulation of merging sections in express highway that expresses traffic jams. The judgment of right and wrong at merging sections is decided by the lag between two cars, and largeness of the possibility of gap to merging sections is compensated by rest lane length.

Table 3-2 Behavior model on merging sections

Researcher	Object	Model		Basic of judgment	Give-way
		Gap searching	Gap acceptance		
Morikawa (1987)	Merging section	○	×	gap, lag	○
Nakamura (1992)	Weaving section	○	×	relative rate of distance, lag	×
Matsumoto (1992)	Weaving section	×	○	gap, lag	○
Nakamura (1994)	Merging section	×	○	gap, lag	○
Kita (1995)	Merging section	○	×	TTC, utility function	×
Utiyama (1999)	Lane closure under construction	○	×	relative rate of distance, utility function	×
Shimizu (2001)	Merging section	○	×	TTC, utility function	○

Introduction of surrounding vehicles control algorithm in this study

The behavior model on merging sections in this study is applied gap acceptance model that is considered that in the field of traffic engineering calculation amount is small relatively and that is upgraded uniquely. In many models on merging sections in studied of traffic simulation, however, moderate gaps are assessed and selected, moderate accelerations for merging the gaps are decided, it is necessary to estimate the parameters used for gap assessment from actual measurement of traffic flows, so it is difficult to apply it to this study that discusses the road that is not exited. And because the behavior is complicated relatively, it is difficult to control surrounding vehicles depending on the experiments. In this study, for all vehicles aforesaid tracing algorithm is used and all decision problems of tracing vehicles are expressed. Thus, it is projected that calculation amount is small and the control of surrounding vehicles is simple.

In the model on merging section that this study produces, a car in merging section traces a car in main lane. On the other hand, a car in main lane when it runs to merging section traces the nearest car in both main lane and merging section (but the car that TTC is under the border is omitted). By doing this, appropriate gap is made automatically in merging sections, and a car in merging section joins together if the lateral gaps fit on the condition that orders to join together. This idea is near the gap acceptance model. In the theses that use gap acceptance model, they just say “a car is able to change lane in case that the gap of cars in next lane and the lag between two cars are over the border,”[3] and it is not clear what way is used to adjust velocities in interaction between a car in merging section and a car in main lane. But there must be some methods in the theses, and Shimizu (2001) also says “In gap acceptance model it is projected that velocity adjustment for a car in merging section is also done in the same model that supposes tracing behavior as a car in main lane.” Thus in gap acceptance model it is possibility that past studies has already used the same algorithm in this study. But in this study, already mentioned, it is unique that all cars in main lane don’t always pass over the way for cars in merging section, and in tracing algorithm interactions of surrounding vehicles are classified in detail and the artifice that accelerative adjustment near reality is done. And about run-away behavior, it is all explained by tracing behavior, however about acceleration run-away and anticipation run-away they are not considered clearly, so as lane change behavior caused by tracing behavior and reduction of velocity rundown run-away and lane change run-away are recreated.

Surrounding vehicles control algorithm in this study is explained in detail as follows.

Structure of merging section

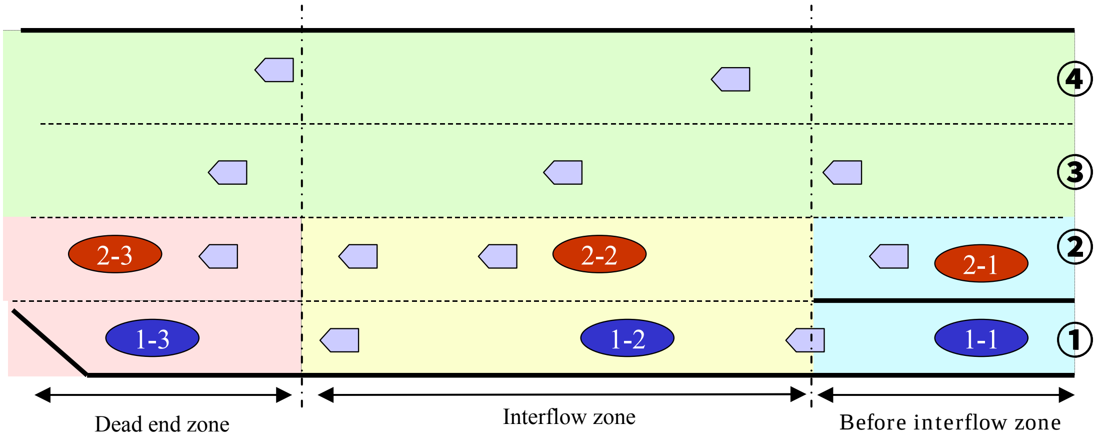


Figure 3-11 Form of merging section

- Before interflow zone･･･approach zone before interflow zone
- Interflow zone･･･zone where cars in main lane can be seen, and can approach to main lane
- Dead end zone･･･zone where it is necessary to reduce speed because of end of merging section

Driving characteristics recreated in inflow sections

Table 3-3 shows driving characteristics recreated in inflow sections.

Table 3-3 Driving characteristics in express highway: inflow vehicles

	Driving characteristics
1	Acceleration to goal rate before acceleration zone
2	Tracking if there is a fore car before acceleration zone
3	In acceleration zone, tracking to the nearest fore car, lateral gap is assessed for interflow
4	Inflow in case that TTC (Time To Collision; time to collision in case that rear car continues to move in actual distance between two cars and relative velocity: (distance between two cars) / (relative velocity)) is over the border or under 0 and the distance between both cars is over the border
5	In dead end zone (about 50m from nose end) lateral gap is assessed with reducing speed to stop at the nose end

Table 4-5-4 Driving characteristics in express highway: main lane vehicles

	Driving characteristics
1	Fundamentally free driving
2	Tracing drive if there is a fore car
3	Lane change if velocity is under moderate speed by over ○○km/h (this ○○km/h is defined as low velocity in tracing except of the case of interflow zone, and it is easy to change lane □ by this way, run-away phenomenon is recreated (all vehicles don't create run- away behavior, so preliminarily cars that are likely to do run-away and cars that aren't likely to do are defined))
4	In interflow zone, tracing to the nearest car in all cars in both lanes (but tracing doesn't occur if TTC of cars in merging sections is under ○○seconds (0<TTC<○○): cars in main lane don't always make space for cars in merging section, especially for cars that have a large variation in velocity)
5	In dead end lane, when there are cars that has not yet done interflow, make space for them (in the lane, it is easy to make relations with surrounding vehicles that exit there)
6	After change lane to overtaking lane, don't come back to first lane in interflow zone

■Algorithm

Figure 3-12 ~ Figure 3-17 show general flow and algorithm in detail of surrounding vehicles control algorithm in single line.

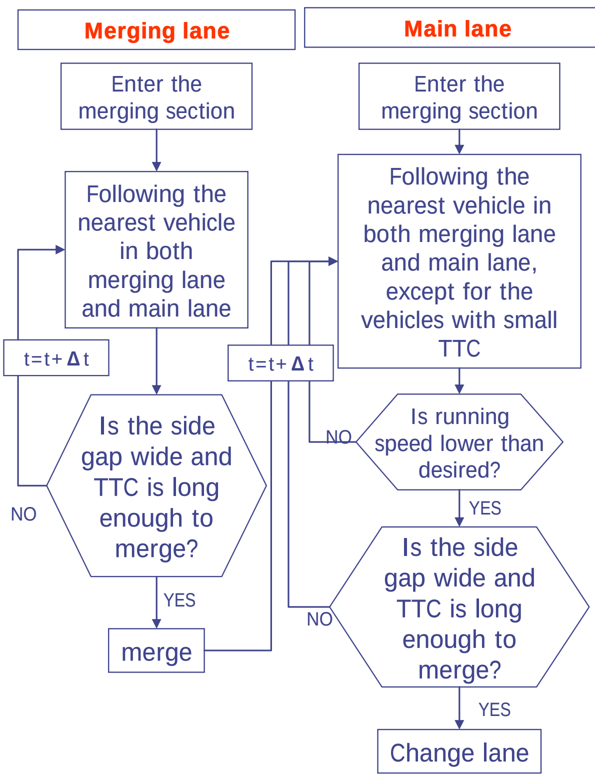


Figure 3-12 General flow of driving model in interflow

//1-1 driving algorithm in interflow lane (before interflow zone)

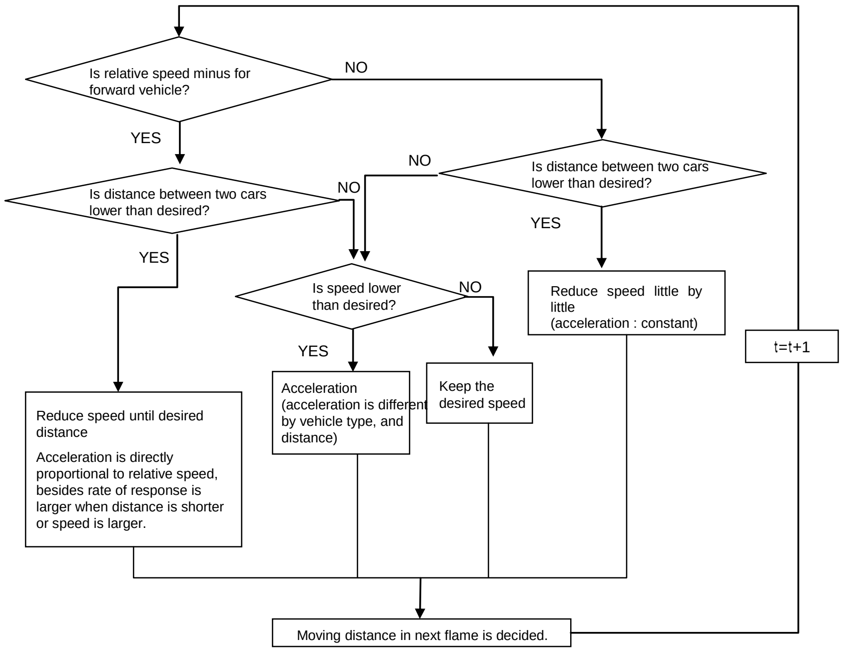


Figure 3-13 Algorithm of surrounding vehicles control (interflow 1-1)

///1-2 driving algorithm in interflow lane (interflow zone)

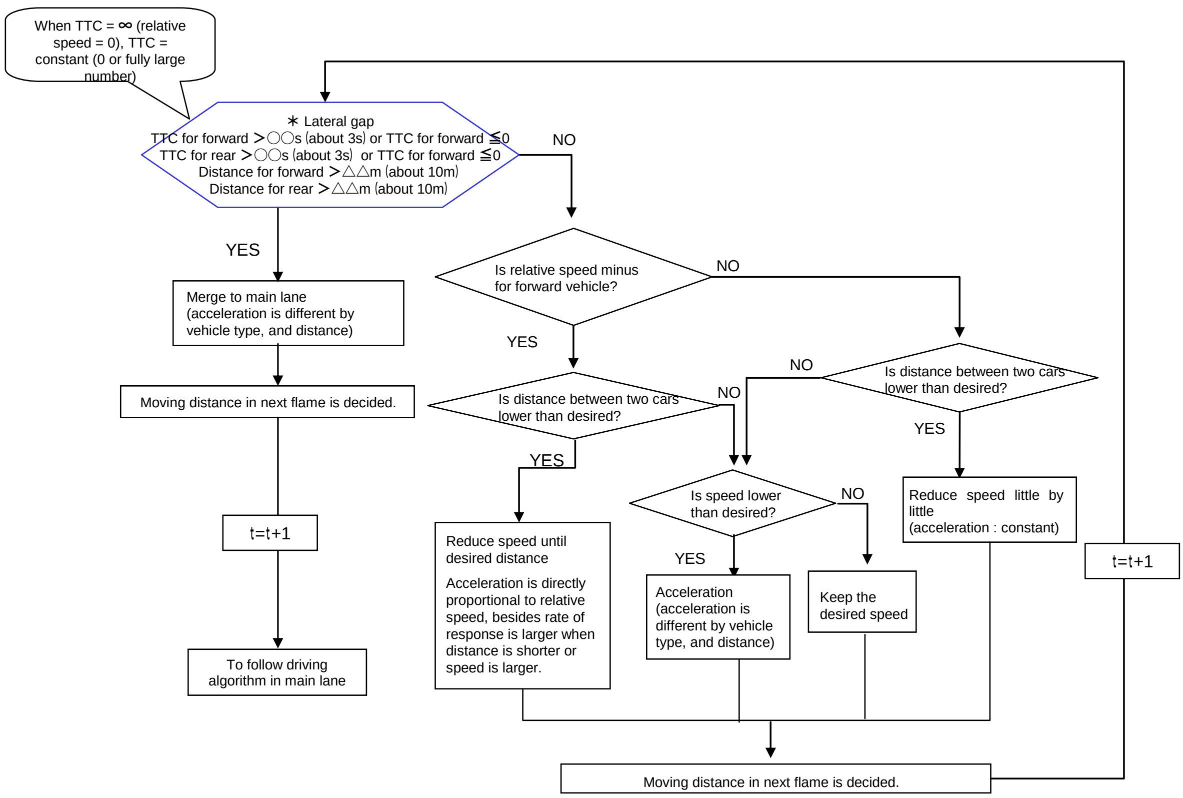


Figure 3-14 Algorithm of surrounding vehicles control (interflow 1-2)

///1-3 driving algorithm in interflow lane (dead end zone)

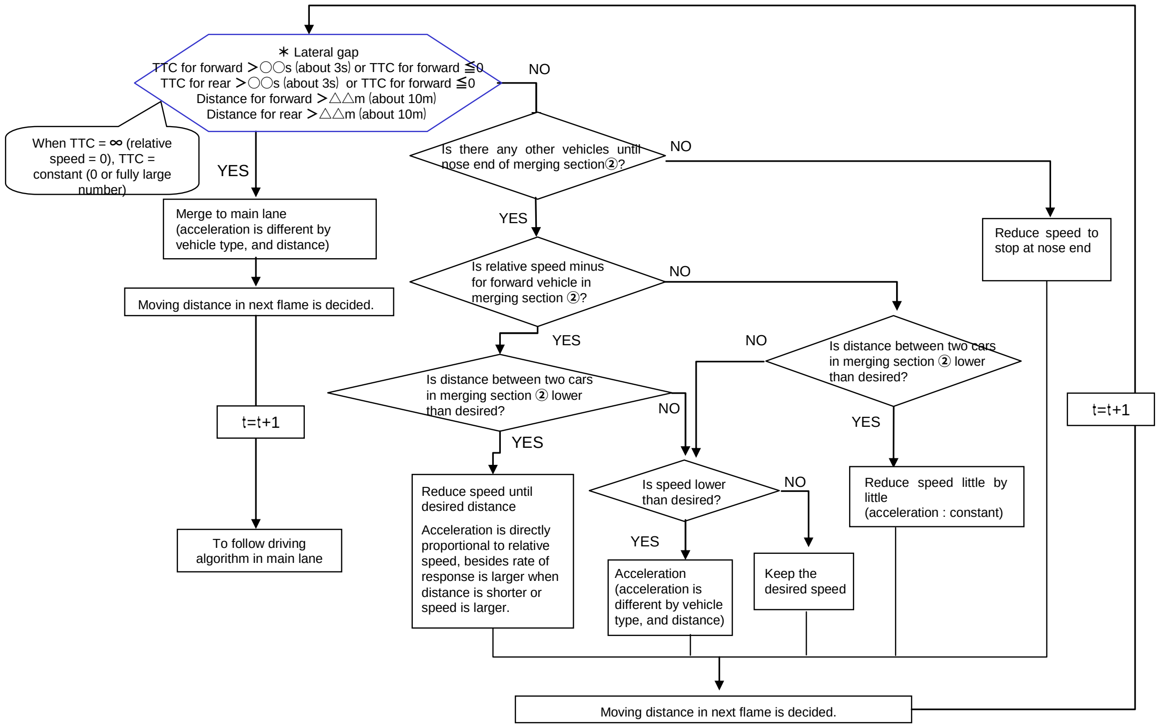


Figure 3-15 Algorithm of surrounding vehicles control (interflow 1-3)

///2-1 driving algorithm in main lane (before interflow zone)

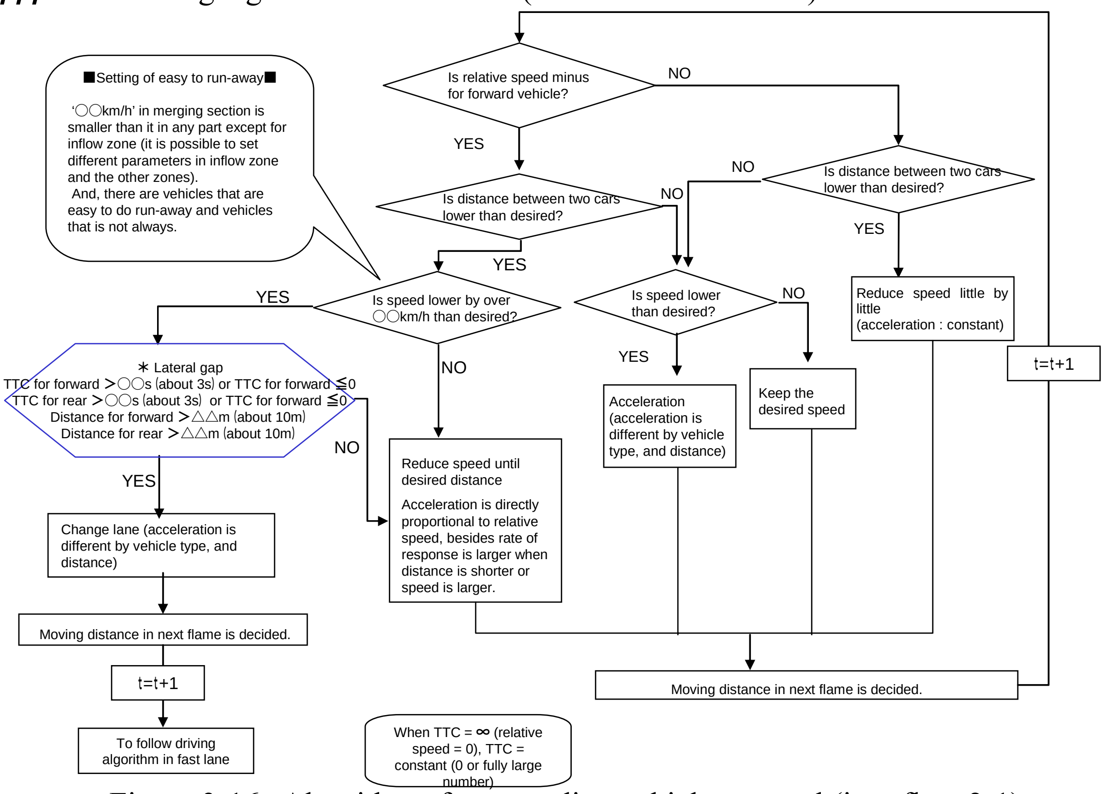


Figure 3-16 Algorithm of surrounding vehicles control (interflow 2-1)

///2-2 driving algorithm in main lane (interflow zone)

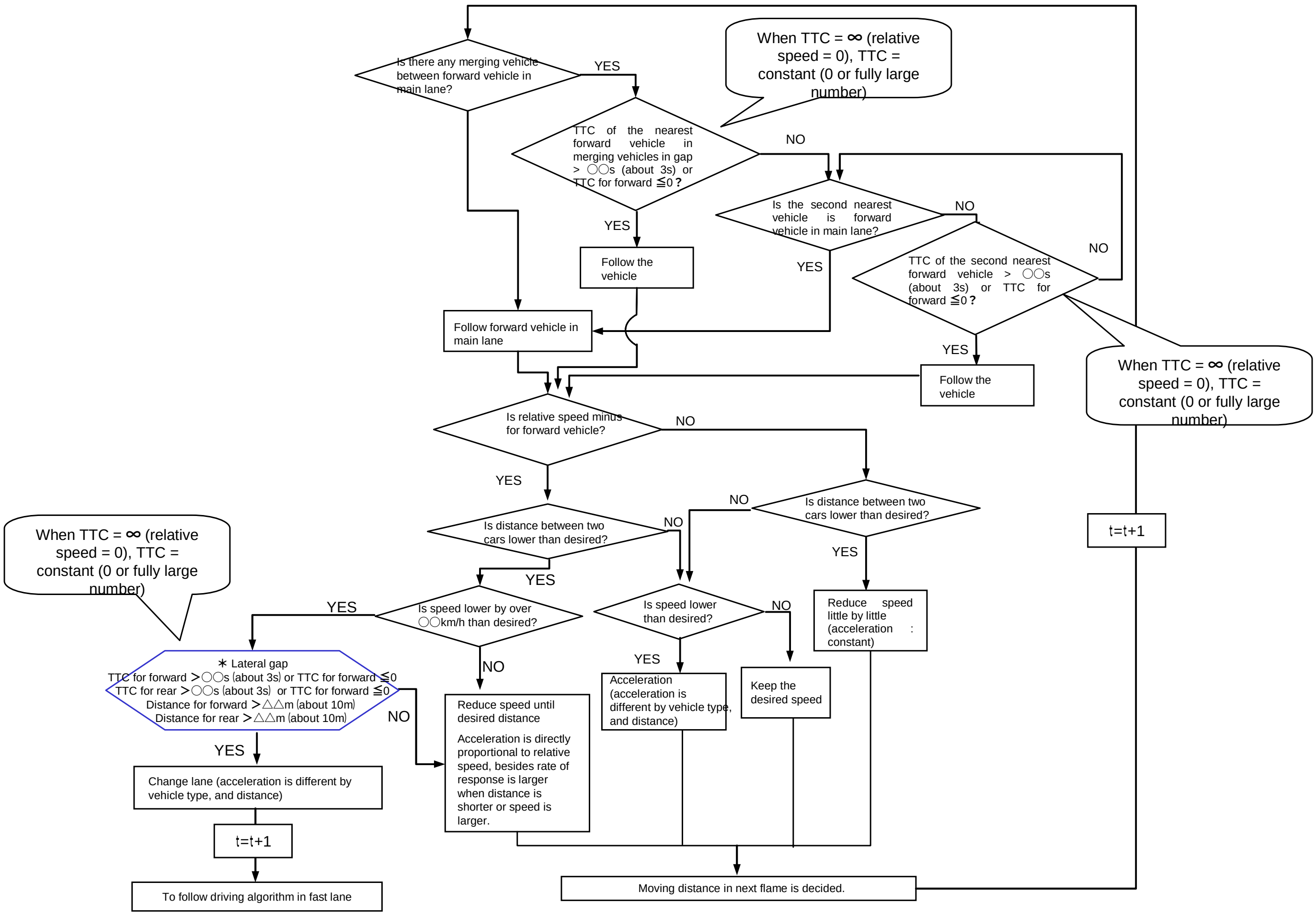


Figure 3-17 Algorithm of surrounding vehicles control (interflow 2-2)

///2-3 driving algorithm in main lane (dead end zone)

Differently from 2-2, in this stage the condition of TTC is loosened. Thus more cars in merging section are easy to approach main lane (if all cars in merging section are easy to approach main lane, cars in main lane suddenly stop in dead end zone.)

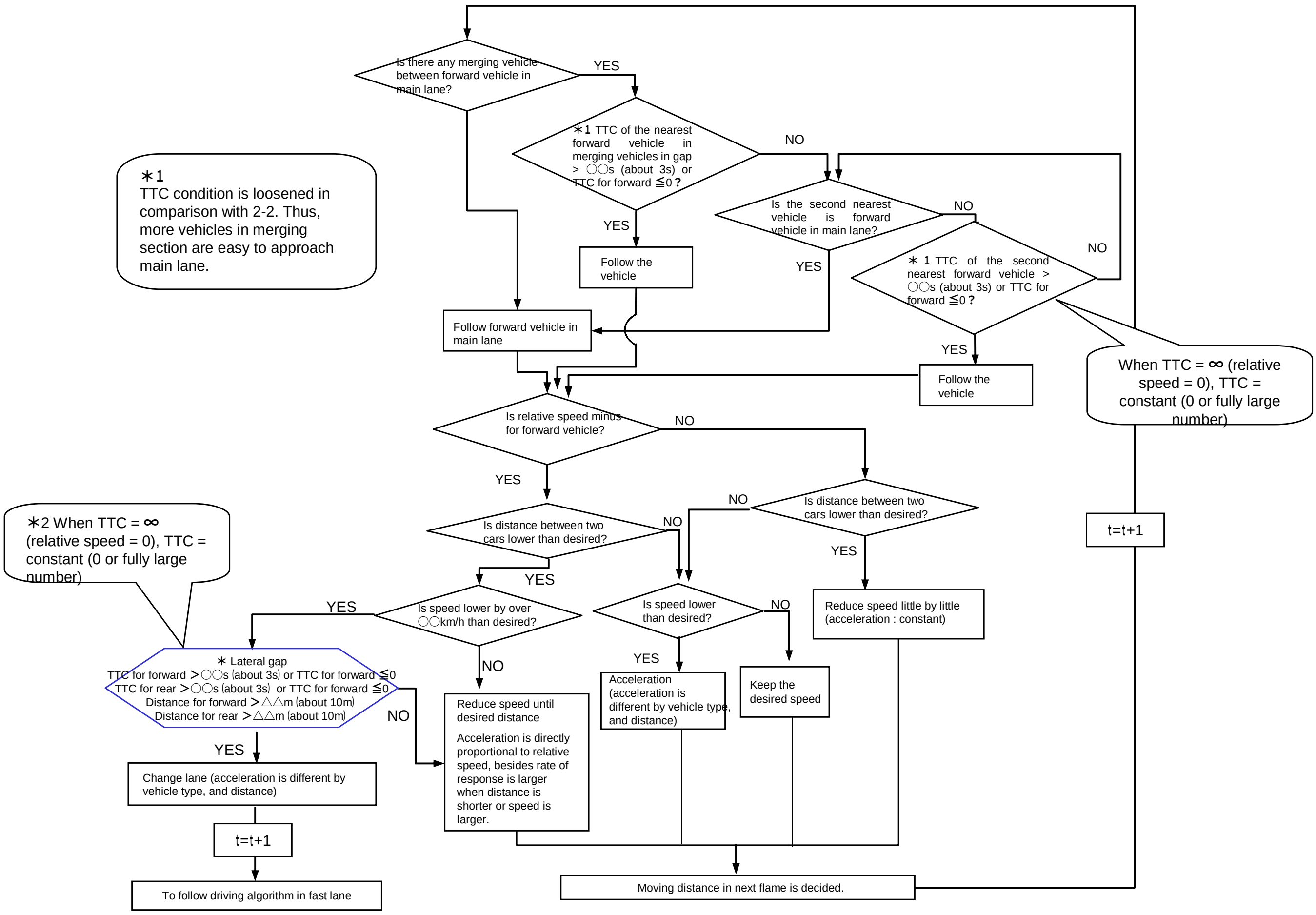


Figure 3-18 Algorithm of surrounding vehicles control (interflow 2-3)

3.4.4. Changeable attributes of surrounding vehicle

Changeable attribute of surrounding vehicle are as follows:

- start position
- desired driving lane
- desired speed
- desired distance headway coefficient
- lane-change decision coeffisient
- vehicle type (normal, sports, SUV, small truck, medium-sized truck, large-sized truck)

3.5. Validation of DS1

3.5.1. Difference of perceived driving speed while driving between inside tunnel and outside tunnel

Student drivers (N=3, see Table 3-4) were asked to drive at three recommended speeds without speed meter information. Each driver drove three times at the each recommended speed. Figure 3-19 shows the average driving speeds of three drivers for underground (inside tunnel) and aboveground virtual driving route in the DS. For each recommended speed, the average speed when driving underground is lower than aboveground. When the all data samples are pooled, Paired t-test shows that the difference of driving speed between inside tunnel and outside tunnel is statistically significant ($t=2.26$, $P<.03$; the average driving speed in each drive shown in Table 3-5 is treated as one sample). Although the drivers intended to drive with the same speed in both sections, they actually reduced driving speed underground because they probably felt that their driving speed underground is higher than when driving aboveground. Generally, drivers feel driving faster than their actual speed inside the tunnel than outside the tunnel (Hanshin Expressway Public Corporation, 1999). This result indicates that the difference in perception of speed between driving inside and outside tunnel is reproduced in DS.

Table 3-4 Profile of experimented drivers for validation analysis

S-01	20th,22th,25th, Nov.,2002	student	23	male	several times a year
S-02	21th,25th, Nov.,2002	student	22	male	several times a month
S-03	26th,Nov.,2002 2nd,Dec.,2002	student	23	male	several times a year

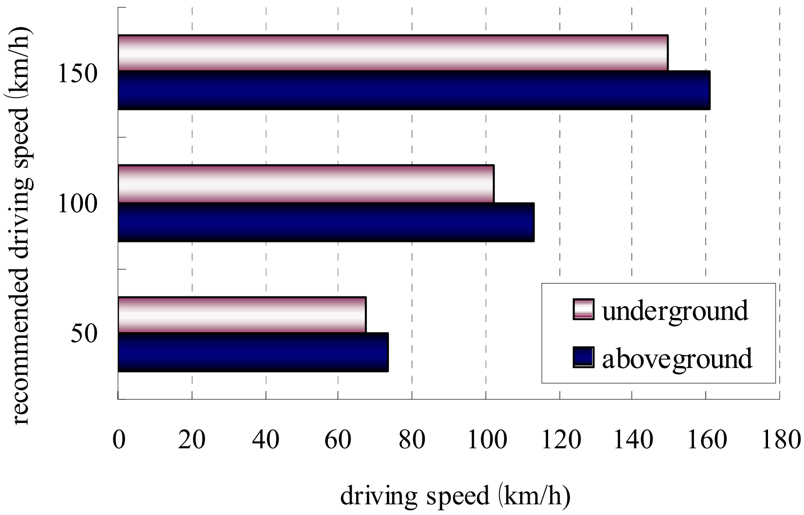


Figure 3-19 Driving speed in underground and aboveground DS

Table 3-5 Average driving speed of each subject in each drive

Recommended speed		50km/h		100km/h		150km/h	
roadway structure		aboveground	underground	aboveground	underground	aboveground	underground
average driving speed (km/h)	subject 1	66.5	73.0	91.4	89.6	150.4	133.0
	subject 2	55.9	59.9	108.8	91.6	155.7	138.2
	subject 3	84.5	64.2	129.3	119.2	162.7	164.3
	average of all	69.0	65.7	109.8	100.1	156.3	145.2

3.5.2. Difference of mental load while driving between inside tunnel and outside tunnel

Student drivers (N=3) were asked to drive five times each in both underground and aboveground DS. Figure 3-20 shows the average RR interval of three drivers for the underground and aboveground cases. The targeted data is the RR interval of the first 90 seconds to analyze proper mental load of drivers inside the tunnel because RR interval might vary due to deterioration of consciousness level further inside the tunnel. But the first 90 seconds may also include the initial disturbance although the practice driving is enough conducted. So the result after the 90 seconds is also described. RR interval is normalized by divided by the average RR over all drive in each subject. RR interval in underground DS was lower than that in aboveground. The difference of RR between aboveground and underground is statistically significant ($t=1.81$, $P<.05$ in the first 90 seconds; $t=1.35$, $P<.10$ after the first 90 seconds). This indicates that drivers have more mental load underground than aboveground. The difference of mental load between inside and outside tunnel due to spatial pressure and low visibility inside tunnel is reproduced in DS.

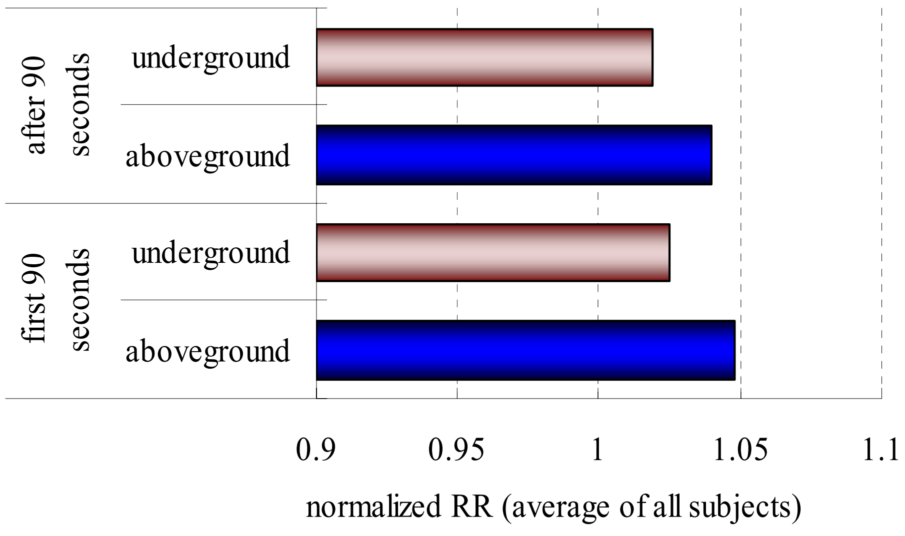


Figure 3-20 The difference of RR interval between in underground and in aboveground

3.5.3. Summary and the limitation of this system

In the validation of DS1, we validated only the difference of the perceived driving speed and mental load between inside and outside tunnel. The results showed that this apparatus is eliciting the same visual stimulus inside tunnel as real world. However, absolute validity (numerical correspondence between the simulator and the real world) cannot be checked in these data. Previous study by the same authors (Hirata et al, 2002) revealed that driving speed at merging section was higher in the simulated road than in the real road. Also, regarding mental load, the variation trend at merging section in the simulated road was close to that in the real road, but the absolute value of mental load index differed. Because our simulator is fixed-base (no moving device) and has no peripheral vision, there is an odd feeling of driving slower than nominal speed. So subjects were required to drive a little faster in simulated road than they usually drive in actual road. If possible, the DS experimental data including the driving behavioral data such as speed choice, headway choice and lateral position choice must be compared with the driving data in a real world. However the roadway database of DS1 is the nonexistent roadway, so the direct comparison cannot be conducted. Therefore DS1 is considered to be able to be applied only to the driving experiments where subject drives in some monotonous traffic conditions such as just following the forward vehicle or no changing lane. With these reasons, in the experiments of the next chapter, drivers were not subjected to experimental traffic conditions in simulated road that required them to change lateral position frequently and the DS did not generate merging or diverging vehicles because the subjects' visual field was limited in the front monitor.

Chapter4. Analysis of driver's awareness level in an underground urban expressway

4.1. Driver's awareness level while driving inside tunnel

In tunnels, one usually drives under a high mental load because of low visibility and spatial pressure. There is also very little change in the visual stimulus caused by a lack of variation in scenery. Consequently, the driver's awareness level can deteriorate. Deterioration of the awareness level does not mean drowsiness, but rather a deterioration of the attention level. The driver will tend to follow a certain vehicle inside a tunnel because of the difficulty in gauging a sense of speed. If the front vehicle is large-sized, the driver's visibility becomes even more limited. If this driving pattern is continued, the sense of speed is dulled and the driver can get the illusion that his/her vehicle is slowing down. In this state, one drives in synchrony with the front vehicle and the brain's activity level deteriorates (Kato, 1980). Awareness level deterioration slows down the driver's response to surrounding traffic (Kato, 1980, Nishimura, 1983)), and deteriorates the useful visual field with the prolongation of the monotonous driving task (Roge et al, 2002).

4.2. Hypothesis: awareness level deterioration in underground urban expressway

This chapter focuses on the deterioration of awareness level as the first approach to a traffic safety analysis in underground urban expressways. The driver's awareness level can deteriorate in urban expressway tunnels regardless of increased mental load induced by conflicts with other vehicles. This study hypothesizes that the awareness level can deteriorate in some monotonous traffic conditions such as following a certain vehicle along basic segments. If a driver enters a merging section with a low awareness level, an accident may occur because the driver is not able to properly assess traffic flow. Therefore, it is important to focus on the time series behavior of the driver's awareness level and mental load in analyzing driving safety in long urban expressway tunnels.

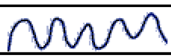
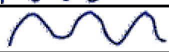
4.3. Index to evaluate driver's awareness level

Brain waves and awareness level

Electroencephalogram is the figure which amplified the amount of change of electrical potential resulted from potential activity of innumerable neurons in the brain. In 1929, H.Berger(Switzerland, 1873-1941) examined with setting electrodes on the scalp and found some-dozen-of-μm change of periodic electrical potential. This is the first record of brain waves. Electroencephalogram is usually recorded at the outside of the skull. While electrical resistance inside the skull is nearly zero, that of the skull itself is high. But, it’s not an important problem where brain waves, which result from the most of the concept of consciousness, breaks out. To draw electroencephalogram, we find the change of electrical potential between 2 points on the scalp, amplify the amount of change, and record it.

Brain waves are classified into 4 types with the frequency and amplitude.

Table 4-1 types of brain waves

brain waves	frequency	waveform	state of consciousness, features
βwaves	14Hz～		conscious and strained. when mentally calculating and paying attention
αwaves	8～13Hz		conscious and quiet. when not paying attention or being asleep
θwaves	4～7Hz		shift from being awake to being asleep
δwaves	0.5～2Hz		sleeping deeply

Awareness level can be measured objectively to the first time with electroencephalogram. Usually α wave is recorded in the state where a human is awake and quiet, but β wave is intermixed when α wave is conspicuous. β wave is conspicuous in the state where the awareness level is high; when a human does a sum in his head, when he pays attention to the noise, or when he is excited.

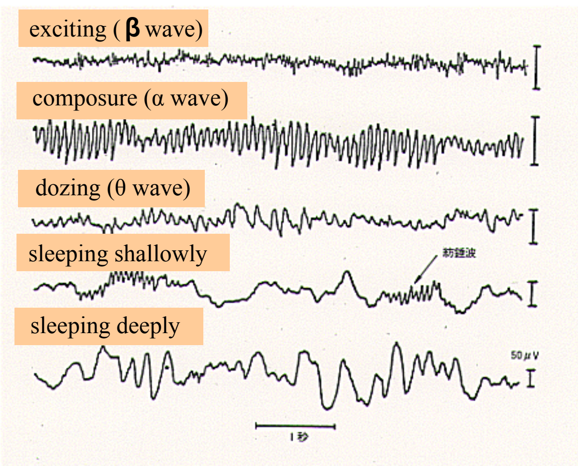


Figure 4-1 Awareness level in each type of brain waves

When a human is sleepy, α wave is inconspicuous and β wave and unstable θ wave are recognized. This appears when a human is moving from awake to asleep. Then, when he begins to sleep, it is thought that θ wave is conspicuous. In this situation, he can do judgment imperfect in consciousness. When he cannot do judgment, σ wave appears. This shows that he starts to sleep. And when he starts to sleep deeply, δ wave appears. Brain waves can become an index reflecting change of the consciousness in a low level when a human is asleep.

Skin potential response and awareness level (Kubota et al., 2000)

While brain wave is the index reflecting a low awareness level when a human is sleepy, skin potential response has been used as the one reflecting a high awareness level when a human is awake since 19th century.

Skin potential response is the perspiration activity in the palm which happens according to a mental cause. It is the activity of the sweat gland so-called "having sweaty palms" in strained situations. Since skin potential response is so sharp that it is used for the lie detector.

Main method of measuring skin potential response is to measure the conductance of the skin although there are various measuring methods of it. Electrodes are stuck on 2 points in a palm or a tip of a finger on the palm side and make them have a constant voltage, then skin potential response is measured. Conductance is a reciprocal of resistance and indicates how easy to pass the electric current. It is said that conductance is proportional to the density of the activity sweat gland on the skin.

A subject becomes strained in a moment when an external sensuous stimulus is given. It is called skin conductance response (or skin potential response) that the conductance increases temporarily reflecting this strain. It becomes smaller and smaller as the same stimulus is given repeatedly and a human is practiced. This phenomenon is called as the acclimatization of skin potential response. This acclimatization runs slowly when the awakening level of a subject is high, and it runs rapidly when the awakening level is low. Skin potential response changes voluntarily as well, and it is said that the frequency in the change is much related to the awakening level.

Evaluation index of awareness level in driving situation

A decline of awareness level in driving situation is so dangerous that it leads to doze. Thus the many studies with various indices have been made in order to establishment the detection method of decline of awareness level which is more trustworthy, easier, and not disturbing to drivers. The evaluation indices of awareness level are firstly classified into objective indices and subjective ones; objective indices are external observations or measurements, and subjective indices are reports by drivers themselves. Secondly objective indices are classified into driving behaviors indices and physiological ones; former is estimated by performances and states which is based on observation of drivers' behavior and latter is estimated by observation of drivers' physiological transition. Driving behavior indices are movement of car body, reaction time, achievement rate of task, etc. And physiological indices are brain wave, skin potential response, motion of eyeball, etc (see Table 4-2). It is said that movement of eyeball implies information about awakening level. The lower awakening level becomes, the fewer the saccade (fine and fast movement of eyeball) is. When the awakening level falls more, eyeballs are served as stared at one point, and soon the eye is closed unconsciously. The flicker value is the influential index to evaluate fall of awakening level caused by fatigue, but it is faulty that the measurement interrupts the original task.

Table 4-2 Indices of awareness level

objective index	physiological index	electro-encephalograph	brain waves
			voltage related phenomenon
		electrical dermatologic activity	skin potential activity
			skin resistant change
		motion of eyeball	ocular movement
			blink
		electro-cardiograph	heart rate
			heart rate variation
	index on driving behavior	action of operation	lateral movement of body
			longitudinal movement of body
			wheel operation
			accelerator operation
			brake operation
		reaction time	reaction time
			reaction time in selection
subjective index	declaration oneself		

Blink

Usually, a blink is classified into 3 types; physiological one, reflective one, and conscious one. They have the different mechanism and neurological control respectively, and the blink related to awareness level is voluntary one. Feature of ach type of blink is described below.

Conscious blink:

A blink arises 100-200 seconds after receiving the command of blinking. An intentional blink like this is called as an optional blink. This action is generated by optional contraction of the muscle surrounding the eyes under the control of facial nerves or by optional slackness of the muscle of upper eyelids. Usually this kind of blink is generated by contraction of the muscle surrounding the eyes, but the blink generated by only slackness of the muscle of upper eyelids also becomes possible with training. In this slackness case, a wink which closes only one eye cannot be performed. Usually duration of an optional blink is longer and amplitude of it is bigger than the other types of blinks, so we can distinguish between optional blink and voluntary one with the waveforms of blinks.

Reflective blink:

This kind of blink is generated by obvious external stimulus. The one which the reflective nervous channel is clear is called as a reflective blink. There are feeling, seeing, hearing, radically environmental change, ache etc. in the stimulus which causes reflective blinks. Reflective blinks are distinguished from kinds of stimulus and channel, the center of reflexes of all types is in the brainstem. The channel from the center of reflexes to the muscle surrounding the eyes is specified. Usually, the incubation of reflective blinks is 30-60ms, occasionally 10ms.

Physiological blink:

A physiological blink is generated periodically without an obvious stimulus. It is also generated synchronizing with a certain phenomenon and the method of generating changes with commands. Furthermore this has no choice but to consider as the voluntary one because there cannot be any obviously reflective stimulus and intention of blink, and it is thought that this is generated as a result of a certain mental process. A healthy human blinks physiologically about 5-20 times per minutes. This blink is controlled by a hypothalamus and its circumference. Stern et al. (1984) used a blink rate, a blink waveform, a blink lasting time, a time distribution of a blink rate as scales of blinks in order to know the state of mind. A blink rate is what converted the number of blinks which occurs in executing a certain subject into the number per 1 minute. Cautions to a certain stimulus decrease a blink rate. A blink waveform is what shows a time change of a distance interval between upper and lower eyelids and it shows the speed at which opens and closes an eyelid and the amplitude of a blink. The amplitude of a blind becomes small when a visual demand is high, such as driving. A blink lasting time is the time after a blink starts until it finishes. While the start time of a blink can be estimated comparatively easily, the estimation of the end time of a blink is difficult. So Stern et al. have recommended measuring the lasting time in the position which the eyelid has closed 70% or 50%. A time distribution of a blind rate is a frequency distribution showing a time change which a blink generates. The other indices are a time interval of a certain blink and the following one, a time interval until the first blink occurs from a certain stimulus, and so on.

By Hall and Cusack (1972), works of a blink are;

- protection of an eyeball (against injury from the outside, cold, wind, and strong light)
- relation with a tear (equalization of a distribution of a tear, supply of moisture, cleaning, and promotion of exclusion of a tear)
- increase in the pressure inside an eyeball
- recovery from a fatigue of an eyelid
- function of seeing (prevention of an image fading, supply of darkness, and renewal of the sensitivity of the retina)
- keeping up the awakening level and the visual activity level, and so on.

A blink is performed by the muscles surrounding the eyes and the ones of the upper eyelids mainly. Usually a blink is performed by contraction of the muscles surrounding the eyes, and relaxation of the muscles of the upper eyelids. The lower eyelids don't move. In the case of an optional blink the frontalis and the brow muscles also move, and it can be recognized easily as an optional blink with the electro-oculoguraphy. A control by nerves of a blink is mentioned above 3 types of controls. The mechanism of control has been not yet solved completely, but it is described below.

A nervous mechanism of a voluntary blink has been gradually clear from some animal experiments and pathological cases. While a reflective blink generates peripheral nerve as origin, a voluntary one generates central nerve as origin, and it is thought that the upper nerves have exerted various changes on a voluntary blink. It has been presumed for a long time that a voluntary blink relates to a core part of a cerebrum. Furthermore, it is presumed that other parts, such as the bridge, a cerebellum the back part of head skin and so on, are related.

There are methods of measuring a blink with video tape recording and a change of voltage between electrodes etc.

Video tape recording: This is the way that a movement of an eyelid is recorded on videotape and observed. Observation without attaching excessive equipment to a subject's face enables his natural blink, and collecting and processing data can be carried out with easy equipment. Furthermore the data can be rewrite any number of time. But it cannot be analyzed automatically and a huge labor and tedious work are needed.

Method used by the electro-oculoguraphy (EOD): It has static potential to which human's eyeball considers a retina side as minus, and a cornea side as plus. So the motion of the perpendicular eyeball movement can be recordable by sticking electrodes on the skin near the corner of eyes. Because the output waveform corresponds almost linearly with movement of an eyelid, this method is suitable for measurement of amplitude, or analysis of waveforms. However, since the face is equipped with electrodes, a subject feels sense of incongruity or is conscious of them.

In this study, I detected the blink of a subject by video recording because the data of a natural blink of a subject could be obtained with easy equipment with this method.

It has been clear that a blink becomes about human's mental phenomenon and the important index for exploring especially a cognitive process. Firstly, the feature of relation between a cognitive process and a blink is that momentarily cutting visual information off by a blink is not generally noticed by oneself. A system which controls the input of visual information in a blink makes a blink control temporarily when important visual information is input, and makes a blink lasting time shorten then. Secondly, generating a blink doesn't become random in processing a certain stimulus, whether the stimulus is visual or not. In other words, a blink is controlled completely just before and in a stimulus, and the numbers of blinks reach a peak at the moment processing of the stimulus finished. When a movement reaction, tapping keys for example, to a certain stimulus is performed, a blink is controlled to the time of start of the movement reaction, and the numbers of blinks reach a peak at the moment the movement reaction is started. In this case, it is easy that the high rate situation of participation to a stimulus generates a blink simultaneously with a movement reaction and that the low rate situation generates a blink outdistanced with a movement reaction.

It is thought that a blink has a close relation to awareness level because the place over which the control parts of a physiological blink is distributed is the same as the one of the place of important channel in which awareness level is decided. There are plural indices which evaluate awareness level using a blink, a blink rate, a time which an eye is opening in a blink, a blink swarm, and so on.

Index to Evaluate Driver's Awareness Level in this study

In this study, "(eye) blinking frequency" and "RR-interval, or Inter-Beat-Interval (IBI), the time between successive heartbeats" were selected as indexes to evaluate the driver's awareness level. The relation between the blinking frequency and awareness level is described in the following section in greater detail. A shorter RR-interval period suggests a higher awareness or mental load. Both can be measured without expensive equipment and can be successfully recorded with only a small burden on the drivers. Blinking frequency is considered to be sensitive to variations in the condition where the awareness level is relatively low, such as feeling sleepy. RR-interval is considered to be sensitive to variations in the condition where the awareness level is relatively high, such as being excited (Yamamoto, 2000). The blinking frequency is used mainly as a driver's awareness index, is used complementarily with the RR-interval.

The vehicle's lateral position was also recorded, but it could not be used as a driver behavior index due to the difficulty to quantify it, and its weak relationship with awareness level (Tada et al, 1991). Steering amplitude has a stronger relationship with awareness level (Tada et al, 1991), but it was not possible to gather this data due to physical restrictions of this simulator system.

Relation between Blinking Frequency and Awareness Level

Blink types can be broadly categorized into three categories. They are "physiological blink", "reflective blink", and "intentional blink". Among these blinks, the frequency of "physiological blink" is correlated with the awareness level. The frequency of physiological blink is normally 5-20 times a minute. The controlling nerves of physiological blink are in the hypothalamus and limbic system. The hypothalamus and limbic system are considered to have an active and inhibitory effect on the cerebral neocortex, and the cerebral limbic system is closely related to the awareness level. When the awareness level deteriorates, the neural communication channel is affected and inaccurate information is perceived, such as dryness of the eyeballs. Consequently, the blinking frequency increases as a physiological response. Other changes in blinking are the increase in bursting blinking frequency and the time of one blink (Tanaka et al, 1989).

In the experiments, the drivers' faces were recorded by video camera. After the experiments, blinking frequency was counted during video playback.

4.4. Experiments for the analysis of driver's awareness level in underground urban expressway

4.4.1. Procedure

Introduction

In the experiments of this study, relatively monotonous traffic conditions were assumed, where drivers followed a certain vehicle in the same lane. Merging or diverging vehicles were not generated in the experiment. By changing the number, type, and speed of surrounding vehicles, the effects of surrounding vehicles and roadway structure on the driver's awareness level, mental load and behavior were analyzed.

Verification Items

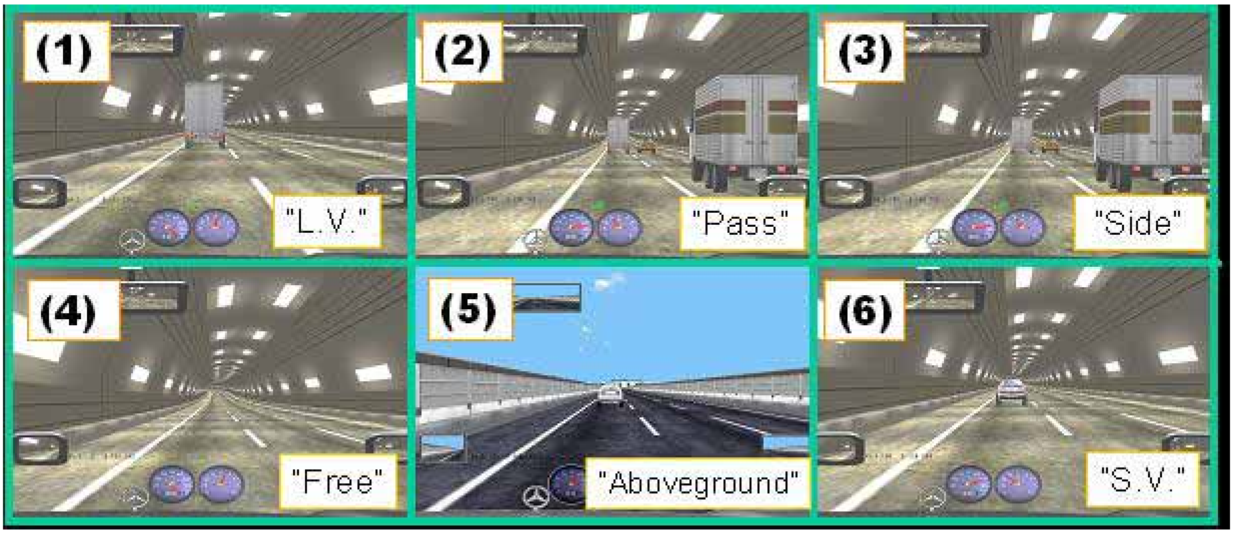
Specific verification items in this experiment are shown below. The detailed traffic conditions to verify those items are explained in the next section.

(a) Can the driver's awareness level deteriorate in underground urban expressways where traffic volume is high?
(b) If vehicles with the same speed are always present on the side of driver, will the awareness level still deteriorate regardless of side vehicle pressure?
(c) Do roadway structures such as merging or sharp curving sections have any effect on awareness level?
(d) Are there any differences in the degree of awareness level between elderly drivers and taxi drivers?
(e) Does the type of the followed vehicle have any effect on awareness level?
(f) Can audio information that gives a warning upon approaching merging and diverging sections prevent deterioration of the driver's awareness level?

Considering these verification items, changes in awareness level with driving time, especially along basic segments between merging sections are analyzed.

Detailed Traffic Conditions

Figure 4-2 shows the detailed traffic conditions for the simulation. There were no merging or diverging vehicles. Elderly drivers were subjected to six traffic conditions (No.1 – 6) and taxi drivers were subjected to eight conditions (No.1 – 8). For elderly drivers, the sixth condition is set as the limit because of their virtual reality sickness and physical strength. In all conditions, the experiment took around nine minutes because the followed vehicle ran at the same speed of 100 kph in all conditions, and after each experiment the driver took a rest for more than ten minutes. The order of the traffic conditions was randomized for each driver.



	Roadway structure	Traffic condition	Abbreviated name
(1)	underground	Following large-sized vehicle* (no other vehicles)	"L.V."
(2)	underground	Following large-sized vehicle + passing vehicles in center lane (900vehicles/hour/lane)	"Pass"
(3)	underground	Following large-sized vehicle + side vehicles at same speed	"Side"
(4)	underground	Free driving (no other vehicles. driving at recommended speed, 100 kph)	"Free"
(5)	Aboveground**	Following standard-sized vehicle (no other vehicles)	"Aboveground"
(6)	underground	Following standard-sized vehicle (no other vehicles)	"S.V."
(7)	underground	Following large-sized vehicle + Stopping vehicle at first half section	"F.H."
(8)	underground	Following large-sized vehicle + Stopping vehicle at last half section	"L.H."

*the speed of followed vehicle is around 100kph in all conditions.
**aboveground : the line shape of roadway is the same as that of underground DS, and surroundings of roadway are grass field.

Figure 4-2 Detailed traffic conditions in the experiments for the Analysis of Awareness Level Deterioration

Normalization of Blinking Frequency and RR-interval Data

Eye blinking frequency (blinks/minute) and RR interval were different among individuals. For a specific individual it was also different among experiments due to getting accustomed to driving in DS. Therefore, normalization of such data was necessary. The first 90 seconds in each experiment was the pivot condition to normalize the observed data. Figure 4-3 shows the pivot traffic condition. Blinking frequency was normalized by dividing the targeted blinking frequency data by the average of blinking frequencies in pivot condition of underground DS.

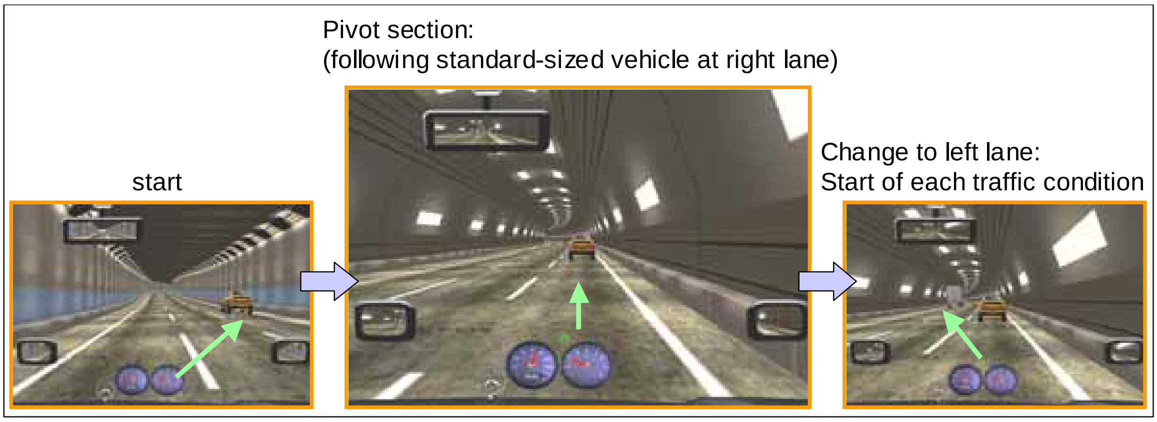


Figure 4-3 Pivot traffic condition

4.4.2. Participants

Experiments for the analysis of awareness level deterioration are conducted on elderly drivers (N=10) and taxi drivers (N=9). The traffic safety of elderly drivers is analyzed by comparing them with taxi drivers who are more experienced drivers. This study focuses on the traffic safety of elderly drivers who are expected to have a higher risk of accident than other category drivers. The traffic safety of elderly drivers will become more serious in the future as the elderly population increases. Taxi drivers are comparative participants whose driving skill is relatively high and uniform. Table 4-3 shows the profile of the drivers in the experiments, including 10 elderly drivers and 9 taxi drivers.

Table 4-3 Profile of participants for the experiments for the analysis of driver's awareness level in underground urban expressway

ID	date	attribute	age	sex	drive frequency
O-01	18th,Dec.,2002	elderly driver	68	male	several times a week
O-02	3rd,Feb.,2003	elderly driver	66	male	several times a month
O-03	2nd,Feb.,2003	elderly driver	67	male	several times a week
O-04	25th,Dec.,2002	elderly driver	74	male	once a month
O-05	25th,Dec.,2002	elderly driver	64	male	once a week
O-06	26th,Dec.,2002	elderly driver	67	male	everyday
O-07	26th,Dec.,2002	elderly driver	75	male	everyday
O-08	9th,Jan.,2003	elderly driver	70	male	several times a week
O-09	10th,Jan.,2003	elderly driver	65	male	everyday
O-10	11th,Jan.,2003	elderly driver	75	male	several times a month
T-01	15th,Jan.,2003	taxi driver	56	male	everyday
T-02	15th,Jan.,2003	taxi driver	33	male	everyday
T-03	18th,Jan.,2003	taxi driver	46	male	several times a week
T-04	18th,Jan.,2003	taxi driver	44	male	several times a week
T-05	20th,Jan.,2003	taxi driver	53	male	everyday
T-06	20th,Jan.,2003	taxi driver	51	male	everyday
T-07	21th,Jan.,2003	taxi driver	41	male	everyday
T-08	21th,Jan.,2003	taxi driver	57	male	everyday
T-09	22th,Jan.,2003	taxi driver	41	male	everyday

4.4.3. Results and discussion

4.4.3.1 Awareness level in "Pass" condition

At first, the driver's awareness level in "Pass" condition is analyzed to verify whether the driver's awareness level deteriorates or not in underground urban expressway when there is a high traffic volume (verification item: 4.4.1 (a)).

Figure 4-4 shows the change of blinking frequency with driving time. The data is average of blinking frequencies of the six elderly drivers. Some elderly drivers made fewer blinking compared with normal individuals, and the data of such drivers are excluded in this analysis. As mentioned in section 3.2, increase of blinking frequency means deterioration of awareness level. The dotted arrows point to pairs of blinking frequency levels that have statistically significant differences ($P<0.10$: tested by Least Significant Difference Method). In this figure, blinking frequency increases from 3 min. to 4 min., which means awareness level deteriorates from 3 min. to 4 min. The section from 3 min. to 4 min. is a basic segment, around 2km long without merging or diverging sections (see Figure.4). This result indicates that awareness level of elderly drivers might deteriorate in relatively short basic segment, which means that they enter the merging section under low awareness level where the traffic flow might be disturbed.

After 4min., low awareness level continues.

Figure 4-5 shows the average change of blinking frequency for eight taxi drivers. The data for one taxi driver is excluded due to its abnormal value. Awareness level of taxi drivers does not deteriorate from 3 min. to 4 min., but deteriorate at more latter section. This indicates that awareness level of elderly drivers tend to deteriorate more easily than that of taxi drivers.

Blinking Frequency of elderly drivers in “Pass” condition

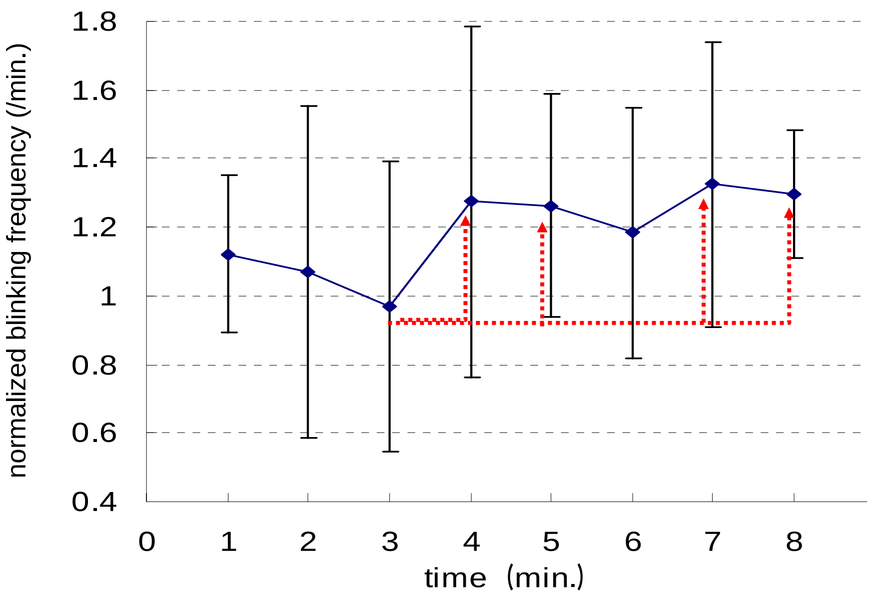


Figure 4-4 Blinking Frequency of elderly drivers in “Pass” condition

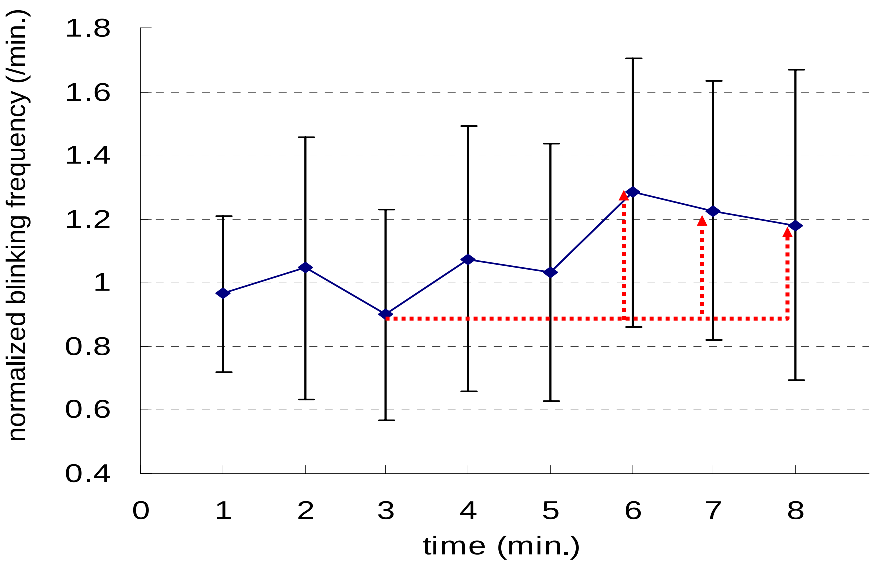


Figure 4-5 Blinking Frequency of taxi drivers in “Pass” condition

4.4.3.2 Awareness level in "Side" condition

The driver's awareness level in "Side" condition is analyzed to verify whether the awareness level hardly deteriorates due to side vehicle pressure. (verification item: 4.4.1 (b)).

Figure 4-6 shows the average of RR-intervals of elderly drivers in "Pass" and "Side" condition. RR-interval was normalized by subtracting the average of RR interval in each pivot section from targeted RR-interval. As expected, RR-interval in "Side" condition is lower than that of "Pass" condition. This means that mental load in "Side" condition is higher than in "Pass" condition. Figure 4-7 shows the average change of blinking frequency of the six elderly drivers. Due to the high mental load, awareness level ameliorated from 1min. to 3min. However, despite having high mental load, awareness level deteriorated from 3min. to 5min., when subjects drive at basic segment. After 5min. when subjects drive into relatively hard roadway structure with sharp curves and many merging/diverging sections, awareness level ameliorated again. The effects of both side vehicles and hard roadway structure can be considered to be the causes of this amelioration.

Figure 4-8 shows the average of RR-intervals of taxi drivers in "Pass" and "Side" condition. For taxi drivers, mental load in "Side" condition is higher than that in "Pass" condition similar to the elderly drivers. Figure 4-9 shows the average change of blinking frequency of eight taxi drivers. Even with high mental load, awareness level consistently deteriorated. Compared with "Pass" condition, the deterioration rate is a bit milder. At relatively hard roadway structure, amelioration of awareness level did not occur. These results indicate that the mental load as high as this might not affect the change of awareness level.

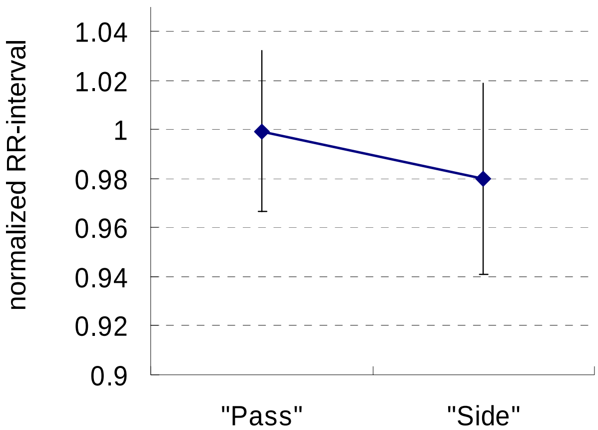


Figure 4-6 RR-intervals of elderly drivers in "Pass" and "Side" condition

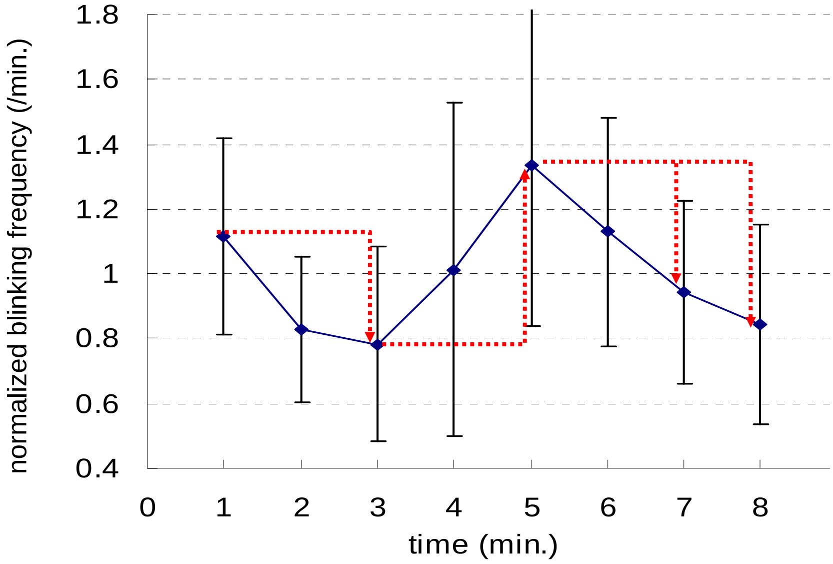


Figure 4-7 Blinking Frequency of elderly drivers in "Side" condition

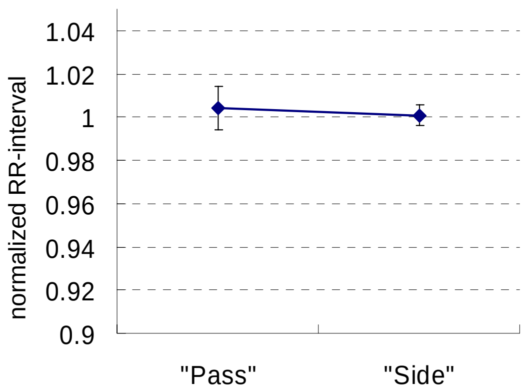


Figure 4-8 RR-intervals of taxi drivers in "Pass" and "Side" condition

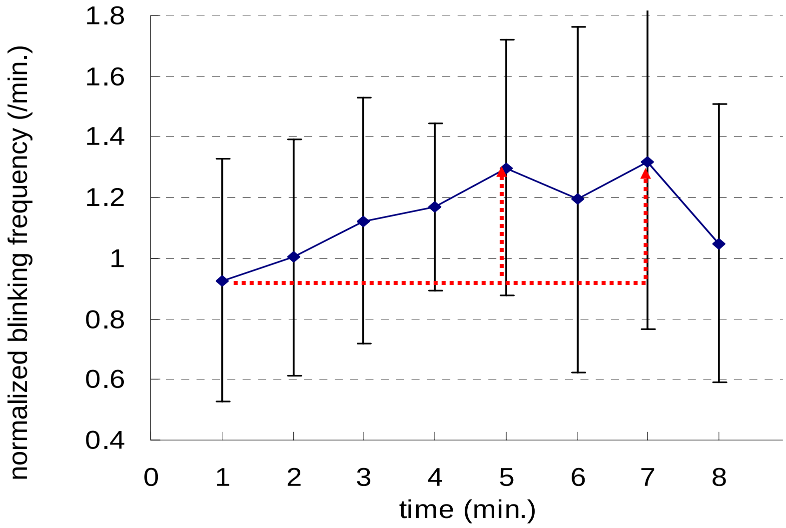
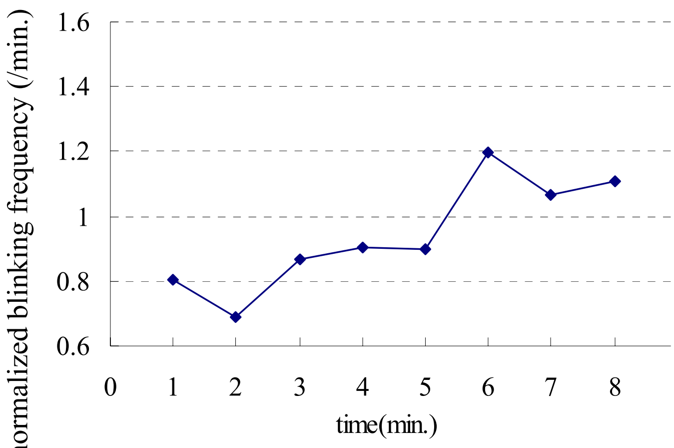


Figure 4-9 Blinking Frequency of taxi drivers in "Side" condition

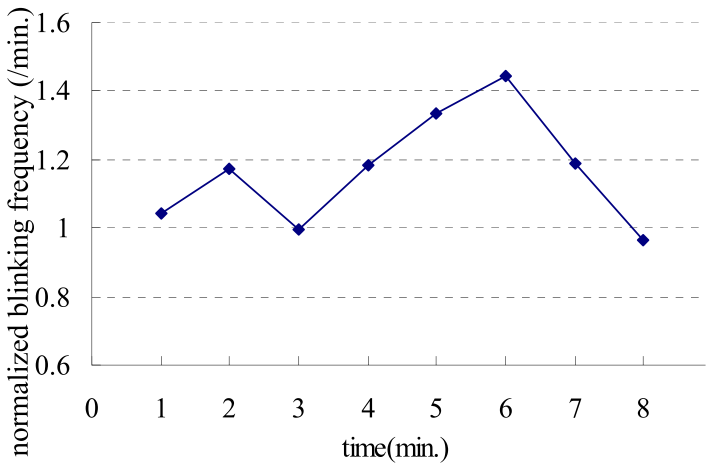
4.4.3.3 Effect of followed vehicle type: normal or heavy vehicle

To see the effect of followed vehicle type, the blinking frequency variations for "L.V." and "S.V." conditions are shown in Figure 4-10, Figure 4-11, Figure 4-12 and Figure 4-13. The pairs of blinking frequencies that have statistically significant differences are indicated under each graph. Figures 17 and 18 shows that the number of pairs of blinking frequency levels that are significantly different is small in "S.V." condition for both elderly and taxi driver such that the clear difference between the two conditions is difficult to deduce. However, comparing the trends in "L.V." and "S.V." trends of blinking frequency level changes, results imply that awareness level deteriorates more easily in "L.V." condition than in "S.V." condition. As mentioned in chapter.1, a large-sized vehicle causes awareness level deterioration of following driver, because it restricts the visual field and consequently lowers visual stimulus for the following vehicle.



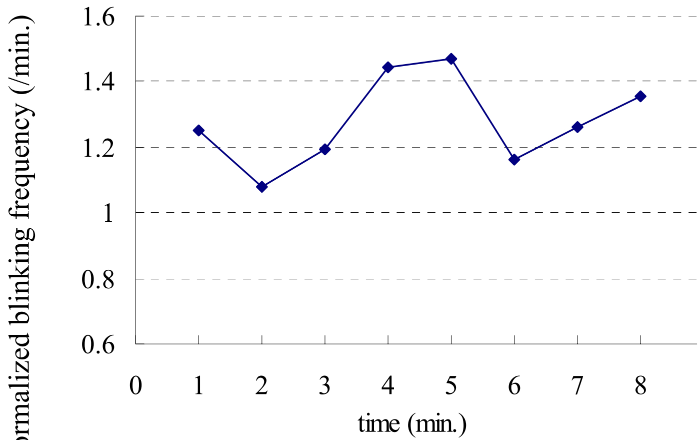
statistically significant difference (P<.10)		
1min. - 6min.	2min. - 6min.	2min. - 7min.
2min. - 8min.	3min. - 6min.	

Figure 4-10 Blinking Frequency of elderly drivers in "L.V." condition



statistically significant difference (P<.10)		
1min. - 6min.	3min. - 5min.	3min. - 6min.
5min. - 8min.	6min. - 8min.	

Figure 4-11 Blinking Frequency of taxi drivers in "L.V." condition



statistically significant difference (P<.10)
2min. - 4min.

Figure 4-12 Blinking Frequency of elderly drivers in "S.V." condition

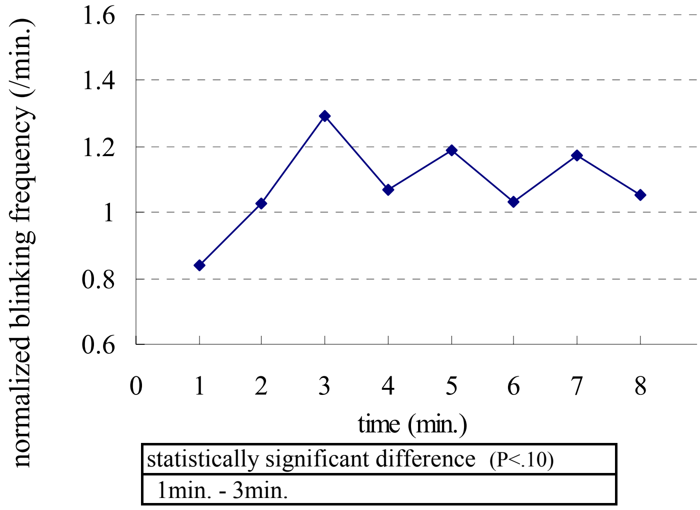
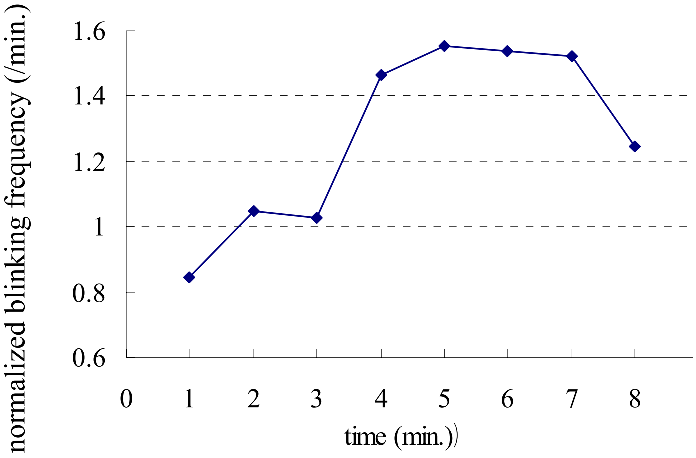


Figure 4-13 Blinking Frequency of taxi drivers in “S.V.” condition

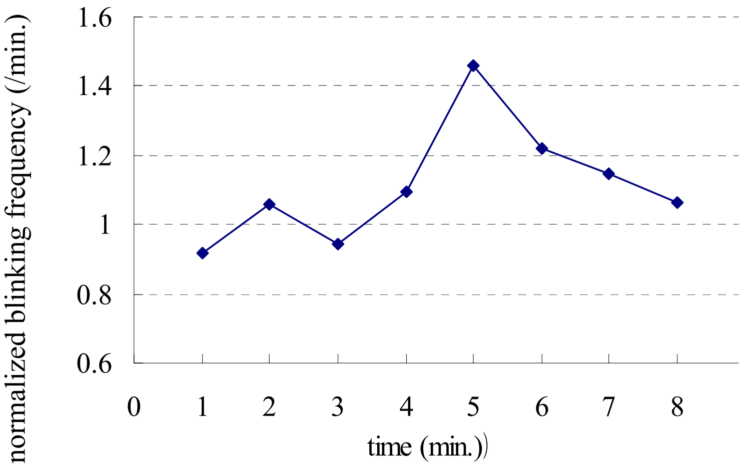
4.4.3.4 Comparison between inside and outside tunnel

The results of experiments in “Aboveground” condition for elderly and taxi drivers are shown in Figure 4-14 and Figure 4-15. Compared with the results in “S.V.” condition shown in Figure 4-12 and Figure 4-13, it can be seen that awareness level deteriorated in “Aboveground” condition as much as in underground DS. This result might have occurred because the roadway surrounding is grass field for the “Aboveground” condition and this might have caused a monotonous visual stimulus for the driver. In real road, there are more visual variations around drivers such as buildings and mountains that provide stronger visual stimuli.



statistically significant difference (P<.10)			
1min. - 4min.	1min. - 5min.	1min. - 6min.	1min. - 7min.
1min. - 8min.	2min. - 4min.	2min. - 5min.	2min. - 6min.
2min. - 7min.	3min. - 4min.	3min. - 5min.	3min. - 6min.
3min. - 7min.			

Figure 4-14 Blinking Frequency of elderly drivers in "Aboveground" condition

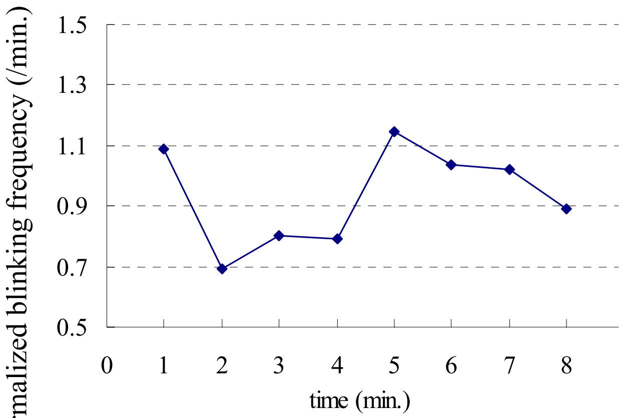


statistically significant difference (P<.10)	
1min. - 5min.	3min. - 5min.

Figure 4-15 Blinking Frequency of taxi drivers in "Aboveground" condition

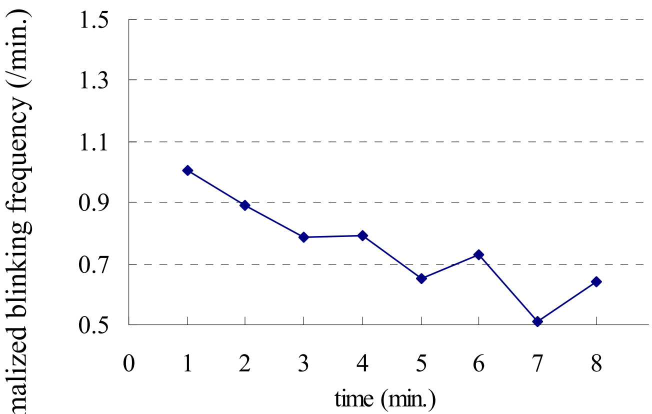
4.4.3.5 Following or not following

The results of experiments in "Free" condition for elderly and taxi drivers are shown in Figure 4-16 and Figure 4-17. For both elderly and taxi drivers in "Free" condition, awareness level tended to ameliorate. Awareness level remained high because drivers needed to control their driving speed by themselves without following any other vehicles. Following another vehicle seems to cause deterioration of awareness level.



statistically significant difference (P<.10)		
1min. - 2min.	1min. - 4min.	2min. - 5min.
2min. - 6min.	2min. - 7min.	3min. - 5min.
4min. - 5min.		

Figure 4-16 Blinking Frequency of elderly drivers in "Free" condition



statistically significant difference (P<.10)			
1min. - 3min.	1min. - 4min.	1min. - 5min.	1min. - 6min.
1min. - 7min.	1min. - 8min.	2min. - 5min.	2min. - 7min.
3min. - 7min.	4min. - 7min.		

Figure 4-17 Blinking Frequency of taxi drivers in "Free" condition

Figure 4-18 shows the summary of awareness level variations in all conditions as reference.

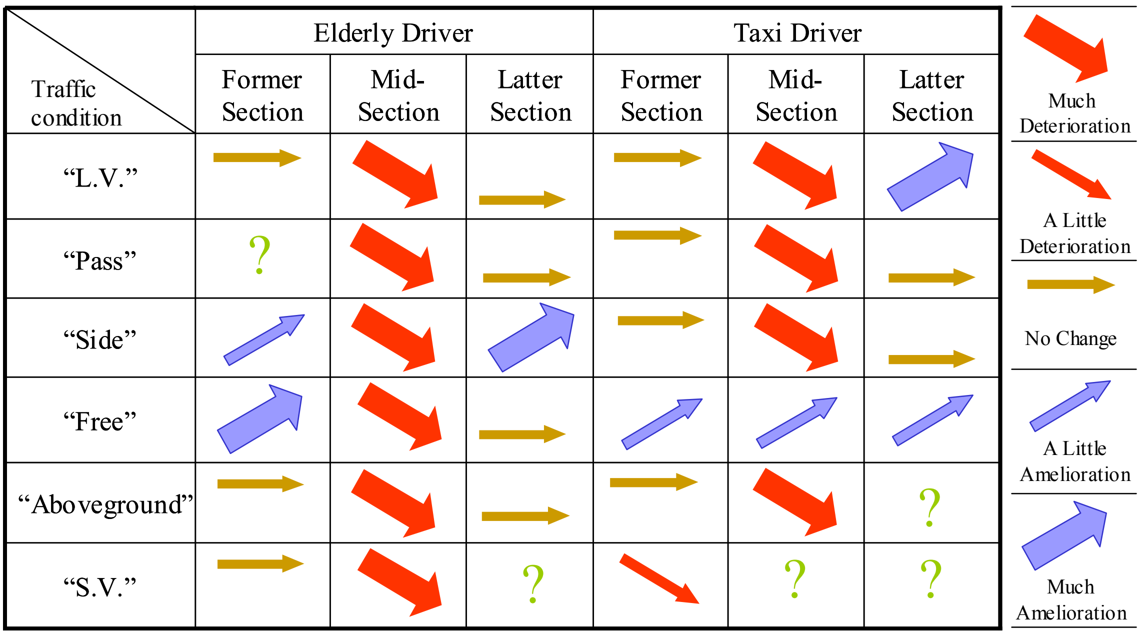


Figure 4-18 Change of awareness level for all traffic conditions

4.4.3.6 Reaction time to the stopping vehicle

In this section, the reaction time to stopping vehicle is analyzed. Since the correlation between reaction time and awareness level is considered to be high, the reaction time is reliable as an index of awareness level. Comparing reaction time and blinking frequency, the reliability of blinking frequency is also checked.

The positions of stopping vehicle were at the first half and the last half of roadway, and both are along straight sections (shown in Figure 4-19). These two experiments were randomly conducted on five taxi drivers among the eight traffic conditions (Figure 4-2). The traffic conditions of “F.H.” and “L.H.” condition are the same as “L.V.” condition except for the generated stopping vehicle. Drivers were not informed about the existence of a stopping vehicle. Reaction time and Changing ratio of blinking frequency are defined as follow.

a) Reaction time: time from when followed car starts to decelerate due to stopping vehicle to when driver starts to brake.
b) Changing ratio of blinking frequency: ratio of blinking frequency in the first one minute to that in one minute just before driver starts to brake.

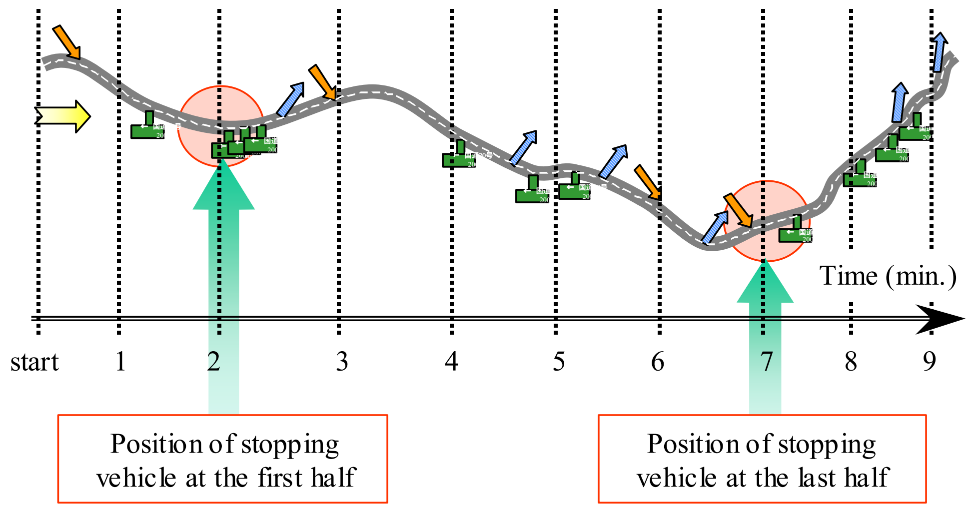


Figure 4-19 Position of stopping vehicle

Figure 4-20 shows the average reaction time of five taxi drivers (the other drivers are excluded because some did not brake or followed the stopped car with unexpected manner.). Reaction time at the last half is longer than that at the first half ($P<0.10$; tested by Repeated Measures ANOVA). Considering each individual, this result is true for four of five subjects. These observed reaction times imply that awareness level might deteriorate with driving time. Figure 4-21 shows the average changing ratio of blinking frequency. The changing ratio at the last half is bigger than that at the first half ($P<0.15$; tested by Repeated Measures ANOVA). Considering each individual, this result is again true for four of five subjects. Although the level of difference is not significant, these observed blinking frequencies also imply that awareness level might deteriorate with driving time. These results suggest that there is correlation between reaction time and blinking frequency. Therefore, blinking frequency can be considered to be a reliable index of awareness level.

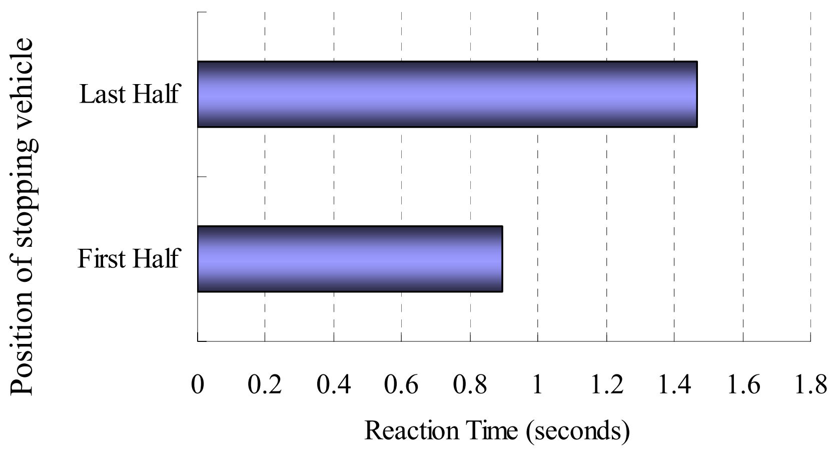


Figure 4-20　Reaction time to the stopping vehicle

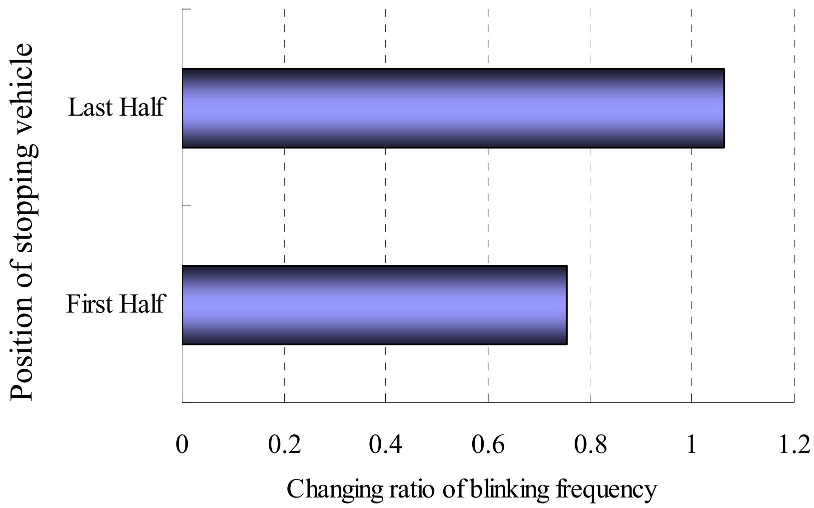


Figure 4-21　Changing ratio of blinking frequency

4.4.3.7　Summary of the analysis result

The summary of results from experiments in this chapter is mentioned below.

In the "Pass" condition, which is the case most similar to real traffic flow in urban expressway, the driver's awareness level deteriorated while driving along a 2km basic segment between merging/diverging sections.

Especially for elderly drivers, in the “Side” condition, which is the case that induced much mental load, driver’s awareness level also deteriorated along the same 2km basic segment.

Following a vehicle, especially large-sized, caused more deterioration of awareness level.

In addition to blinking frequency, the deterioration of awareness level with driving time can be verified also by reaction time to stopping vehicle.

Awareness level of elderly drivers might deteriorate more easily than that of taxi drivers.

These results indicate that at basic segment between merging/diverging sections in underground urban expressway, driver’s awareness level can deteriorate, and enter merging section at a low awareness level, where the traffic flow might be disturbed. This driving situation can be considered extremely dangerous.

4.5. Experiments for the analysis of the audio information system to prevent driver’s awareness level deterioration in underground urban expressway

4.5.1. Procedure

The information system (IS) was applied to two traffic conditions: “Pass” and “Side” which are shown in Figure 4-2. For each subject, four types of experiments were randomly conducted: “Pass” without IS, “Pass” with IS, “Side” without IS, and “Side” with IS. The audio information is given to the driver one time upon approaching each merging, and three times upon approaching each diverging section. In the experimental virtual roadway, merging and diverging sections are sometimes closely spaced. In order not to confuse drivers with too much information, a warning for each merging section is given only one time. The timing of information and roadway structure are shown in Figure 4-22.

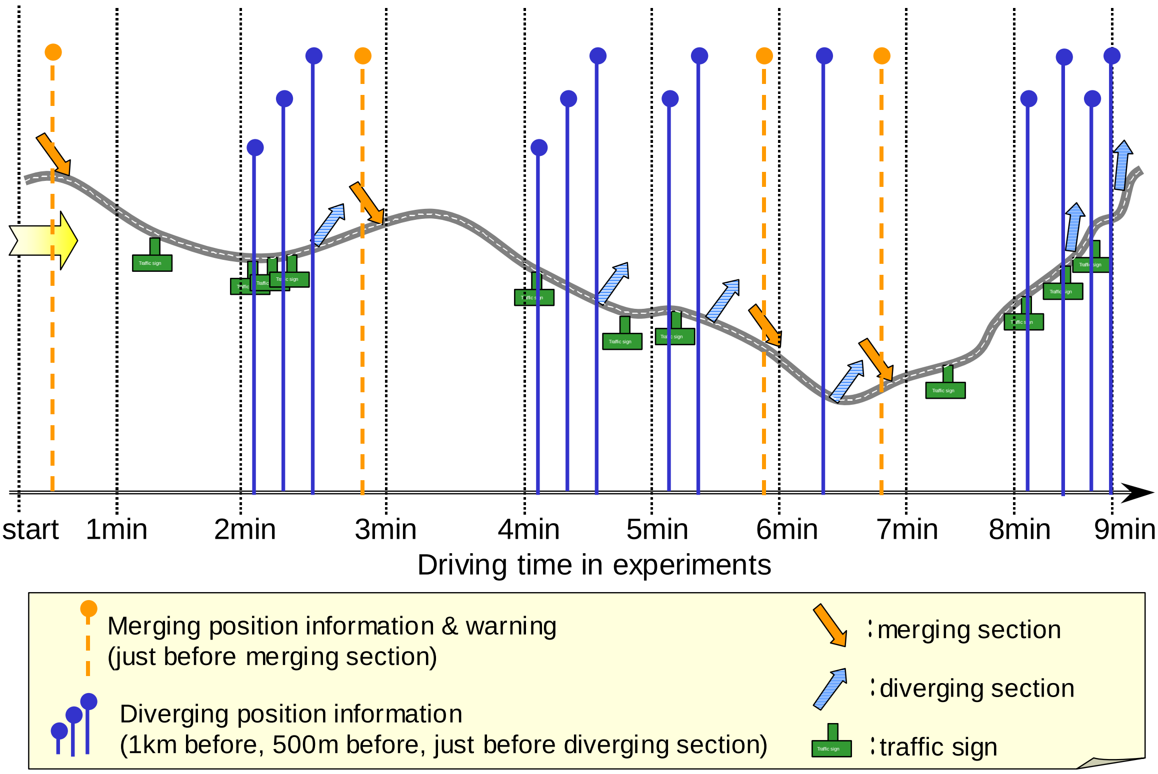


Figure 4-22 Roadway Structure and Information Timings (Horizontal Projection).

4.5.2. Participants

Experiments of the audio information system as a measure to prevent driver's awareness level deterioration were conducted on six elderly drivers (see Table 4-4).

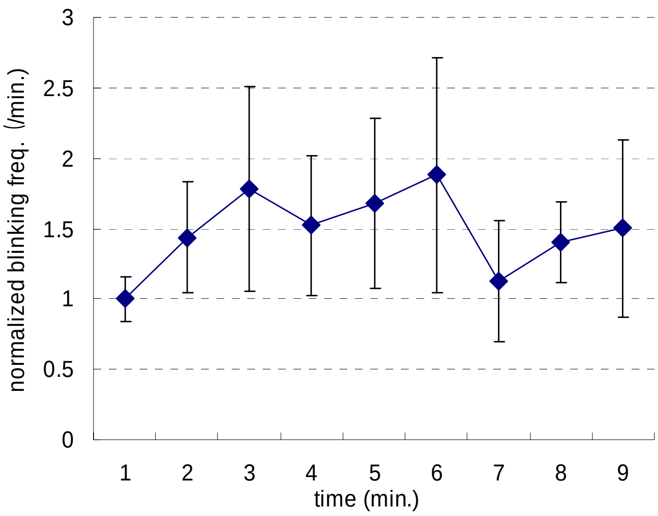
Table 4-4 Profile of participants for the experiments for the analysis of the audio information system

Experiments for the analysis of audio information system

ID	date	attribute	age	sex	drive frequency
O･11	1st,Jul.,2003	elderly driver	65	male	everyday
O･12	1st,Jul.,2003	elderly driver	67	male	once a month
O･13	2nd,Jul.,2003	elderly driver	68	male	once a week
O･14	3rd,Jul.,2003	elderly driver	69	male	everyday
O･15	3rd,Jul.,2003	elderly driver	74	male	several times a month
O･16	4th,Jul.,2003	elderly driver	64	male	several times a week

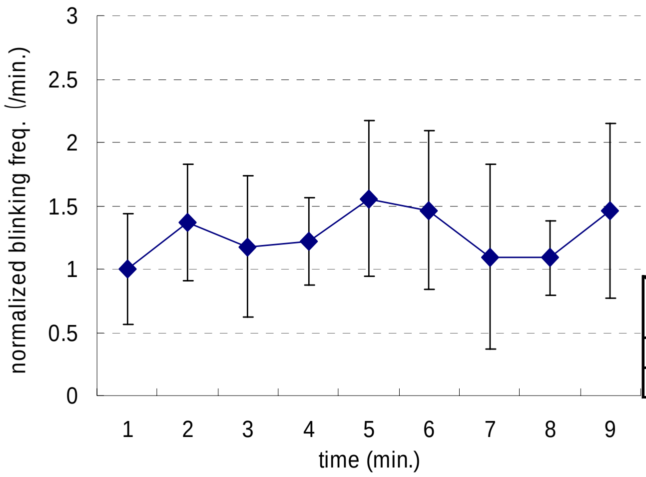
4.5.3. Results and discussions

The results in the "Pass" condition without and with IS are shown respectively in Figure 4-23 and Figure 4-24. Each data point reflects the average for the six elderly drivers. In "Pass" condition without IS, there were statistically significant changes in blinking frequency as driving time progressed [$F(8,40)=1.834$, $P<0.10$: tested by repeated measures ANOVA]. This means that the driver's awareness level changed with driving time. On the other hand, in "Pass" condition with IS, practically no statistically significant blinking frequency changes were observed [$F(8,40)= 0.894$, $P>0.52$: tested by repeated measures ANOVA] and this means that the driver's awareness level did not change with driving time. Comparing these two results, it can be deduced that the driver's high awareness level can be maintained by giving information on merging and diverging positions. In more detail, without IS, awareness level deteriorated from time period 2min. to 6min., but after 6min. when subjects drove into a relatively hard roadway structure with sharp curves and many merging/diverging sections, awareness level increased again. In contrast, with IS, awareness level deteriorated from 4min. to 5min. (if level of significance is < 0.05, this change was not statistically significant), but in the other sections, awareness level remained high due to the IS. From 3min. to 4min. awareness level did not deteriorate even though there was no information. The prior information might have been effective even for subsequent sections located further downstream.



	Pair of blinking freq. that have significant difference (tested by L.S.D)
P<0.05	1min. - 3min. 1min. - 5min. 1min. - 6min. 3min. - 7min. 6min. - 7min.
P<0.10	1min. - 4min. 5min. - 7min.

Figure 4-23 Blinking Frequency of Elderly Driver in "Pass" Condition without IS.

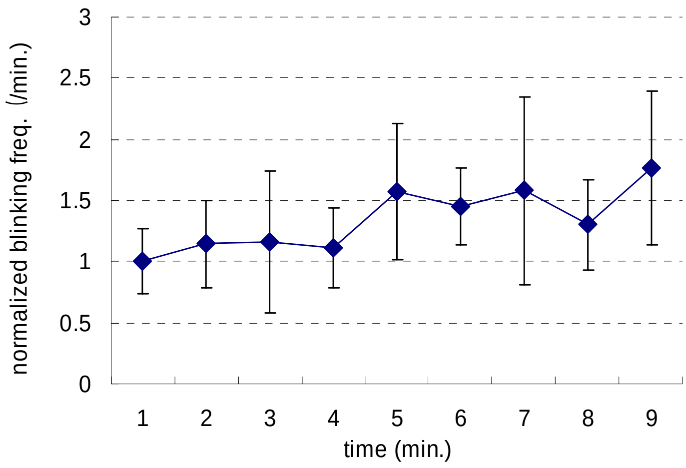


	Pair of blinking freq. that have significant difference (tested by L.S.D)
P<0.05	No pair with significant difference
P<0.10	1min. - 5min.

Figure 4-24 Blinking Frequency of Elderly Driver in "Pass" Condition with IS.

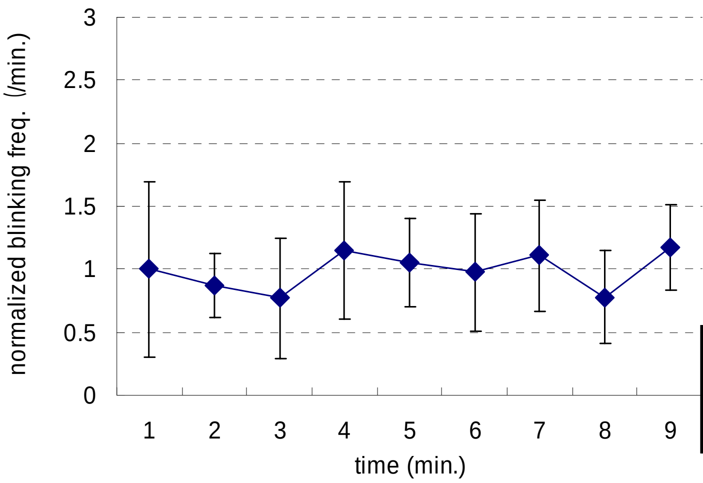
The results in "Side" condition without and with IS are shown respectively in Figure 4-25 and Figure 4-26 . Figure 4-27 shows the average RR interval of each condition. Without IS, RR-interval in "Side" condition is a little lower than that of "Pass" condition (but the difference is not significant, t=0.21, P=.41). Due to the slightly higher mental load, the awareness level might remain high, but after 4min. of driving the awareness level deteriorated because the drivers may have become accustomed to the pressure of the side vehicles during the latter half of the driving course. On the other hand, with IS, RR-interval in "Pass" condition is lower than that of "Side" condition (but the difference is not significant, t=1.35, P=.12). There seems to be no clear explanation for this result for now. However, as is the case with "Pass" condition, in "Side" condition without IS, there were statistically significant changes in blinking frequency as driving time progressed [F(8,40)= 2.197, P<0.05: tested by repeated measures ANOVA], and in "Side" condition with IS, practically no statistically significant blinking frequency changes were observed [F(8,40)= 0.787, P>0.61: tested by repeated measures ANOVA]. Therefore, in both conditions ("Pass" and "Side"), it can be deduced that the driver's high awareness level can be maintained by giving information on merging and diverging positions.

These experiments were conducted after the participant practiced driving the simulator for around 1 hour. This was done to determine if the audio warnings still had an impact on alerting the participant after the novelty effect wore off.



	Pair of blinking freq. that have significant difference (tested by L.S.D)		
P<0.05	1min. - 5min.	1min. - 7min.	1min. - 9min.
	2min. - 9min.	3min. - 9min.	4min. - 9min.
P<0.10	1min. - 6min.	2min. - 5min.	2min. - 7min.
	3min. - 7min.	4min. - 5min.	4min. - 7min.
	8min. - 9min.		

Figure 4-25　Blinking Frequency of Elderly Driver in “Side” Condition without IS



	Pair of blinking freq. that have significant difference (tested by L.S.D)
P<0.05	No pair with significant difference
P<0.10	No pair with significant difference

Figure 4-26　Blinking Frequency of Elderly Driver in “Side” Condition with IS

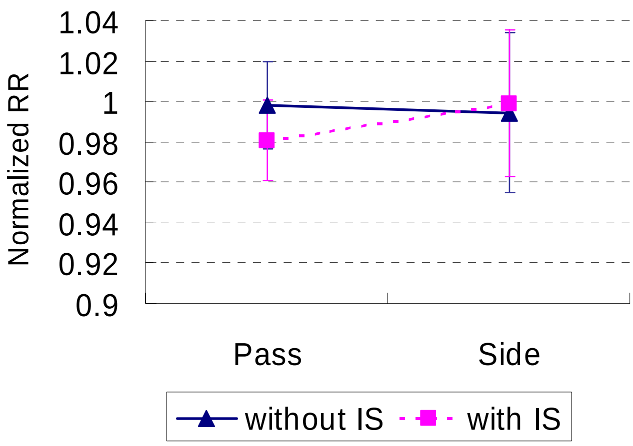


Figure 4-27　Average of Normalized RR-interval in Each Condition.

4.6. Summary

In an underground urban expressway, there are several traffic accident risks. In this chapter, deterioration of driver's awareness level is especially analyzed through the simulator experiments conducted on elderly drivers and taxi drivers. Results of analyses indicated that at basic segment between merging/diverging sections in underground urban expressway, the driver's awareness level could significantly deteriorate, especially for elderly drivers as compared to taxi drivers. It was also shown that an audio information system that gives warning on approaching merging and diverging sections could prevent deterioration of the driver's awareness level. This study was not able to clarify the differences of awareness level between an underground and aboveground expressway. However, the audio information system is considered to be effective against the deterioration of the awareness level prior to merging diverging sections.

Chapter5. Development of Moving Virtual Cockpit driving simulation system “MOVIC-T4”

5.1. Need to develop a new driving simulation system

The classical-style driving simulation system using the existing system (hardware) which consists of CRT monitor for the visual system and the fixed-base cockpit might have some limitations such as the narrow visual field of view and no duplicating the acceleration cueing, so it can be used in the limited study area such as the driving experiments in some monotonous conditions shown in chapter 4. When conducting the simulator experiments in more complicated traffic condition such as stopping behaviors and merging behaviors which can induce the conflicts with other vehicles. Conflicts with surrounding vehicles can induce changes in driving behavior patterns and the driver's mental load. It is therefore important to add a motion system to a simulator in order to duplicate the acceleration and turning of a vehicle. Moreover, the wider field of view is also needed when changing lane or merging. In this manner, more realistic driving behavioral and physiological data can be obtained. In addition, a small portable simulator can be used as a demonstration tool in addition to a safety analysis tool. Proposed new roadway projects can be shown to the public using this simulator and the information about the projects can be share among any stakeholders. Therefore the new-type driving simulation system is needed to develop, which has better performance and small portable size.

5.2. General information of MOVIC-T4

Figure 5-1 shows the development flowchart of driving simulation system from DS1 to new simulation system MOVIC-T4. As mentioned in chapter 3, the control algorithm for subject's driving vehicle and automated surrounding vehicle in MOVIC-T4 are based on that in DS1. Figure 5-2 shows the overall system configuration of the driving simulator named MOVIC-T4 (MOving VIrtual Cockpit by Tokyo Tech & Trion for Tokyo highways). Microsoft Visual C++ is the language used to develop the 3D virtual environment, along with the real-time 3D development tool "WorldToolKit" by SENSE8. The simulator has an average frame rate of 30Hz that varies depending on the traffic scenario, such as the number of surrounding vehicles. Hardware components include a HMD, a head-orientation tracking sensor, vehicle control devices, and a two-degree-of-freedom motion-base. The state of the control vehicle is calculated from the subject's driving control input and the roadway geometric structure database. The motion system is then based on the state of the control vehicle.

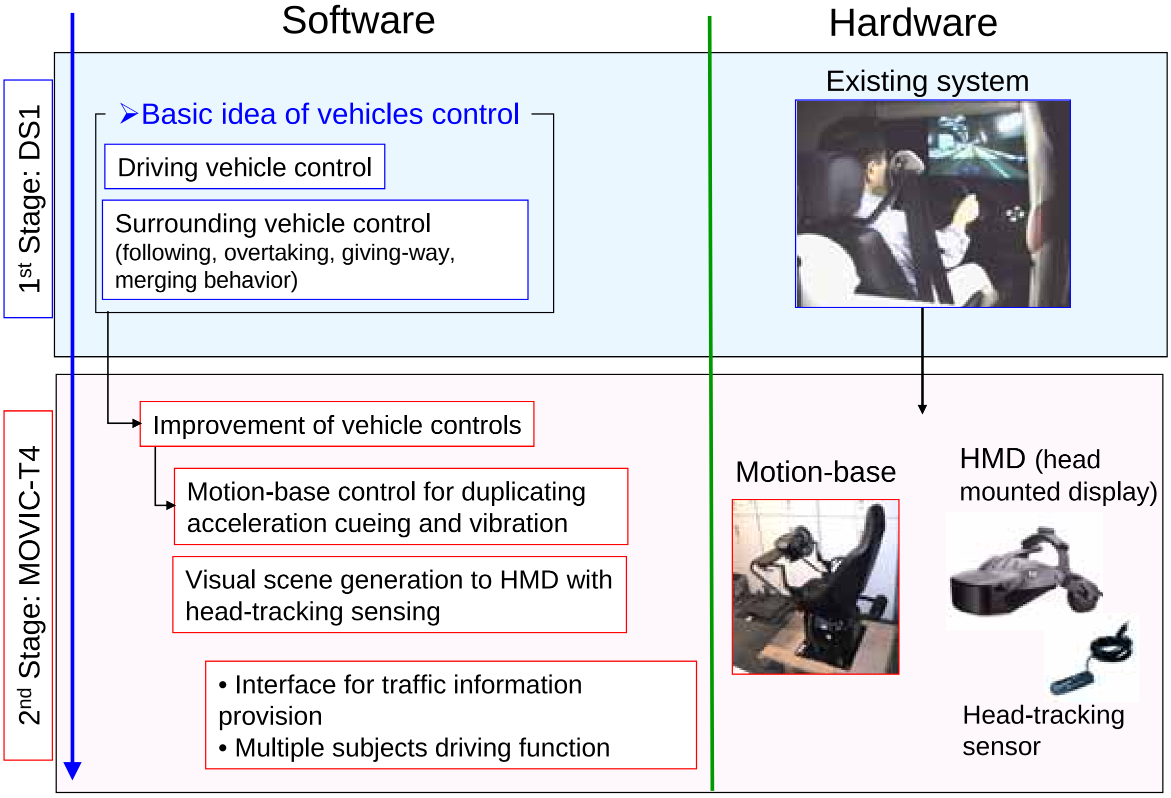


Figure 5-1 Improvement flowchart of DS development (DS1 -> MOVIC-T4)

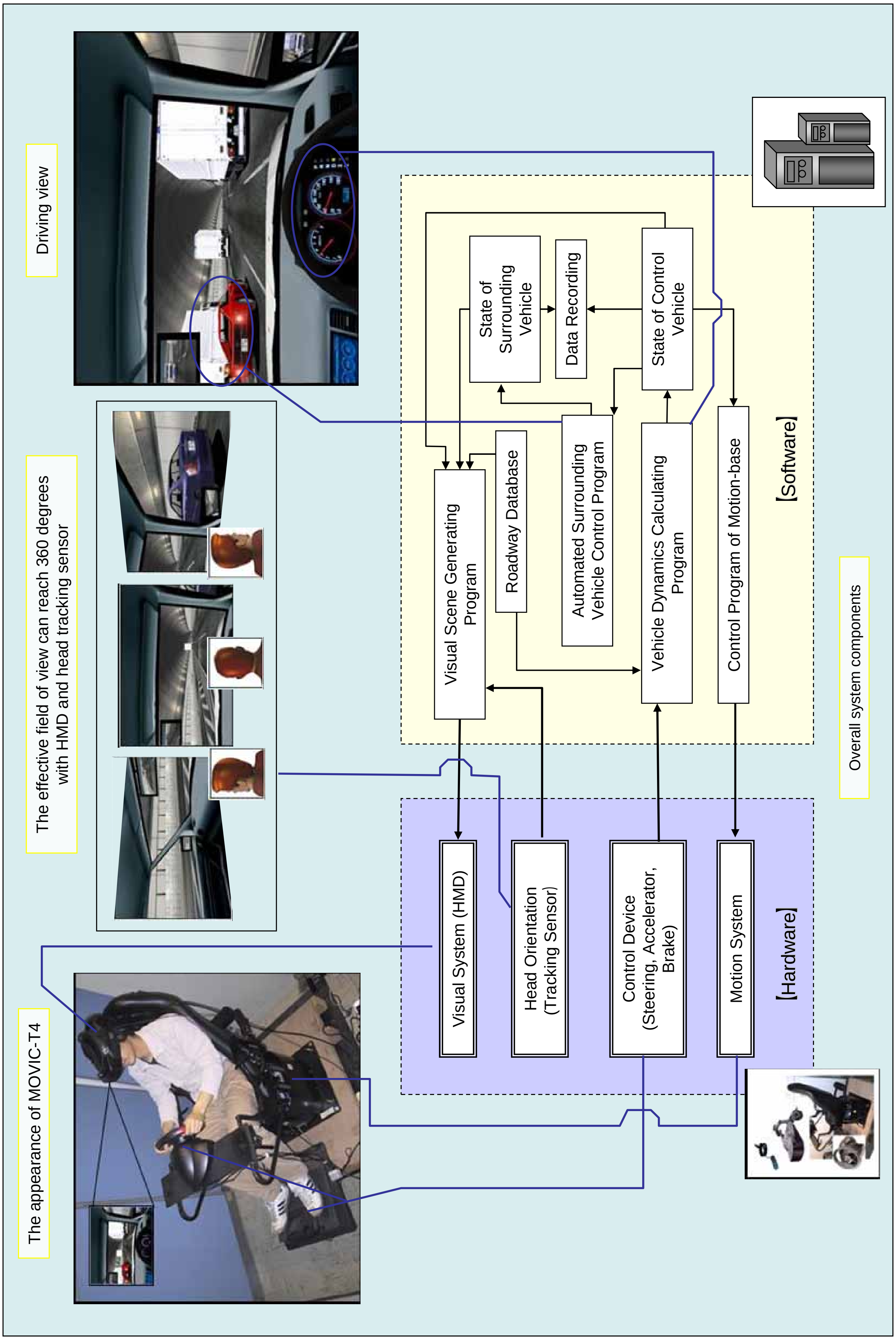


Figure 5-2 Overall system components of MOVIC-T4

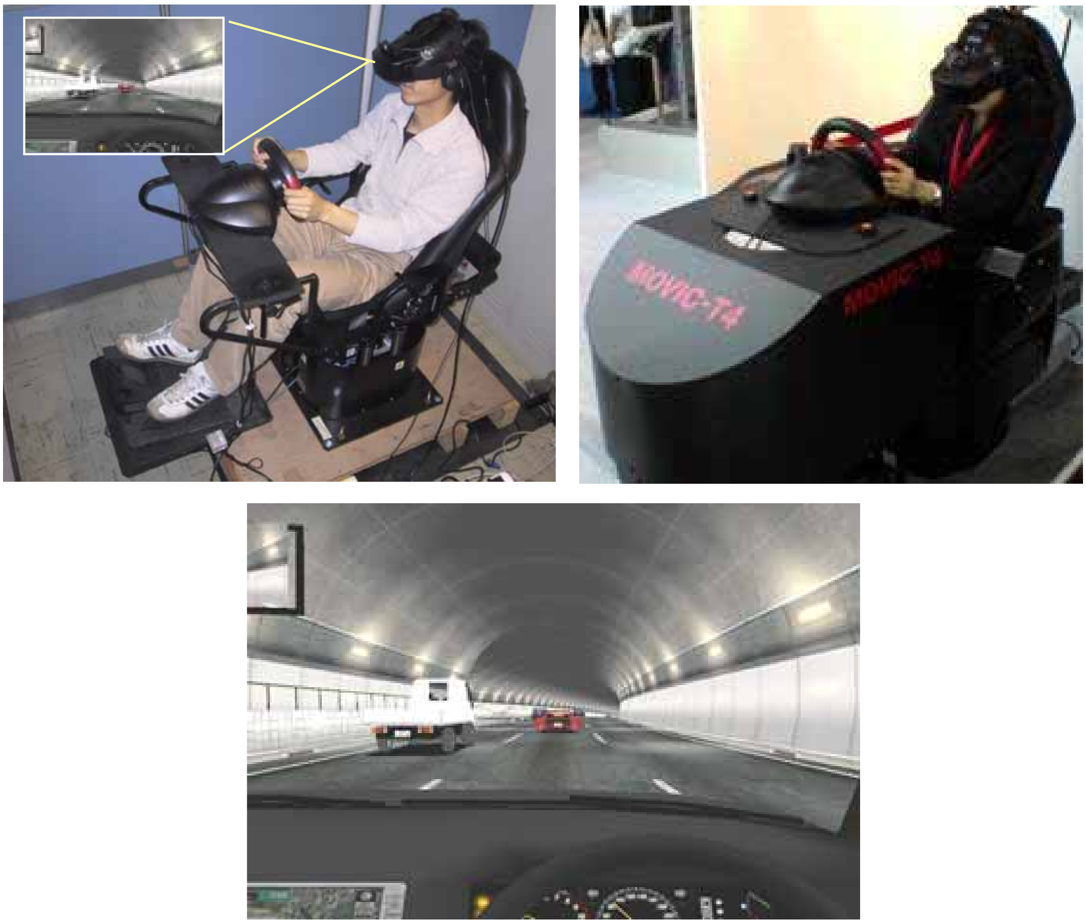


Figure 5-3 Appearance of MOVIC-T4 and virtual driving view

In this simulation system, around 60 surrounding vehicles can be generated. These vehicles are set to run automatically, with initial attributes such as starting position, desired running speed, desired distance headway, criterion of judgment in changing lanes, and vehicle type. Using these attributes, an algorithm for vehicles changing lanes was developed. Recorded data of subject's control vehicle included the driving path, speed, acceleration and braking, steering, and distance headway to the vehicle ahead. The driving path and speed for surrounding vehicles was also recorded.

HMD currently used in MOVIC-T4 is a product named "V8" by Virtual Research Systems, Inc., which has a 60 degree horizontal field-of-view, a resolution of 640*480 pixels and a weight of 1.0 kg. Coupled with the head tracking sensor, the effective field-of-view can reach 360 degrees. Compared with traditional projector-based driving simulators, the HMD-based system can attain a high level of realism due to the immersion into the virtual roadway. In addition, the scope and cost of HMD-based systems may be lower due to the reduction in the size of the physical display equipment and the required graphics requirements.

The virtual roadway in MOVIC-T4 is about 16km in length, consisting of three-lanes, three highway junctions, five roadway interchanges, and a vertical grade of less than three percent.

The appearance of MOVIC-T4 and virtual driving view are shown in Figure 5-3.

5.3. Improvement of control algorithm of driving vehicle

5.3.1. Acceleration performance

There was no concept of running resistance in DS1 described in chapter 3. Without running resistance, driving speed can easily increase even at high speed, moreover driver have difficulty in keeping fixed driving speed. Figure 5-4 shows the acceleration performance of DS1.

Running resistance consists of air resistance, rolling resistance and grade resistance. Air resistance is proportional to square of driving speed, rolling resistance depend on driving speed, and grade resistance is proportional to road grade. Rolling resistance can be ignored due to its small value. In DS, air resistance is only demonstrated now. With this resistance, reality of acceleration has increased especially at high-speed range. And keeping fixed speed becomes to be easier. The parameters are adjusted to fit the acceleration performance of real vehicle (see Figure 5-6 and Figure 5-7). The acceleration performance at low speed is not good, but it might be not a big problem because our target is the analysis of traffic safety in an underground urban expressway.

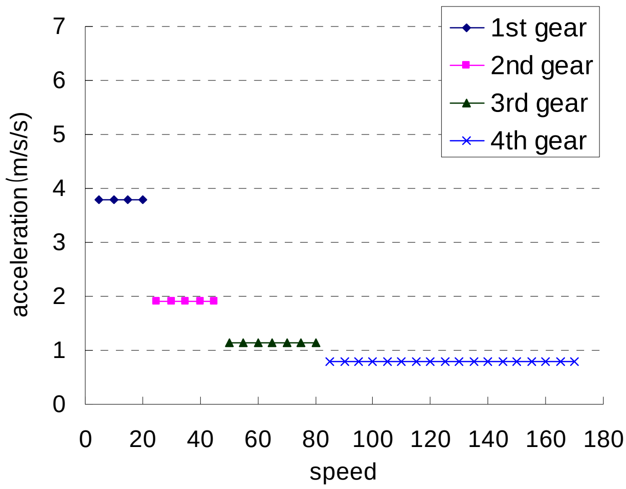


Figure 5-4 Acceleration performance of DS1

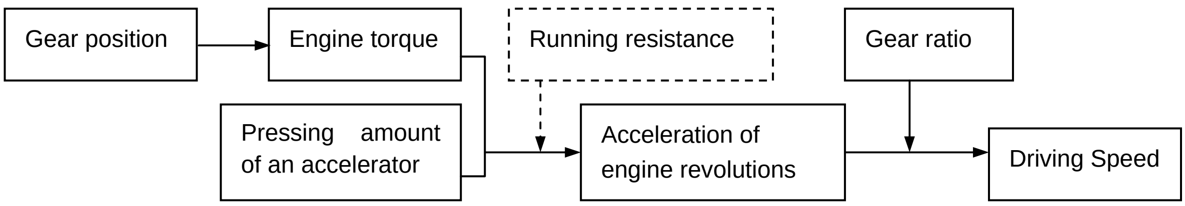


Figure 5-5 Calculation flow of driving speed

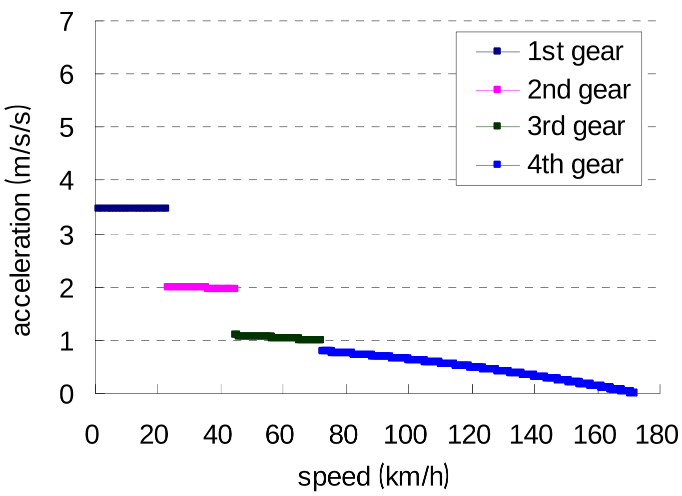


Figure 5-6 Acceleration performance of MOVIC-T4

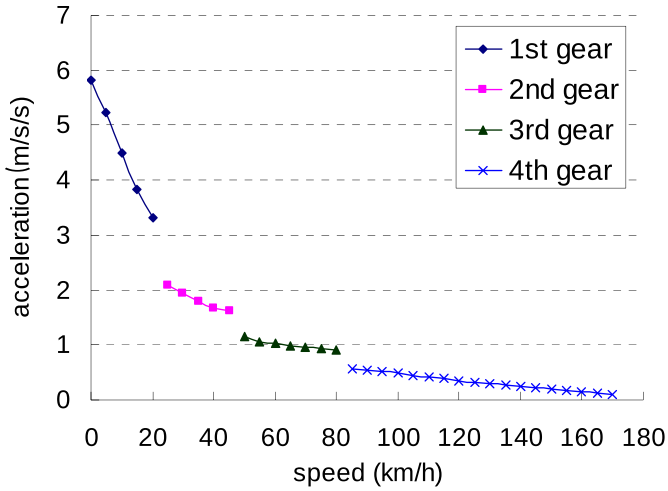


Figure 5-7 Acceleration performance of real car (ISUZU ASKA (AT))

5.3.2. Braking performance

The braking performance was also modified in MOVIC-T4 by using the relationship between deceleration and brake pedal use amount in a real car. With the instrumented car equipped with brake sensor and deceleration sensor, the relationship was measured by varying the use of brake pedal. The result is shown in Figure 5-8. Smaller use of brake less than around 20 % is a play, therefore the deceleration is almost zero. After the play range more than around 20 %, the deceleration increases sharply because the braking is hydraulic drive. In MOVIC-T4, this braking performance is duplicated by the nonlinear function: Y(deceleration)=A*X(use of brake pedal)^3. Coefficient A is adjusted to fit the obtained data.

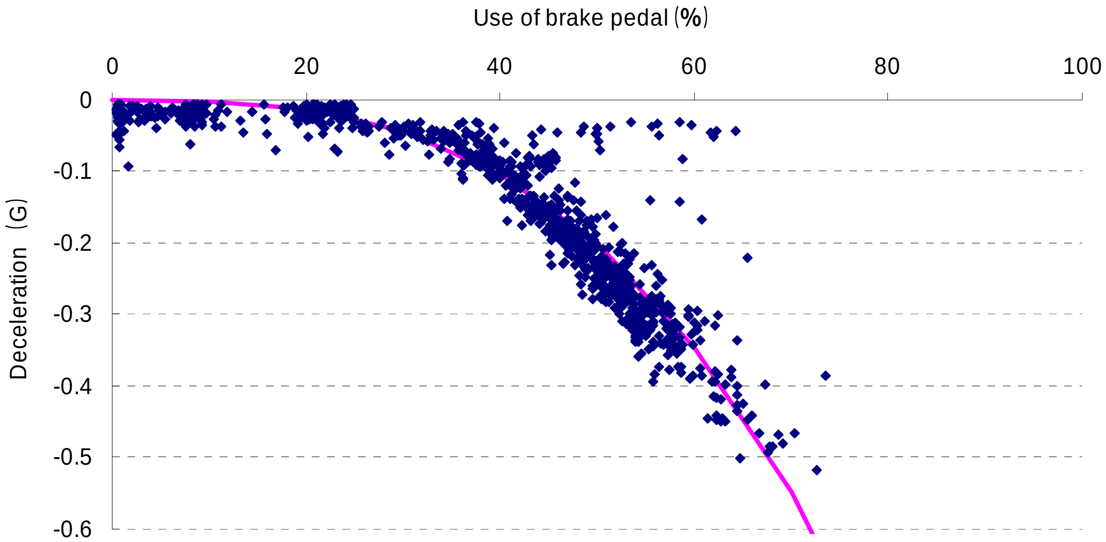


Figure 5-8 Deceleration performance in a real car

5.4. Mitigation of poor visible distance in simulator

In any simulator, there is a limitation of visual resolution which causes the poorer visible distance from subject's viewpoint to some objects while the visual resolution is considered to be infinite in a real world. Moreover, the brightness change of brake lamp cannot be duplicated in simulator, which may also causes the poorer visible distance. It's necessary to investigate how this level of poorness of visible distance can cause the validity of driving data.

First, the visible distance in real tunnel (Aqualine) and in simulator were measured. Figure 5-9 shows the measured visible distance of brake lamp in a real world and in simulator. The visible distance in simulator might be around half of that in a real world.

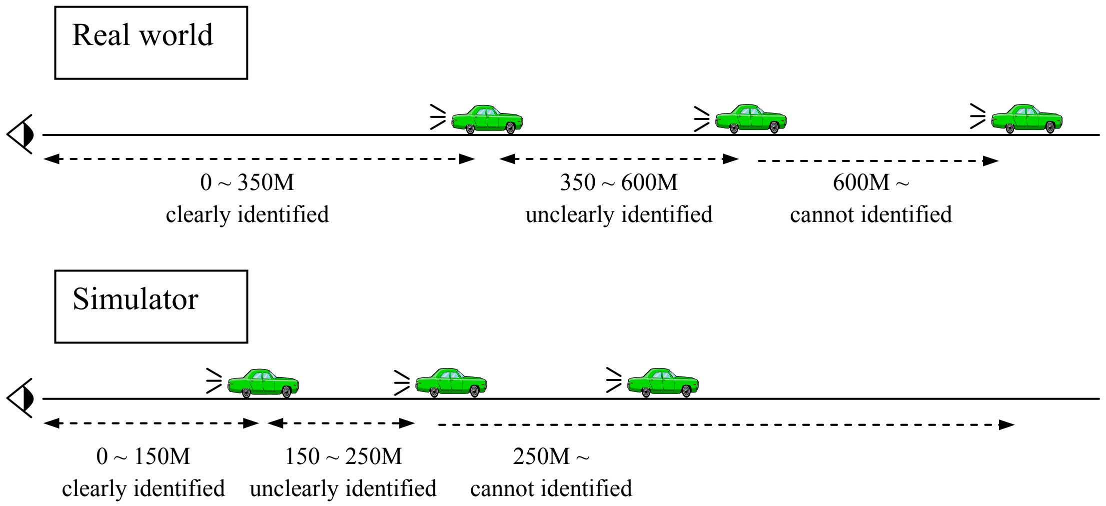


Figure 5-9 Visible distance of brake lamp in a real world and in simulator

The difference of the visible distance between in a real world and in a simulator might be caused by the resolution of a simulator display rather than by the fact that brake lamp is described just by changing its color. By the simple calculations, if the width and height of a car are 1.73M and 1.43M respectively, the car running 250M ahead is described by about 5MM width and 4MM height. One pixel is about 0.5MM (the resolution of our HMD is 640*480 pixel), so the car is described by 80 pixels. This size is considered to be the limit to identify the brake lamp and also the limit to identify the figure as a car.

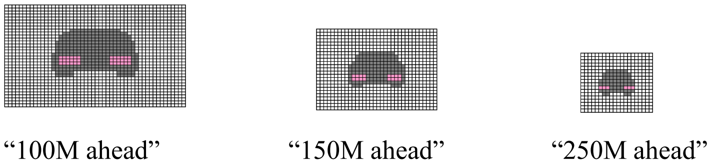
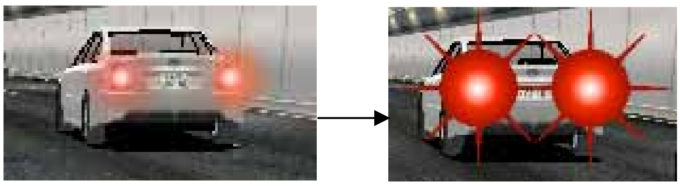


Figure 5-10 Changing image of car with different distances in a simulator

In order to make the brake lamp clearer, it's necessary to make the light of brake lamp bigger. I measured the visible distance of brake lamp using one sample of a light of brake lamp which is bigger but somewhat strange (see Figure 5-11). With this bigger light, the visible distance of brake lump becomes around 100M longer, then the visible distance in simulator can be around 250M. In terms of the reality of visual scene, the bigger lamp is not appropriate. However the aim of this study is to analyze the traffic safety in underground urban expressways, accordingly the reality (or validity) of driving data in simulator is more important. In terms of this viewpoint, the strangeness of the brake lamp must not be inappropriate because the shape of the brake lamp may have little impact on the driving behavior. As same as this way to modify, the bigger traffic sign than real world may also be needed if some assessment regarding traffic signs is conducted.



"Normal light" "Bigger light"

Figure 5-11 Normal light and bigger light in a simulator

However the visible distance of brake lamp (250M) is still shorter than that in real world (350M). Next, the required visible distance in simulator experiments is considered. Figure 5-12 shows the change of required distance to complete stop with driving speed where the three acceleration (-12.3, -17.6 and -24.7 km/h/s) are assumed and reaction time is 1.0 sec. The acceleration -12.3km/h/s (= -0.35G) can be interpreted as normal braking. Even with this normal braking level, driver whose speed is 140km/h can stop at 250M ahead from the point where driver start to brake. Usually one drives at the speed of less than 140km/h, therefore the visible distance of 250M in simulator can be interpreted as enough distance for simulator experiments.

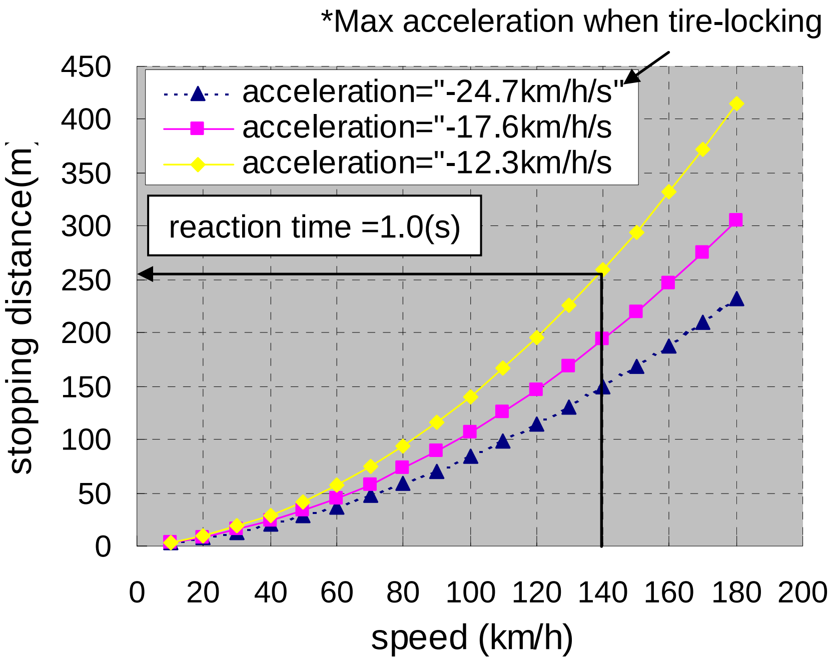


Figure 5-12 Required distance to complete stop

5.5. Motion-base control for duplicating acceleration cueing and vibration while driving

5.5.1. Difference between 2 degree-of-freedom and 6 degree-of-freedom motion-base

Motion systems have been added to many modern driving simulators in hopes of increasing realism, validity of operator responses and reducing simulator sickness. In addition, many researchers have hypothesized and hoped that the addition of accurate motion cues might reduce overall levels of simulator sickness experienced by simulator drivers.

A six-axis motion-based simulator has the movement of 6 degree-of-freedom (DOF): Serge, Sway, Heave, Roll, Pitch, and Yaw. Then, the acceleration cueing while driving is duplicated by combining these movements. A classical motion cueing algorithm commonly used in most 6 DOF motion-based simulators is a combination of frequency filters which:

- remove the low frequency of accelerations by high-pass filtering, then integrate the signal twice to output a position command,

- extract the low frequency horizontal accelerations by low-pass filtering, then compute a tilt coordination' angle which is added to the output command,
- bring the platform back to its neutral position by high-pass filtering of the resulting position commands (see Figure 5-13)

The last processing stage is often referred to as 'motion washout' and is necessary to avoid saturating the actuators. The corresponding platform motion is performed at undetectable rates (G. Reymond et al, 2000).

In case of a 2 DOF motion-base simulator, there can be only pitch and roll movement duplicated. Therefore the complicated control algorithm like a 6 DOF motion-base is not needed and cannot be demonstrated. In the limitation of 2 DOF, the motion-base control algorithm is considered in the following section.

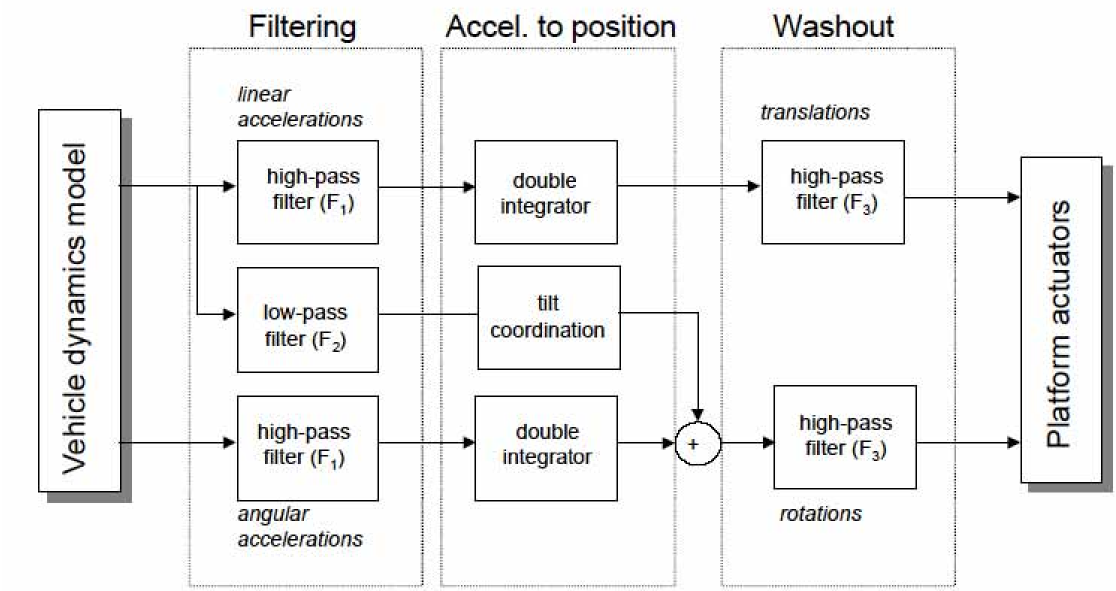


Figure 5-13 Classical motion cueing algorithm commonly used in most 6 DOF motion-based simulators (G. Reymond et al, 2000)

5.5.2. Motion-base control for duplicating acceleration cueing with two-degree-of-freedom motion-base

The motion-base of MOVIC-T4 has 2 DOF, pitch and roll. The maximum rate of tilt for both is 40 degrees per second, with a total range of movement of 15 degrees. Two-degrees-of-freedom was chosen for this motion-base because of its small size and fast response, which can allow us to duplicate higher frequency vibrations of the vehicle, which is discussed later. A 6 DOF motion-base, which is popularly used, tended to be for large-sized simulators and have a slow response rate. Moreover, some researches found that fewer degrees-of-freedom motion may be better regarding the subject's feeling of realism (4). While it is not clear which type of motion is best, this research tries to develop a simulator with appropriate performance for traffic safety analysis in an underground urban expressway. The acceleration cueing during vehicle operation is simulated through the component force of the subject's own weight generated by the tilt of the motion-base. The magnitude of the angle for pitch and roll are calculated as shown in Figure 5-15. The motion-base tilts according to the vehicle longitudinal acceleration for pitch and centrifugal acceleration for roll. These accelerations are calculated from the subject's control of the accelerator, brake, and steering. Because it is impossible to duplicate sustained large accelerations due to the limitations of the motion-base movement range, a scaled cueing parameter must be used.

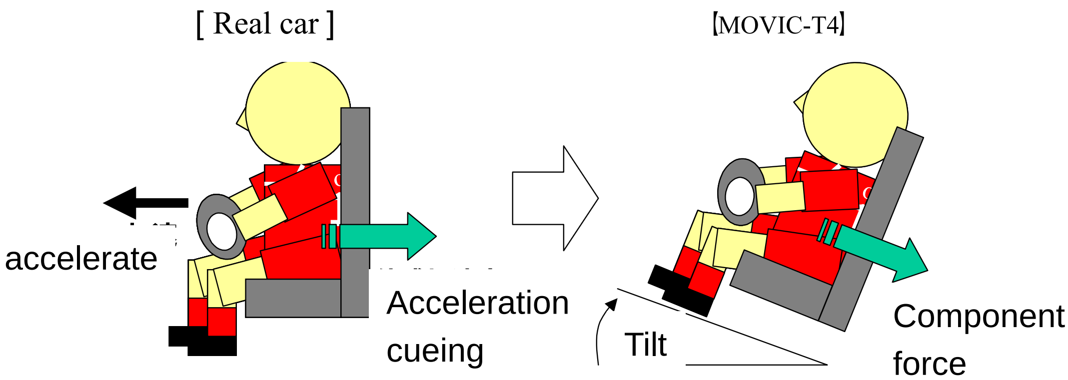


Figure 5-14 Method to simulate the acceleration cueing by the tilt of 2 DOF motion-base

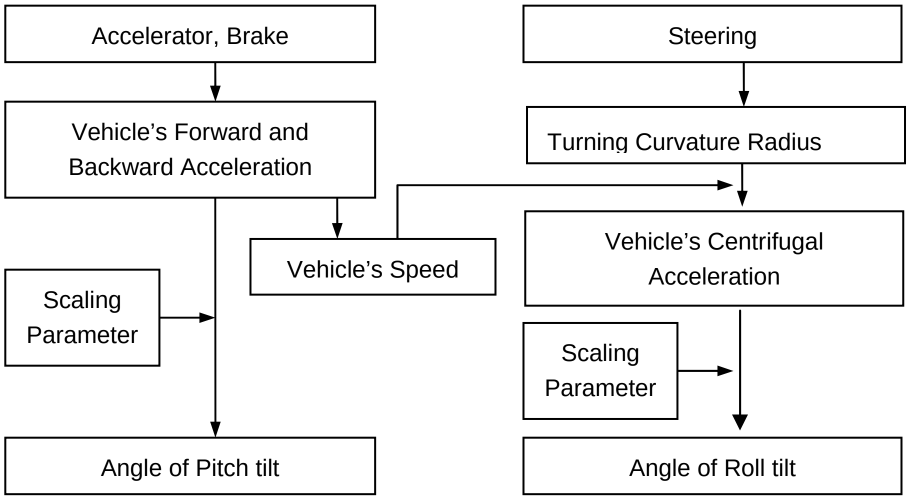


Figure 5-15 Flowchart of calculating tilt angles of pitch and roll

5.5.3. Optimization of scaled cueing through a subjective evaluation

There has been some research done regarding the configuration of parameters for control of a motion-base with six degrees of freedom (5)(6), but there is no research for a motion-base with two-degrees-of-freedom. Therefore, an original investigation of the configuration of parameters for control of a motion-base with two degrees of freedom is needed.

Because there is a small pitch or roll movement in a real vehicle induced by elastic vehicle suspension when longitudinal or lateral acceleration occurs, an excess amount of tilt may induce an odd feeling on some subjects. As a result, a scaling parameter for vehicle acceleration was generated for the motion-base by examining the trade-off between the realism of the perceived size of acceleration cueing and the level of odd feeling. Figure 5-16 shows the flowchart used to determine the scaling parameter through a subjective evaluation. First, eight licensed students from age 21 to 26 conducted simulator experiments, where they underwent several driving behavior patterns such as hard/soft accelerating, braking, and steering. The same experiment was repeated four times for each subject while changing the scaling parameter of motion cueing. Each subject then evaluated the realism of the acceleration cueing and the level of odd feeling induced by the simulator tilts. After determining a rough range for the scaling parameter from these tests, the experiment was refined to obtain a precise and optimal scaling parameter.

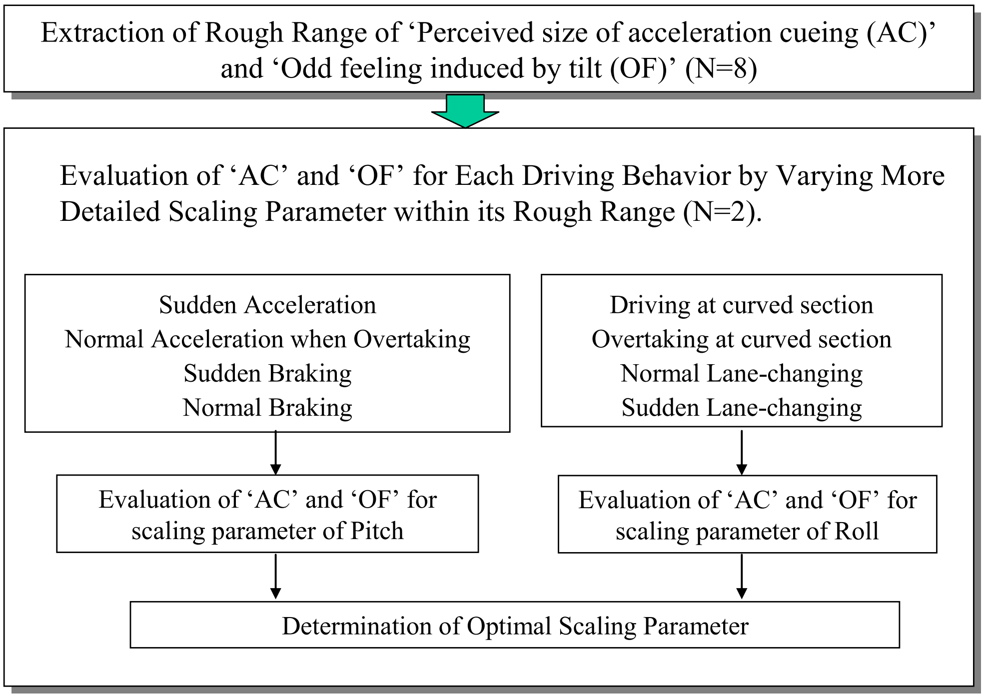
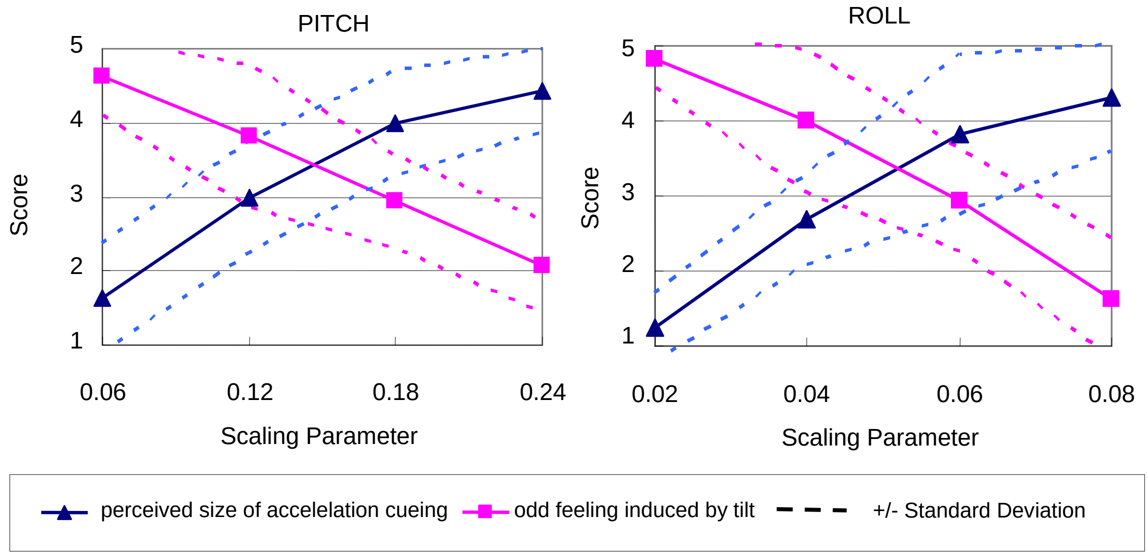


Figure 5-16 Flowchart to determine the scaling parameter of acceleration cueing

The results of the evaluation are shown in Figure 5-17. It was found that for pitch, a scale parameter of 0.16 was optimal. That is, the component force of the subject’s own weight generated by the motion-base was 0.16 times that of a real world acceleration force. Higher scale parameters resulted in unrealistic movement, while lower scale parameters resulted in poor perceived acceleration cueing. The scale parameter for roll was much lower than that of pitch, with a value of 0.05. This may be due to the fact that drivers make very small turns on expressways, resulting in small centrifugal accelerations. However, drivers frequently brake and accelerate, sometimes in large magnitudes, resulting in large longitudinal accelerations.



Score: [Perceived size of acceleration cueing] 1: very small - 2: small - 3:moderate – 4:large – 5:very large

[Odd feeling induced by tilt] 1: very large - 2: large - 3:moderate – 4:small – 5:very small

Figure 5-17 Evaluation of scaling parameter for motion cueing

5.5.4. Consideration about duplicating the vehicle vibration by the motion-base

5.5.4.1 Introduction

Another utilization of the motion-base is to duplicate vibrations in the vehicle while driving. The motion-base used in this study can duplicate relatively high frequency vibrations due to its small size, while a traditional large-sized motion-base with six degrees of freedom generally can only duplicate low frequency vibrations, such as those less than 5 Hz. In this study the vehicle vibration data was obtained through an on-road experiment. The frequency of the vehicle vibration was extracted through a frequency spectrum analysis. Subjective evaluations regarding the reality of the vehicle vibration and the perception of frequency changes in the simulator were conducted.

5.5.4.2 On-road Driving Experiment

This experiment was conducted at a fifteen kilometer section of the TOMEI Expressway in Tokyo (Yokohama-Machida IC ~ Atsugi IC). The instrumented car is HONDA FIT (1300cc). The vertical acceleration was measured by an acceleration sensor that can measure between 0 to 100 Hz of vibration. The experiments were conducted repeatedly at varying driving speeds (70, 90 and 110 kph). For each driving speed, the same experiment was conducted two times. Driving lane is the left lane for 70kph, the middle lane for 90kph, and the right lane 110kph.

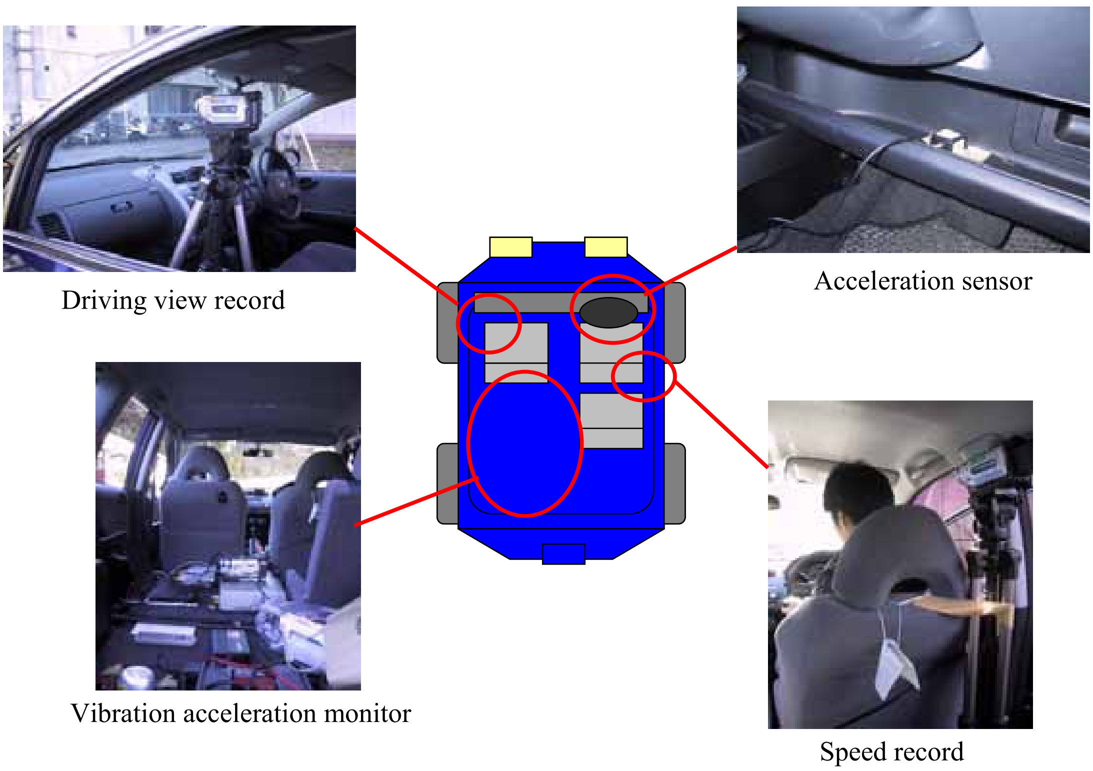


Figure 5-18 Instrumented car for vibration measurement

5.5.4.3 Frequency Analysis

The frequency spectrums of the vibration acceleration every five seconds were calculated by FFT (Fast Fourier Transform), and the average of the all spectrum data within the targeted section was taken (see Figure 5-19). Figure 5-20 shows the results of frequency spectrums of the vibration acceleration calculated by FFT (Fast Fourier Transform). From these results, two types of peak frequency vibration can be seen. One peak is at 1.5 HZ that doesn't change with driving speed. This can be interpreted as the characteristic frequency related to vehicle suspension. Another peak ranges from 11 to 17 Hz that increases monotonically as driving speed increases. This can be interpreted as the frequency related to the vehicle engine vibrations, as well as the vibration generated by the interaction between the vehicle tires and the roadway surface. As a result, the frequency changes with driving speed. An attempt to duplicate the vehicle vibration in the simulator was made by combining these two vibration components.

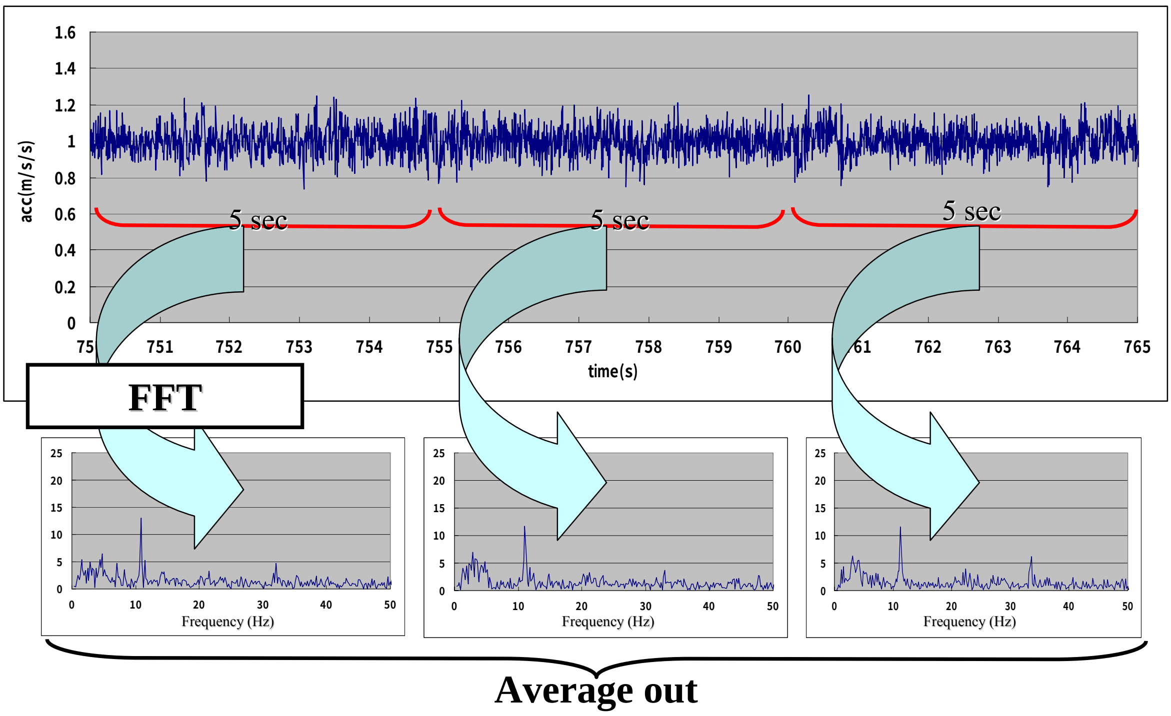


Figure 5-19 Calculation process of frequency spectrums of the vibration acceleration

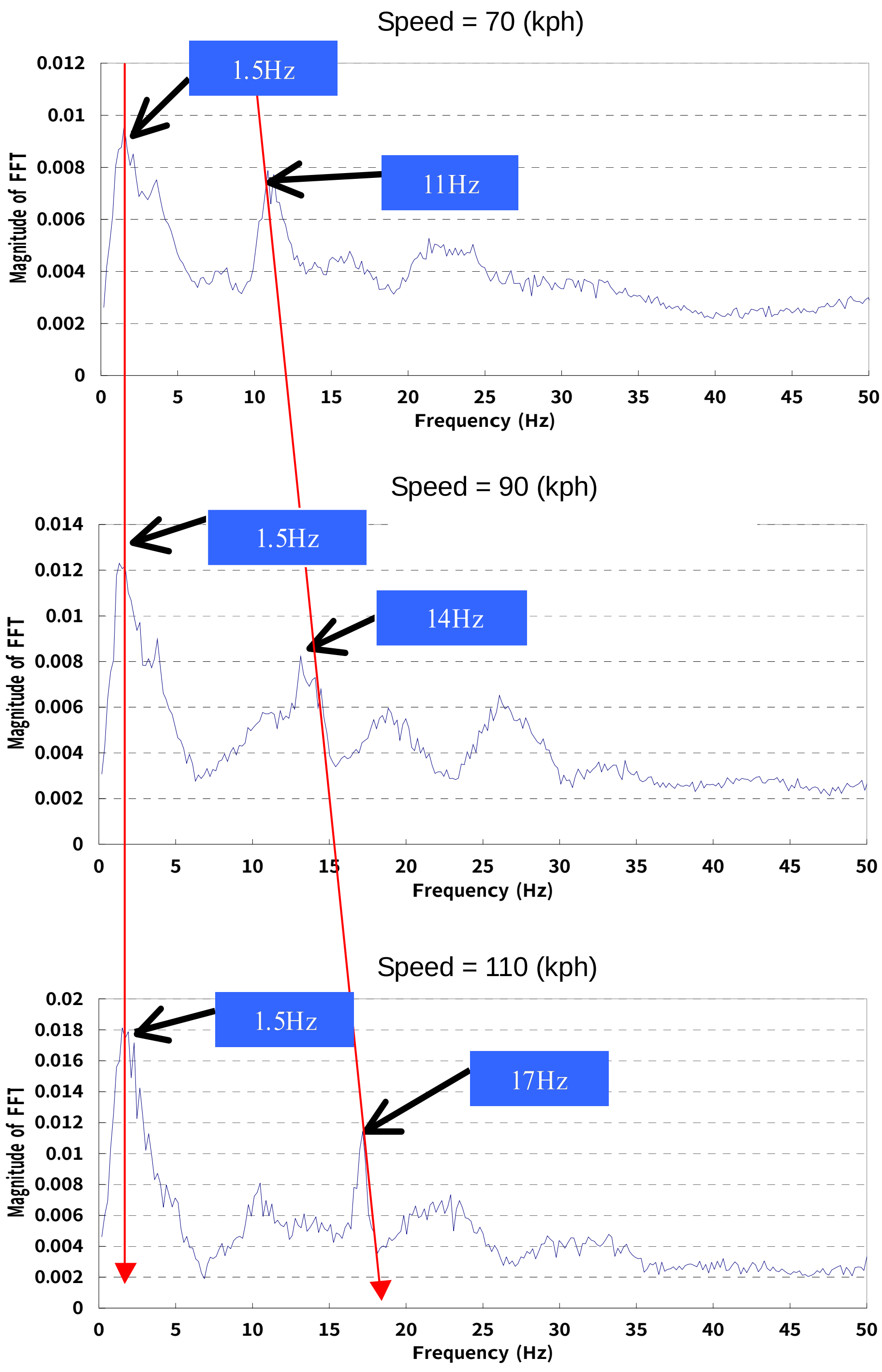


Figure 5-20 Frequency spectrums of vehicle vibration on a real road

5.5.4.4 Evaluation of duplicated vehicle vibration in simulator

Because MOVIC-T4 has only pitch and roll motions, the vibration was duplicated by pitch motion to imitate cracks in the road surface. Five types of vibrations were made by combining the two vibration components described above: (a) 1.5 Hz vibration, (b) 14 Hz vibration, (c) combined vibrations of 1.5 Hz and 14 Hz, (d) constant damped vibrations of 1.5 Hz and 14 Hz, and (e) random damped vibrations of 1.5 Hz and 14 Hz. The pattern diagrams of these vibrations are shown in Figure 5-21. Nine subjects were asked to evaluate the most realistic vibration pattern after driving a vehicle on the simulator at a constant speed of 90 kph. From the results shown in Table 5-1, the 14 Hz vibrations and the constant damped vibrations of 1.5 Hz and 14 Hz are considered to be the most realistic. The 14 Hz vibrations are easily duplicated in the simulator, and may be realistic due to the small amplitude and similarity to the constant ambient vibrations in the real life situation. The constant damped vibrations of 1.5 Hz and 14Hz may be realistic due to the repetition of cracks in the roadway concrete combined with the ambient vehicle vibrations.

Further tests were conducted to determine if a range of frequencies between 11 Hz and 17 Hz adjusted to vehicle speed were necessary. The nine subjects were asked to drive under the following speed scenario:

0s-60s: 70 kph constant,
60s-90s: accelerate to 90 kph,
90s-150s: 90 kph constant,
150s-180s: accelerate to 110 kph,
180s-240s: 110 kph constant.

Three vibration frequency patterns were tested for this driving scenario. The frequencies were changed from 11 Hz to 17 Hz, held at 14 Hz constant, and changed from 17 Hz to 11 Hz. The same experiment was also conducted with the subjects simply sitting in the seat without driving. After each experiment, the subjects were asked whether they could perceive the changes in the vibration frequency. The results are shown in Table 5-2. In all cases, almost all of the subjects could not perceive the changes in the vibration frequency precisely. As a result, it may not be necessary to duplicate the changes in vibration frequency due to speed changes in the simulator. However, these changes may be more pronounced at slower driving speeds because the vibration frequency would also be lower. This may be a further research topic for a simulator of local roads.

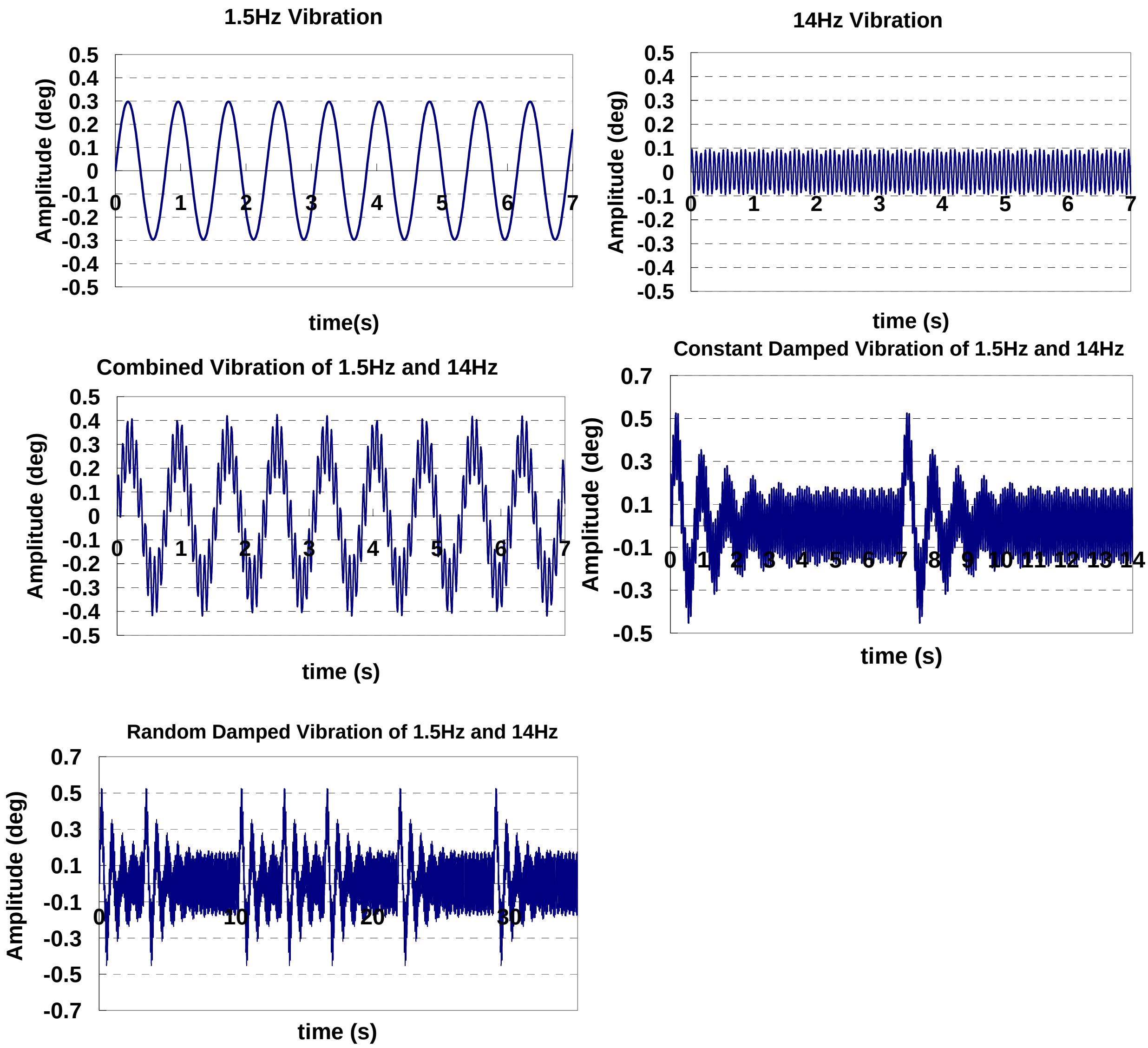


Figure 5-21 The pattern diagram of duplicated vehicle vibration in a simulator

Table 5-1 Subjective evaluation of vehicle vibration in a simulator

Duplicating Vibration	Number of getting highest reality evaluation (times)
1.5Hz Vibration	**1**
14Hz Vibration	**4**
Combined Vibrations of 1.5Hz and 14Hz	**0**
Damped Vibrations of 1.5Hz and 14Hz (constant)	**3**
Damped Vibrations of 1.5Hz and 14Hz (Random)	**1**

Table 5-2 Perceptivity of the change of vibration frequency

	Number of subject who		
	cannot perceive the change of frequency at all	can perceive the change of frequency but cannot perceive precisely how it changes	can perceive the change of frequency completely
Driving	5	4	0
Sitting	3	5	1

5.6. Additional function of MOVIC-T4

Information system

MOVIC-T4 has an interface to provide the traffic information such as the existence of stopping vehicle ahead. The information can provide by analyzing the driving data of subject's vehicle and surrounding vehicle on real-time. Because the whole visual scene including the instrumented panel inside vehicle is created only in HMD, the interface for showing the information to driver can easily change. Therefore the study regarding Human-Machine-Interface can be also easily conducted.

Figure 5-22　Example of information provision

Multiple subjects driving

Multiple subjects can drive simultaneously in the same roadway space. With this function, more realistic driving data regarding the interaction among multiple drivers can be obtained, such as the interaction between vehicles in merging sections. Compact and low-cost DS allows this kind of utilization.

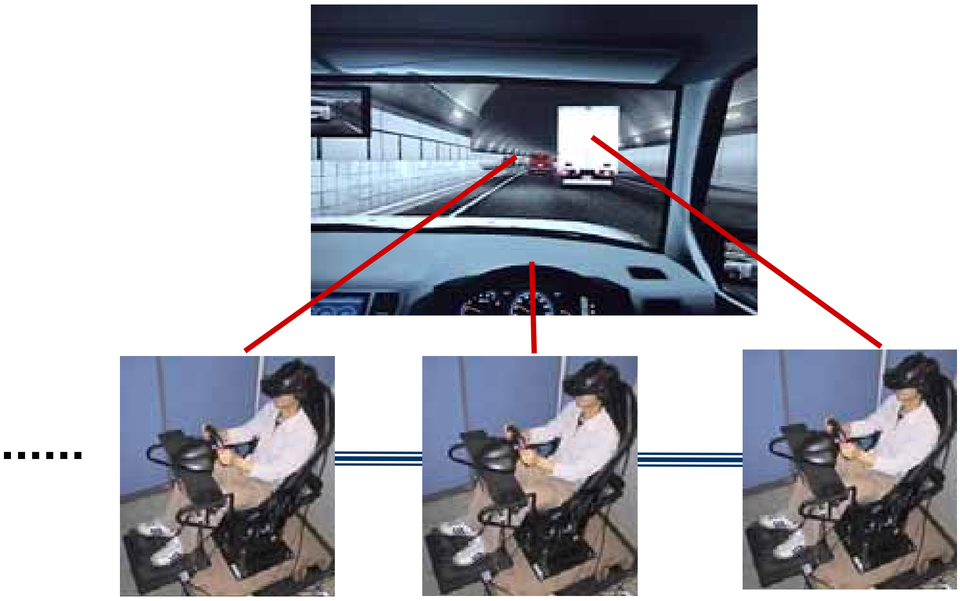


Figure 5-23　Multiple subjects driving

5.7. Preliminary performance evaluations of MOVIC-T4

5.7.1. Subjective evaluation of overall system of MOVIC-T4

Simulator experiments were conducted to evaluate the performance of MOVIC-T4. Subjects were required to follow a vehicle controlled by the author, taking the same actions such as hard/soft acceleration, braking, and lane changing. During these experiments, the subjects were asked how they felt regarding the simulator's performance. After the experiment, each subject was given a questionnaire rating the simulator's performance. These ratings were evaluated using the Semantic Differential (SD) Method, with the results shown in Figure 5-24.

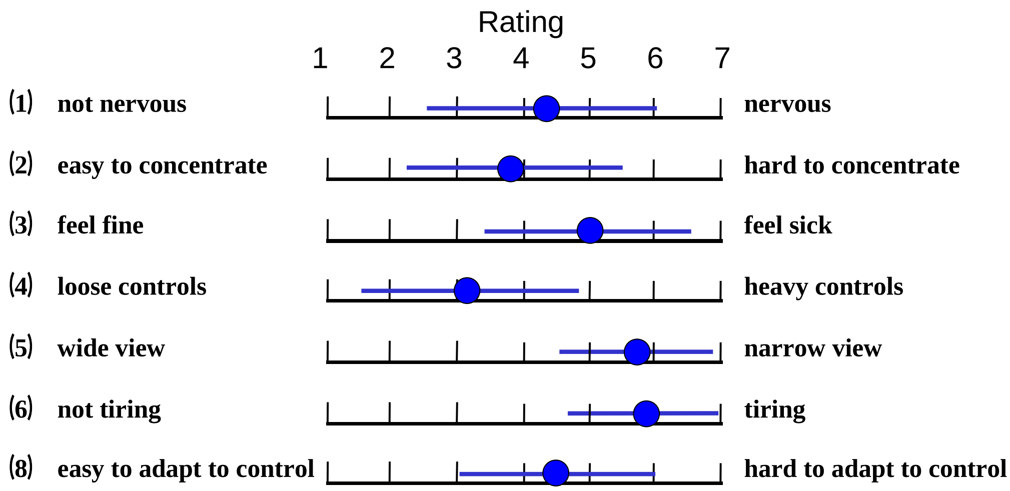


Figure 5-24 Performance Evaluation of MOVIC-T4 by SD Method (Rating: mean and standard deviation)

The evaluation results show that the subjects believe the acceleration and centrifugal acceleration cueing to be realistic, but the deceleration cueing still needs further adjustments. The SD evaluations show that almost all subjects believed the field-of-view to be too narrow as another paper also reported (Michael A, 2004), and they fatigue easily during the experiments. Both of these issues seem to be caused by the HMD visual system; therefore, special care must be taken regarding the HMD unit in further traffic safety analyses.

5.7.2. The difference of speed sensing between HMD and projector

One of the most important characteristics for measuring the performance of a driving simulator is the realism of the driving speed. In order to investigate the effectiveness of the HMD unit compared with the projector system, seven student subjects were asked to drive at two recommended speeds, 60 kph and 100 kph without access to the speedometer for both systems. Traffic conditions for both systems were the same, and the projector system has the same field-of-view (horizontal 60 degree) and resolution as HMD system. The projector screen was located 1.6 meter in front of the subject. The HMD unit and projector system order was randomized.

Table 5-3 shows the comparison of the mean cruising driving speed for all subjects in the HMD-based simulator and the projector-based simulator. For both recommended speeds, the actual driving speed in the HMD-based simulator was significantly lower than that of the projector-based system. As a result, the HMD-based system gives subjects a higher perceived driving speed than the projector-based system.

Table 5-3 Difference of perceived driving speed between using HMD and using projector

Required Speed	60 kph		100 kph	
Visual Equipment	HMD	Projector	HMD	Projector
Mean (kph)	50.9	65.4	72.8	82.2
Standard Deviation (kph)	18.4	11.4	13.4	13.8
Result of T-test of Mean Difference	t=2.97, P<0.02		t=3.01, P<0.02	

5.7.3. Impact of duplicating acceleration cueing on driver's behavioral and physiological data

Hypotheses

Duplicating the acceleration cueing through the motion-base is expected to enhance the realism of the driving environment and change the driver's behavioral patterns and physiological data. Previous research has been done describing the contribution of adding motion cueing to driving behavior, e.g. (Gilles R et al, 1999, Jeff Greenberg et al, 2003). However, because such research used a motion-base with higher degrees-of-freedom, and MOVIC-T4 is an originally calibrated simulator, the original investigation about this issue was necessary. In addition, no research has investigated the motion's effects on a driver's mental load. The impacts of motion cueing on driving patterns hypothesized in this research include:

(1) prevention of extraordinary acceleration, deceleration and steering,
(2) prevention of extraordinary speeding at a sharp curve,
(3) stabilizing the lateral driving position,
(4) enhancement of the variation of mental load during sudden accelerating, braking and steering.

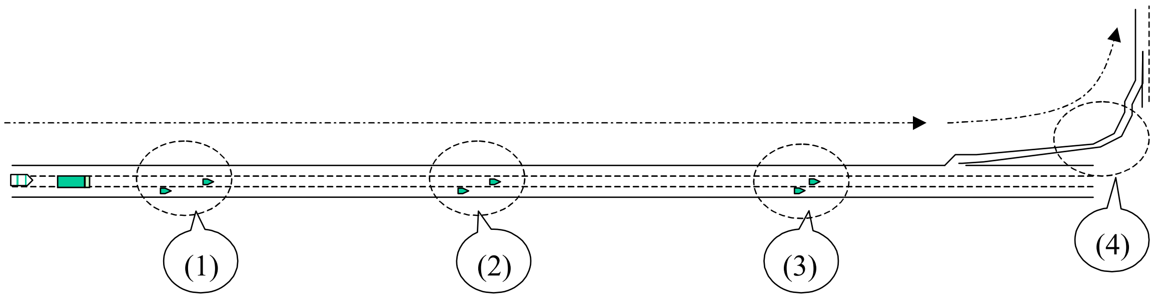
Experimental Setting

Instructions to the Subject and Traffic Conditions: The subject is asked to follow a large-sized vehicle moving at 100kph at some constant distance. There are four sections where the subject is required to take some action as shown in Figure 5-25. One experiment takes around 7 minutes.

Procedure: After a few practice runs, the experiment is randomly conducted four times, twice with motion and twice without motion.

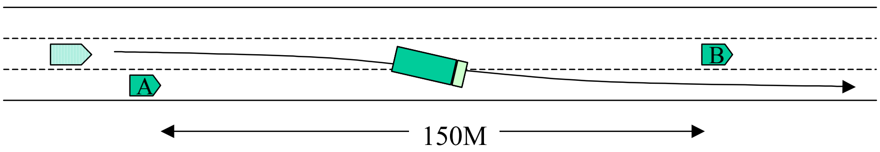
Collected data: The collected behavioral data from the tests are vehicle running position, speed, distance headway, acceleration, braking and steering rate, and physiological data. The physiological data consists of the driver's RR-interval, or Inter-Beat-Interval (IBI), which is the time between successive heartbeats. A shorter RR-interval period suggests a higher mental load (Dick de Waard, 2002).

Subjects: Five licensed students.



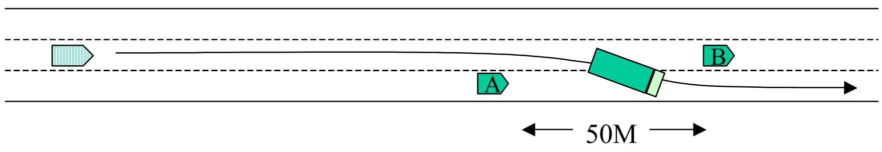
Section (1): Moderate lane changing

In this section, there are two stopping vehicles which distance between the two vehicles is wide enough to pass through. So subject can change lane on free path. The steering data in this section is used for checking the hypothesis (1) prevention of extraordinary steering.



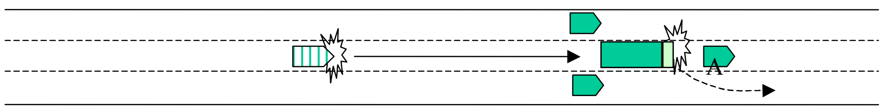
Section (2): Severe lane changing

In this section, there are two stopping vehicles which distance between the two vehicles is narrow. So subject is forced to change lane on severe path, which can be interpreted as a sudden steering. The RR data in this section is used for checking the hypothesis (4) enhancement of mental load variation when sudden steering.



Section (3): Sudden braking

In this section, there are two stopping vehicles which distance between the two vehicles is too narrow to pass through, and followed large-sized vehicle almost stops suddenly just behind the vehicle A. So subject must also suddenly stop behind the large-sized vehicle. The behavioral data and RR data in this section is used for checking the hypothesis (1) prevention of extraordinary deceleration and (4) enhancement of mental load variation when sudden braking.



Section (4): Sharpe curve

This section is a sharp curved section. Subject is required to drive at the speed as they usually drive. Here they don't follow any vehicles. The speed data in this section is used for checking the hypothesis (2) prevention of extraordinary speeding at sharp curve section (150<R<300).

Figure 5-25 Experimental conditions for the analysis of impact of duplicating acceleration cueing.

Results

Table 5-4 shows the summary of the experiment results.

The maximum mean centrifugal acceleration at section (1) showed no significant difference between tests with motion and tests without motion ($t=0.66$, $P<0.27$: tested by paired sample t-test) as shown in Table 5-4-a. It was expected that the centrifugal acceleration cueing with motion would prevent extraordinary steering while changing lanes, but this was not the case. In addition, normal centrifugal g-forces in the real world are less than 1.0G (Furuya et al, 2002), so subjects in this simulator tend to steer too severely. This is because the scale of centrifugal acceleration cueing in this simulator is lower than that in real world.

In order to study the variation of mental load during different driving conditions, a mental load variation index originally developed in this research is used. Figure 5-26 shows a sample mental load variation (MLV) graph used in this analysis. The MLV index is calculated by integrating the decreasing RR-interval over time, and dividing by the total analytical time. The index is based on the assumption that subjects have a higher mental load when the RR-interval decreases (Dick de Waard, 2002). Table 5-4-b shows the average of the MLV index during a severe lane change. The difference of MLV index between driving with motion cueing and without motion cueing is not significant ($t=0.52$, $P<0.31$). As a result, the effect of visual conflicts with other vehicles on the RR-interval is considered to be stronger than the effect of motion cueing.

The effectiveness of the motion-base was also tested for preventing extraordinary deceleration. The effectiveness was measured with respect to the maximum deceleration G-force and the average deceleration G-force, as shown in Table 5-4-c and Table 5-4-d. There was no significant difference between driving with motion cueing and without motion cueing for either the average or the maximum deceleration (Average g-force: $t=0.98$, $P<0.18$, Maximum g-force: $t=0.88$, $P<0.20$).

The change in mental load during sudden deceleration was also tested, with the MLV index measured during periods of hard braking. Table 5-4-e shows that there is a significant difference in the MLV index between driving with motion cueing and without motion cueing ($t=1.98$, $P<0.04$). It is shown that motion cueing has an impact on the mental load during periods of hard braking. However, in a simulator there is no risk of real injury or death due to accidents, so the mental load in a simulator should be lower than that of real life. The motion-base is therefore successful in making the effects of deceleration as realistic as possible on the mental load.

Table 5-4-f and Table 5-4-g shows the standard deviation of the lateral position at straight and curved sections of the highway. In other words, a high standard deviation would correspond with a large amount of swerving of the vehicle in the lane. At the straight sections, there is no significant difference between tests with motion and tests without motion ($t=0.24$, $P<0.41$) because there is no g-force. However, along curved sections there is a significant difference ($t=1.91$, $P<0.044$), so the standard deviation of the lateral position with motion is lower than that of one without motion. This result indicates that the feeling of a centrifugal G-force at curved sections heighten the stability of the lateral driving position. However, the value of the lateral movement in the real world is unknown.

Table 5-4-h shows the average driving speed at a sharp curve section. The results show that there is no significant difference in the driving speed between tests with motion and tests without motion ($t=0.39$, $P<0.36$). As a result, duplicating the centrifugal force has no impact on speeding along sharp curves with a minimum radius of 150 meters.

Table 5-4 Results of impact analysis of motion cueing on driver's behavioral and physiological data

Driving Behavioral Indices for Hypotheses		Experimental section (see Figure 7)	With Motion		Without Motion		Result of paired sample T-test of mean difference between with- and without-motion
			Mean	(SD)	Mean	(SD)	
(a)	Maximum centirifugal acceleration when moderate lane-changing (G)	(1)	1.67	(0.62)	1.52	(0.53)	t=0.66, P<0.27
(b)	MLV index when severe lane-changing (s)	(2)	0.0491	(0.0593)	0.0376	(0.0372)	t=0.52, P<0.31
(c)	Average Deceleration when sudden braking (G)	(3)	-0.47	(0.04)	-0.48	(0.03)	t=0.98, P<0.18
(d)	Maximum Deceleration when sudden braking (G)	(3)	-0.65	(0.048)	-0.66	(0.013)	t=0.88, P<0.20
(e)	MLV index when sudden braking (s)	(3)	0.0188	(0.0114)	0.0115	(0.0092)	t=1.98, P<0.04
(f)	Standard deviation of lateral position at straight section (m)	straight section in main-lane	0.572	(0.059)	0.575	(0.050)	t=0.23, P<0.41
(g)	Standard deviation of lateral position at curved section (m)	curved section in main-lane	0.473	(0.056)	0.509	(0.074)	t=1.91, P<0.05
(h)	Speed at severe curved section (kph)	(4)	76.7	(11.4)	75.3	(14.9)	t=0.39, P<0.36

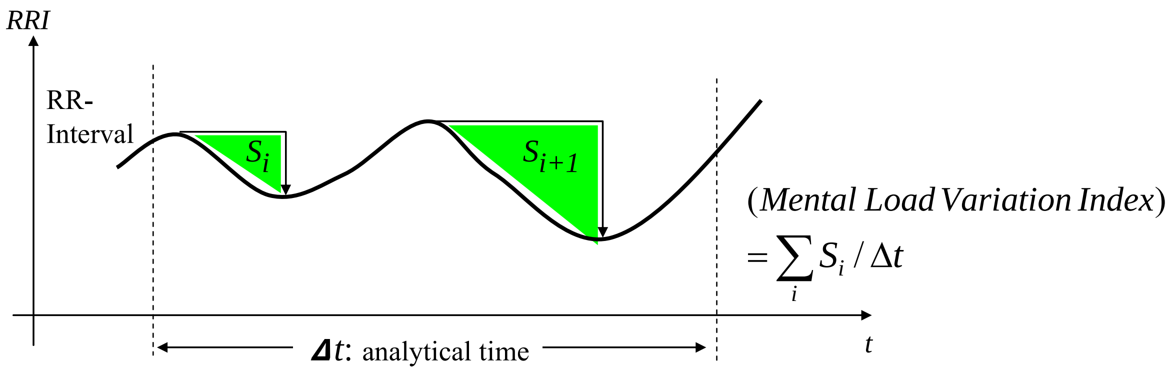


Figure 5-26 Mental load variation (MLV) index

5.8. Summary

This chapter presented the experiments undertaken to develop a driving simulation system MOVIC-T4. The results show that an HMD-based simulator results in a higher perceived driving speed compared with projector-based simulators. Subjects believed that acceleration cueing with a low scaling parameter gave the most realistic driving sensation, and the "roll" scaling parameter is much lower than that of "pitch". However, this acceleration cueing had little impact on the subject's driving patterns for various scenarios. Acceleration cueing was effective with respect to the impact on the mental load during periods of hard braking. Vehicle vibration tests showed that an ambient vibration of 14 Hz was the most realistic, with a periodic damped vibration of 1.5 Hz combined with 14 Hz almost as realistic. In the next chapter, validation of driving data in MOVIC-T4 is conducted using driving data from real world tests in order to show that this apparatus is eliciting similar responses as the normal real life situation.

Chapter6. Validation study of MOVIC-T4 using the field driving data

6.1. Aim of validation study for traffic safety analysis

Simulator study has many advantages in traffic safety analysis such as the ease of data collection, ease of controlling traffic conditions and safety of participants to the driving experiment. However it has also shortcomings. The most important shortcomings must be the validity of the data which is obtained in the simulator experiments.

Simulators must have real world validity to be useful human factors research tools. Two levels of validity associated with simulators have been proposed by Blaauw (1982) as follows:

i) Physical validity: Physical correspondence between the simulator and its real world counterpart. This deals with issues such as the simulator's components, layout, and dynamic characteristics,

ii) Behavioral validity: Correspondence between the simulator and the real world in the way the human operator behaves,

(iii)Physiological validity: Correspondence between the simulator and the real world in the way the human physiological data changes.)

Although fidelity of a driving simulator is attractive, often too much importance is placed on it. In the search for simulators with ever greater fidelity, it should be remembered that, ultimately, no level of physical validity is useful to human factors research if behavioral validity cannot be established. Accordingly, a more sophisticated (and therefore greater physically valid) simulator may not have more behavioral validity than a less sophisticated and expensive one. If so, it will not be more useful for behavioral research (Triggs, 1996).

And also, behavioral validity has two level of validity as follows (Blaauw (1982)):

i) Absolute validity: Absolute validity is achieved if the numerical values between the two systems are the same,

ii) Relative validity: Relative validity is achieved if the differences found between experimental conditions are in the same direction, and have a similar or identical magnitude on both systems.

Tornoros (1998) observed that relative validity is necessary for a simulator, but absolute validity is not essential. This is because research questions usually deal with matters relating to the effects of independent variables, with experiments investigating the difference between a control and treatments, rather than aiming to determine numerical measurements.

6.2. The driving data which are validated in this study

For determining the driving data to be validated, it's necessary to investigate the safety indices which will be used to assess the traffic safety in an underground urban expressway in this study. If some specific safety countermeasures are determined to prevent the traffic accident or risk, then we just have to compare the effect of similar kind of countermeasure in two conditions, in simulator and in real car. However this study will firstly proceed to the analyses which try to find which kind of risk an underground urban expressway have, so there is not any specific countermeasures yet. Therefore, the validation in this study deals with the basic driving data which are necessarily used to calculated the safety indices. The safety indices that are expected to use are TTC (Time to collision), PICUD (Potential Index for Collision with Urgent Deceleration: the possibility that two consecutive vehicles might collide assuming that the leading vehicle applies its emergency brake), collision frequency and the collision avoidance toward the stopping vehicle (urgent deceleration). To calculate these safety indices, the following basic driving data have to be used: driving speed, distance headway, deceleration toward the stopping vehicle (and lateral position). Therefore those driving data should have validity in order to say that the results of accident analysis are reliable.

In order to conduct accident analyses with simulator, correlation between "stimulus" and "action" (A) is generally checked because the indices used for analyzing accident risks is normally calculated from driving action data (see Figure 6-1). However, some driving data in real world is somewhat difficult to collect. For example, if letting subject driver drive at a speed which is his/her desired speed when he/she usually drive, he/she might have difficulty in choosing the desired speed. In these situations, validation of correlation between "stimulus" and "perception" (B) is considered to be efficient. If correlation (B) is validated, then (C) and (D) are to be validated for complete validation. But (C) and (D) are difficult to validate. But even only validating (B) enhances validity of a simulator.

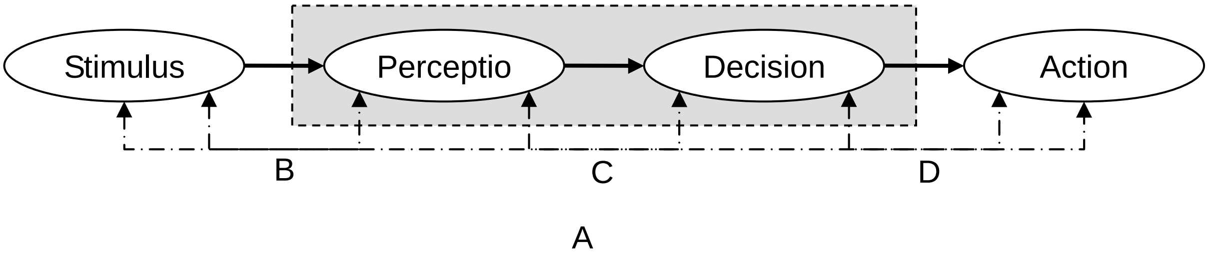


Figure 6-1 Driving model

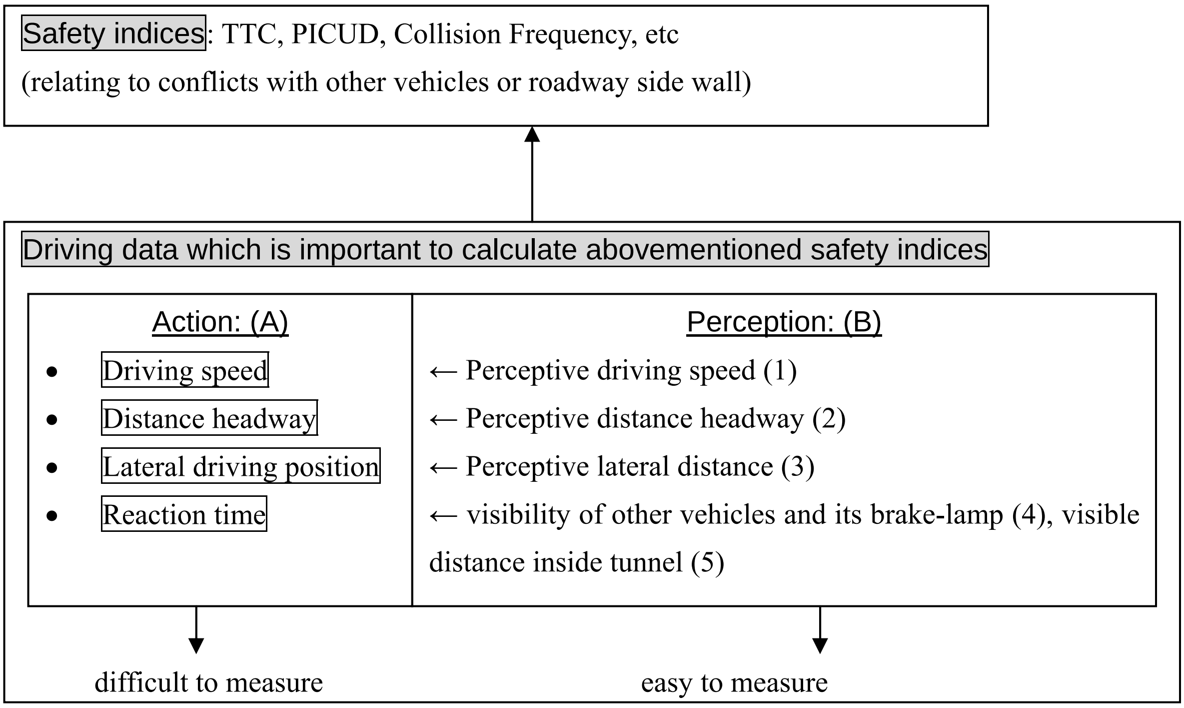


Figure 6-2 Process to validate the driving data

6.3. Experimental conditions

6.3.1. Instrumented car for the field driving experiment and measured data

In order to measure the driving behavioral and physiological data in the real field, the instrumented car was made by attaching the several measuring devices. The detail information of instrumented car and the measuring devices are as follows:

Car type:
TOYOTA Carolla Fielder (X), 1500cc, 4AT, 2WD

Figure 6-3 Instrumented car

Measuring devices:

1) Safety Recorder (SR) (datatech, Co. Ltd. in Japan)
Default SR consists of GPS receiver and acceleration censor. It can measure the acceleration G-force (longitudinal and lateral), GPS time and driving position (latitude, longitude). And the accelerator and brake pressing amount meters (small laser distance meter) and speed pulse meter (pulse receiver of the magnetized tire) are incorporated to SR. The data are recorded by memory stick every 0.1 second.

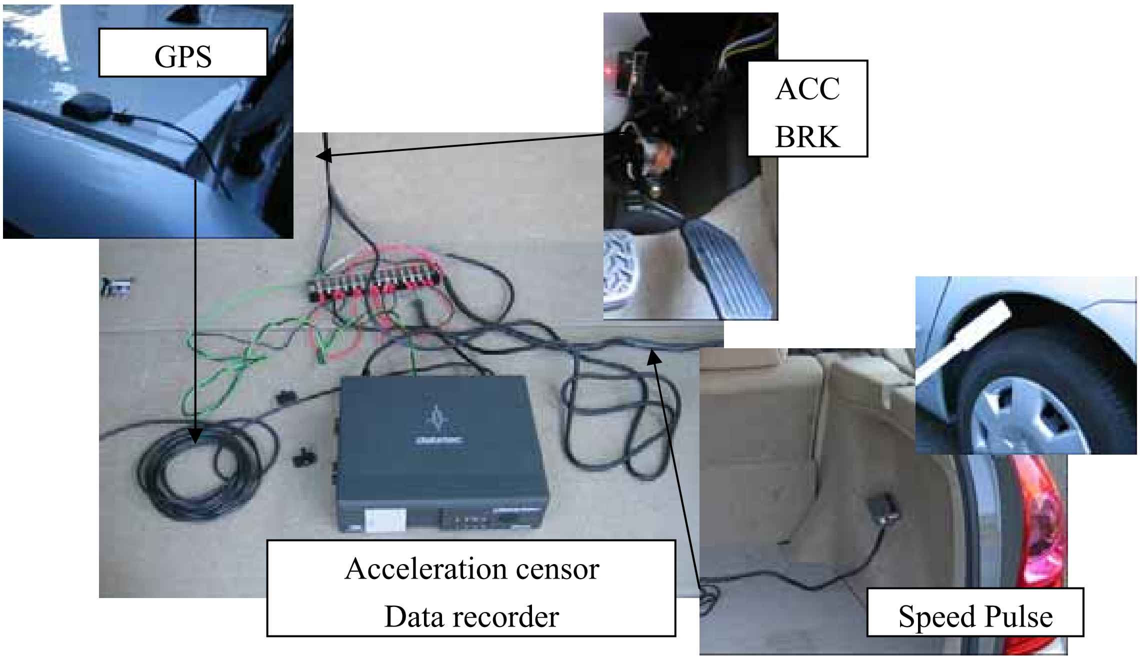


Figure 6-4 Customized Safety Recorder

2) Laser distance meter: Contour XLR (LaserCraft, Inc. in USA)
Contour XLR's specification is as follows:

/ Maximum Range 1850 meters
/ Range Accuracy 0.10 meter to a white target at 85 m
/ Range Resolution 0.1 meter (0.1 ft)
/ Instant distance data can be recorded every 1 seconds by connecting to the PC with RC232 cable.
Person in the assistant seat measured the distance with this device hold.

Figure 6-5 Laser distance measuring device

3) Physiological data

RR-interval

RR-interval (RRI), or Inter-Beat-Interval (IBI), is the time between successive heartbeats, see Figure 6-6. A shorter RR-interval period suggests a higher mental load. Driver's RRI was measured by holter monitor (NIHON KOHDEN, Co), see Figure 6-7. The RRI data was recorded to a memory card in holter monitor, and the time is adjusted to synchronize the GPS time.

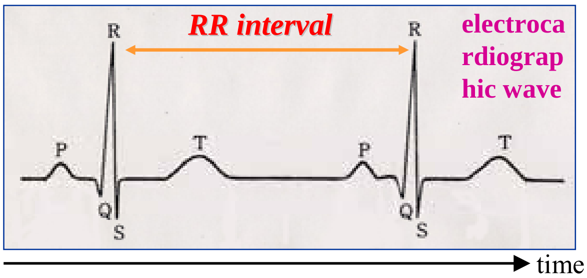


Figure 6-6 RR-interval

Figure 6-7 RR-interval measurement device

Skin potential level

Skin potential level (SPL) is the electronic potential in one's palm and near part of forearm to elbow, see Figure 6-8. SPL is said to be able to be an index to assess the human's awareness level (Fujisawa, et al, 1998). Lower SPL means lower awareness level. And the sudden increase response of SPL is said to be Skin potential response (SPR). The number of SPR increases as one's awareness level is relatively high.

Figure 6-8　Skin potential level measuring

4) Video recorder
The driving scene and the voice of subject were recorded with handy video recorder.

6.3.2. Participants

Participants for the validation study were ten licensed drivers including the students and staff in our university.　Six drivers have their own vehicle and usually drive at least once a week.　The other four drivers don't have their own vehicle and usually drive at least once a month averagely.

Table 6-1　Information of participants for validation experiment

Subject ID	licenced period (yrs)	Drive Frequency (times/month)	Age (yrs)
S1	5	12	23
S2	5	8	24
S3	4.5	12	23
S4	3.5	4	23
S5	2	8	21
S6	5	4	25
S7	11	0.5	30
S8	5	1	25
S9	4	1	24
S10	3	0.5	23
Average	4.8	5.1	24.1

6.3.3. Experiment procedure in the field

First, the subject wore the holter monitor for measuring RRI and the SPL electrodes at the point A (see Figure 6-9). At this point, the RRI and SPL under resting condition were measured. After that, subject drove the instrumented car as a practice driving from point A to point B where is close to the entrance of Aqualine. During this practice driving, the speed meter was hidden for the first experiment. After arriving the point B, subject took an enough rest.

1) Experiment 1: perceived speed test
Site: Aqualine (to Kisarazu)
Requirement:
Aqualine has two lanes, and the width of each lane is 3.6m. First, subject was required to drive at the speed which was felt to be 60 km/h for around 30 seconds in the left lane. Next, subject was required to drive at the speed which was felt to be 100 km/h for around 30 seconds in the right lane. And after that, the required speed was changed to "60 km/h ->100 km/h ->60 km/h ->100 km/h ->60 km/h". During each required speed, subject was asked to state the sign verbally when he felt the current driving speed as a required speed, and its time was recorded by the video recorder. The data of the first required speed of 60 km/h was excluded because it might be affected by initial disturbance.

2) Experiment 2: safety distance choice test
Site: Aqualine (to Kawasaki)
Requirement:
After an enough rest at the point C (Umihotaru Parking Area) for more than 10 minutes, subject started to drive for Kawasaki. First, subject was required to follow the other experimental car (called F-car) which was controlled by our staff at the distance which was felt to be his safety distance for around 30 seconds. First 30 seconds F-car drove at the speed of 60 km/h in the left lane. Next, F-car changed lane to the right and drive at the speed of 100 km/h. Subject was also required to change lane and follow F-car at the distance which was felt to be his safety distance for around 30 seconds. And after that, the F-car's driving speed was changed to "60 km/h in the left lane ->100 km/h in the right lane ->60 km/h in the left lane ->100 km/h in the right lane ->60 km/h in the left lane". During each speed, subject was asked to state the sign when he felt the current distance as his safety distance. The data of the first safety distance under 60

km/h condition was excluded because it might be affected by initial disturbance similar to the experiment 1.

3) Experiment 3: perceived distance headway
Site: Aqualine (to Kisarazu)
Requirement:
After an enough rest at the point B for more than 10 minutes, subject started to drive for Kisarazu. During driving in Aqualine tunnel, subject was required to follow F-car whose speed is constant 70 km/h, and follow at the required distances which are 25m, 50m, 100m, and 150m. During each required distance, subject was asked to state the sign when he felt the current distance as the required distances. These four required distances ware randomly changed, and the sample of each distant data were more than 3 (sometimes 2 samples especially of 150m due to the surrounding vehicle’s disturbance).

4) Experiment 4: Physiological data trend test
Site: Aqualine (to Kawasaki)
Requirement:
After an enough rest at the point C (Umihotaru Parking Area) for more than 10 minutes, subject started to drive for Kawasaki. First, subject was required to follow F-car at the distance which was felt to be his safety distance for around 210 seconds. F-car drove at the speed of 60 km/h in the left lane in this first 210 seconds. Next, F-car changed lane to the right and drove at the speed of 100 km/h. Subject was also asked to change lane and follow F-car. During this experiment, subject was asked not to speak anything and also experiment staff didn’t also speak anything. The physiological data such as RRI and SPL in this experiment were analyzed whether the trend of the data were similar to that in the simulator experiment.

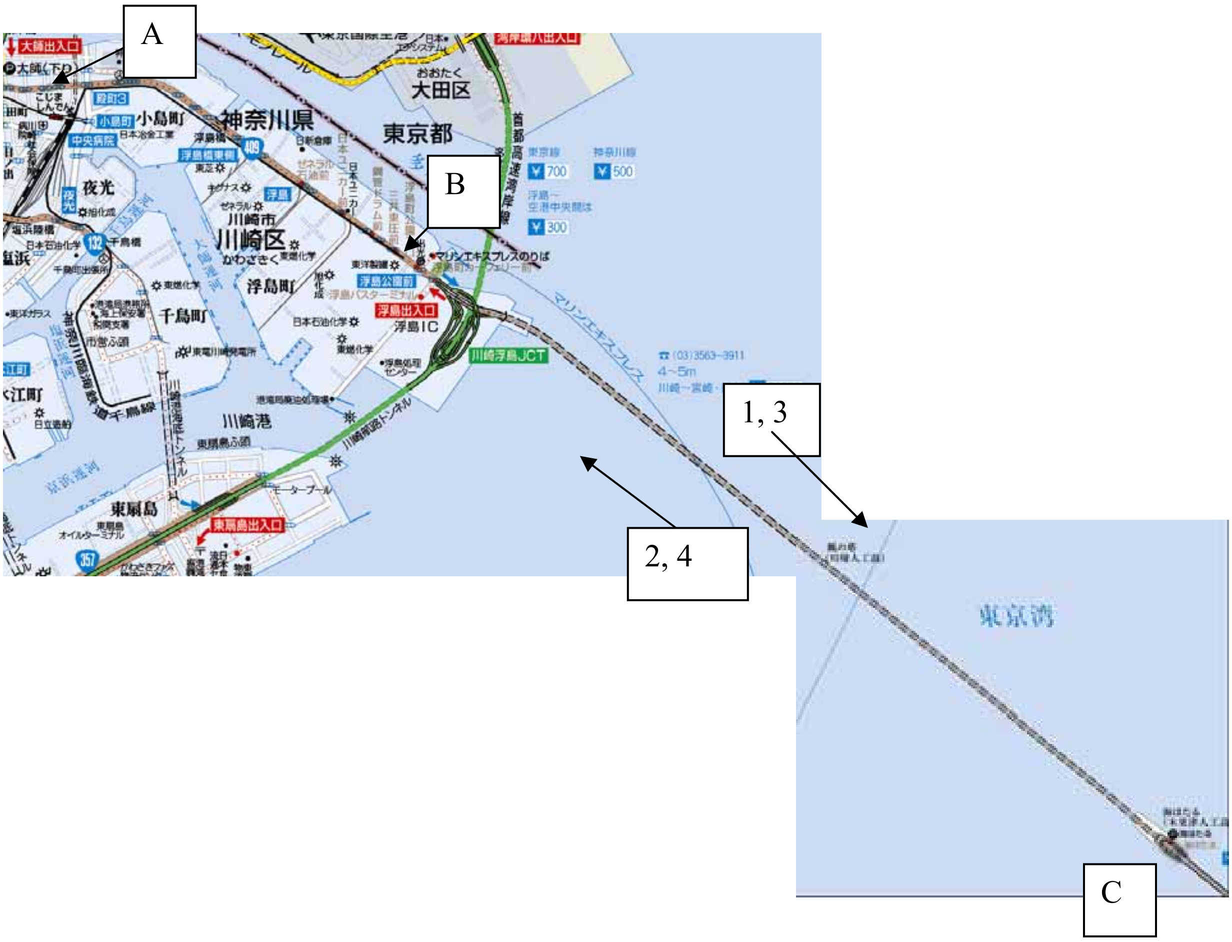


Figure 6-9 Experiment site (Aqualine: expressway under the sea)

5) Experiments 5: Decelerating behavior

Site: Kanjo 4-gou in Seya-ku, Yokohama-city (long straight section)

Requirement:

Subject was asked to accelerate to the speed of 80 km/h by the sign “A” where subject was required to start to decelerate and stop as close to the stop position sign “B” (see Figure 6-11. And also subject was required not to release the brake pedal after starting decelerating, that is, keeping decelerating. Adjusting the magnitude of deceleration was allowed. The same experiment was repeated 4 times after once practice experiment. In this experiment, the decelerating behavior including trend and maximum deceleration G-force and stopping position from the stop sign were analyzed.

Figure 6-10 Site of decelerating experiment (Kanjo 4-gou in Yokohama-city)

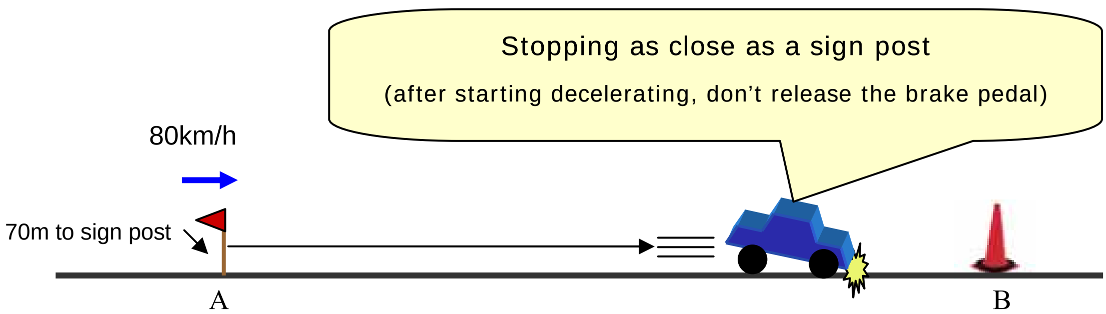


Figure 6-11 Decelerating experiment

6.3.4. Experiment procedure in the simulator

Experiment procedure in the simulator is basically same as that in the field. First, the subject wore the holter monitor for measuring RRI and the SPL electrodes in the experiment room. And the RRI and SPL under resting condition were measured. After that, subject drove the simulator MOVIC-T4 freely as a practice driving from point A to point B in MOVIC-T4. During this practice driving, the speed meter was hidden for the first experiment also in simulator experiment. After this practice driving, subject took an enough rest.

The other procedures of experiment 1 ~ experiment 4 were the same as that of the field driving experiments.

Figure 6-12 shows the photograph image inside Aqualine of the real road and MOVIC-T4.

Figure 6-12 Photograph image inside Aqualine in the real road and MOVIC-T4

6.4. Results and discussions

6.4.1. View point of the validation analysis

The main validated driving data are perceived speed, perceived distance and desired safety distance. These driving data have relationship between each other. Figure 6-13 shows the hypothesized relationship. Perceived speed and distance were indirectly measured by the produced speed and distance under required speed and distance. Larger produced speed and distance means smaller perceived speed and distance. Perceived distance might well directly affect the desired safety distance positively. The other factor which can determine the desired safety distance is perceived risk. Perceived risk might be difficult to measure directly and several factors can affect it. Perceived distance is considered to be one of the factors which can affect the safety distance. Higher perceived speed might induce higher perceived risk. Therefore the validated driving data in this analysis have relationship each other shown in Figure 6-13. However there must be also the other factors affecting these driving data, so we cannot say the result of the relationships definitively.

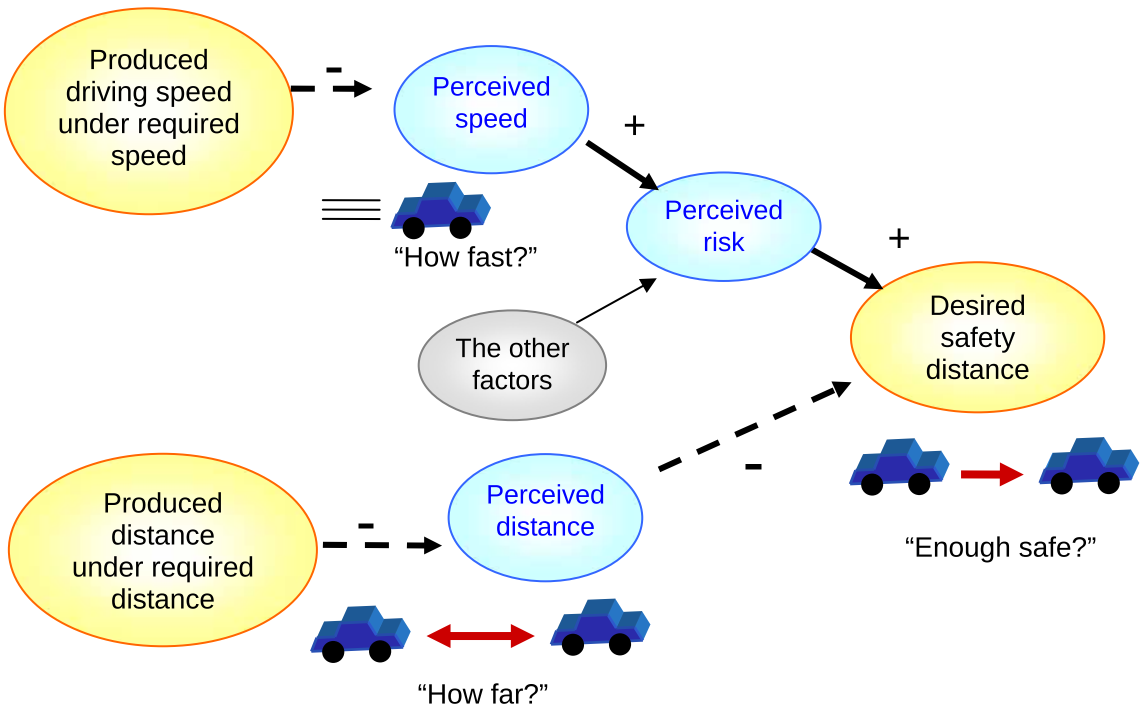


Figure 6-13 Relationship between the validated driving data

6.4.2. Analysis of average data for all subjects

6.4.2.1 Perceived driving speed

For each subject, the three samples for each required speed (60km/h and 100km/h) are abstracted from the driving speed data based on the subject's statement. One sample is calculated by taking average of the speed data within five seconds including the two seconds before and after the time of subject's statement (see Figure 6-14).

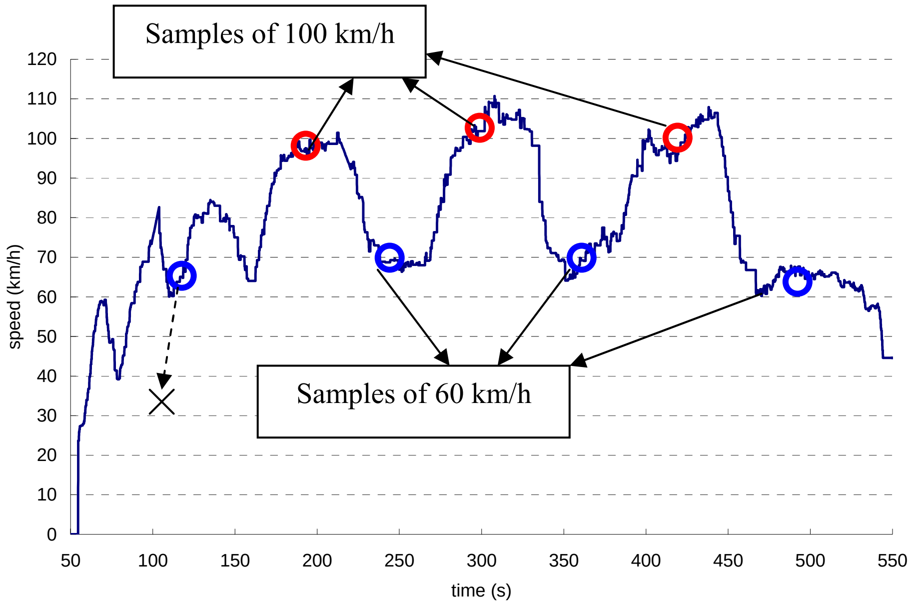
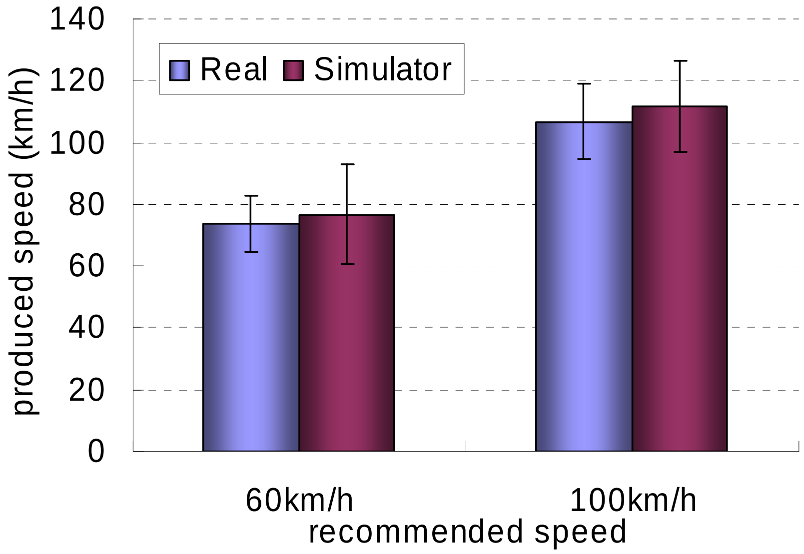


Figure 6-14 Method to abstract the perceived driving speed data

Therefore total sample number per each required speed is 30 (10 subjects * 3 samples). By pooling this data, the test of significance of the difference between two population means (field vs. simulator) is conducted.

Figure 6-15 shows the mean of produced driving speed under the required speed for all subjects (N=10). In addition, the paired t-test result is shown in Table 6-2 when the mean value for each subject is treated as one sample (then total sample is 10) because the original 30 samples is made by gathering 3 samples from one subject. However the test results are almost the same as the normal t-test with 30 samples. As several previous research paper described, drivers tend to produce the larger speed than the required speed in real world. In other words, drivers tend to underestimate the driving speed. And the error from the required speed is larger in slower speed than in faster speed (Recarte & Nunes, 1996,). The same trend can be observed also in simulator experiments. Regarding the difference between in real and in simulator, the mean values under both required speed are slightly higher in simulator than in real car. However the differences are not statistically significant. Therefore the produced driving speed under the required speed in simulator is almost same as that in real car when we see the data averagely for all subjects. That means the perceived speed in simulator is almost same as that in real car.



	60km/h	100km/h
Real	73.6 (10.6)	106.6 (12.5)
Simulator	77.4 (15.8)	111.7 (14.6)
t-test result	t=1.08, P=0.14	t=1.10, P=0.14

*Mean (SD)

Figure 6-15 Produced driving speed under the required speed (Mean of all subjects)

Table 6-2 Produced driving speed under the required speed (Paired t-test result)

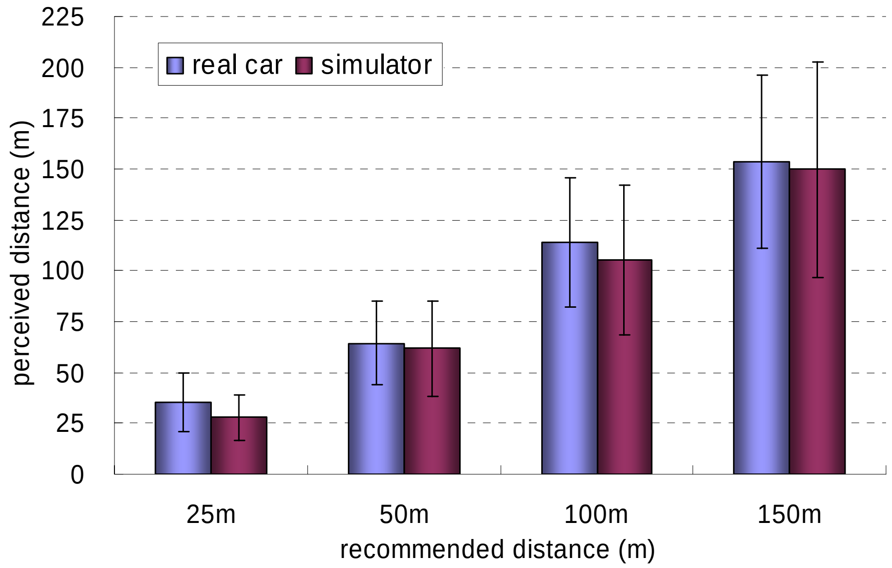
	60km/h	100km/h
real car	73.6 km/h (9.1)	106.6 km/h (12.2)
simulator	76.8 km/h (15.9)	111.7 km/h (15.6)
t-test result	t=0.49,P=0.32	t=0.82,P=0.22

* Mean (SD)

6.4.2.2 Perceived distant headway

For each subject, the more than three samples for each required distance (25m, 50m, 100m and 150m) are abstracted from the distance headway data based on the subject's statement. One sample is calculated by taking average of the distance data within five seconds including the two seconds before and after the time of subject's statement similar to the perceived speed data.

Figure 6-16 shows the mean of produced distance under the required distance for all subjects (N=10). The produced distances in simulator are slightly lower than that in real world. But the difference is not statistically significant except the distance of 25m. The produced distance of 25 m is however still small. Usually the produced distance in simulator tends to be larger than that in real world due to the lack of full depth cues, that is, the image is 2D in simulator and 3D in real world. However the result in this analysis is opposite. Although the clear reason cannot be mentioned, one of the reasons might be the fact that the target roadway is inside tunnel. Inside tunnel the visual scene is very monotonous and dark, therefore the full depth cues in real world might also lack. The variance becomes to be larger in longer distance required. This is considered to be natural. The limitation of the resolution of visual display of simulator might well cause the higher variance at longer distance.



	25m	50m	100m	150m
real car	35.1 (14.4)	64.5 (20.6)	113.9 (31.6)	153.7 (42.8)
simulator	27.8 (11.2)	61.7 (23.6)	105.2 (36.6)	149.7 (53.3)
t-test result	**t=2.63, P=0.051**	**t=0.62, P=0.26**	**t=1.24, P=0.11**	**t=0.34, P=0.37**

***Mean (SD)**

Figure 6-16 Produced distance under the required distance (Mean of all subjects)

Table 6-3 Produced distance under the required distance (paired t-test)

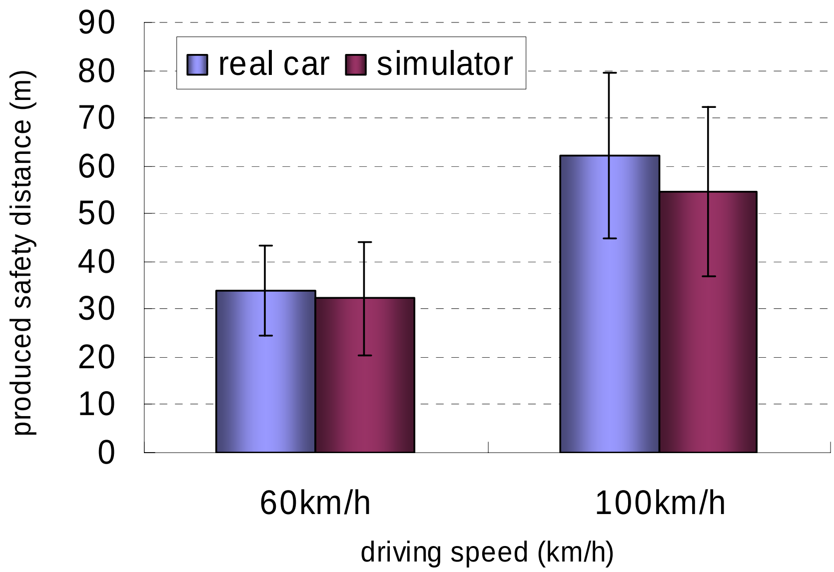
	25m	50m	100m	150m
real car	32.9m (13.0)	64.4m (14.4)	113.7m (29.9)	154.5m (44.7)
simulator	28.0m (10.6)	62.0m (22.9)	105.0m (35.2)	152.5m (52.6)
t-test result	t=1.82, P=0.051	t=0.47, P=0.32	t=0.82, P=0.21	t=0.13, P=0.45
				*Mean (SD)

6.4.2.3 Safety distance choice

For each subject, the three samples for each required distance (distance under the speed of 60km/h and 100km/h) are abstracted from the distance data based on the subject's statement (one subject could take only two samples due to the surrounding vehicle's disturbance in real road, and another subject in simulator could also take only two samples due to his slow verbal statement). One sample is calculated by taking average of the distance data within five seconds including the two seconds before and after the time of subject's statement.

Both in the real and simulator experiments, the safety distance increased as driving speed became higher. This is because the higher driving speed might well give drivers higher perceived risk. As a result, the safety distance increases. This phenomenon is a well-known fact. Therefore, the safety distance change in simulator might be elicited as same response in real world.

Regarding the difference between in real and simulator, the safety distance in simulator was shorter than in real world at the speed of 100 km/h while it was almost same at the speed of 60 km/h. This difference might be occurred the previous two validated data (perceived speed and distance). Although both of the two difference between in real and simulator is not highly statistically significant, the trend of the data helps explain this shorter safety distance in simulator. Of course this relationship cannot be verified completely because the other factors may affect the safety distance choice. But, this difference has to be taken into account when we conduct some safety analysis. For example, the shorter safety distance might induce the safety indices to become to be computed as slightly risky.



	60km/h	100km/h
real car	33.8 (9.4)	62.2 (17.2)
simulator	32.3 (11.9)	54.6 (17.8)
t-test result	t=0.53, P=0.30	t=1.66, P=0.052

* Mean (SD)

Figure 6-17　Produced safety distance under two driving speeds (Mean of all subjects)

Table 6-4　Produced safety distance under two driving speeds (paired t-test)

	60km/h	100km/h
real car	33.7m (8.7)	61.6m (14.7)
simulator	32.4m (11.5)	54.9m (16.6)
t-test result	t=0.39, P=0.35	t=2.55, P=0.02
		*Mean (SD)

6.4.3. Analysis of the individual data

In the previous section, the driving data in tunnel was analyzed averagely for all the subjects. With seeing the data averagely, the difference of the driving data between in real and simulator is not so large. But if comparing within each subject, the difference can be seen more clearly. Within the individual, the sample data is so small that the statistical test of the difference of population mean cannot be conducted. Therefore we can see only the difference of mean value of each individual. As shown in Figure 6-18, Figure 6-19 and Figure 6-20, the trend of the difference of validated driving data varies among the individuals. Roughly speaking, the produced driving speed and produced safety distance have no specific trend between the two conditions (real vs. simulator). These random trends might cause the no significant differences between the two. On the other hand, the produced distances under the required distances, especially 25m and 50m, have a specific trend that the value in simulator condition is lower than that in real world. The produced safety distance at the speed of 100 km/h has also the same trend which caused its significant difference.

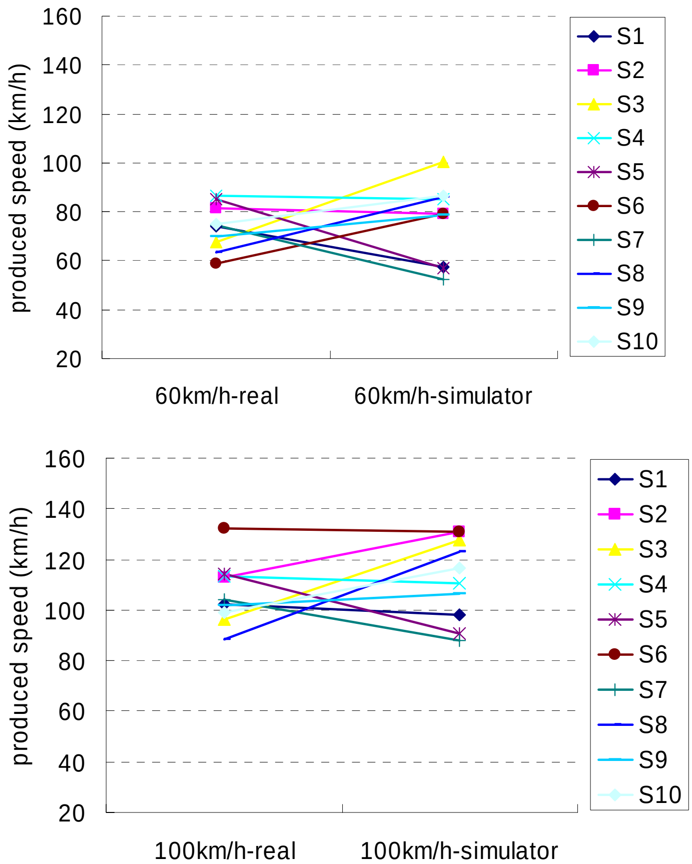


Figure 6-18 Produced speed under the required speed (individual data)

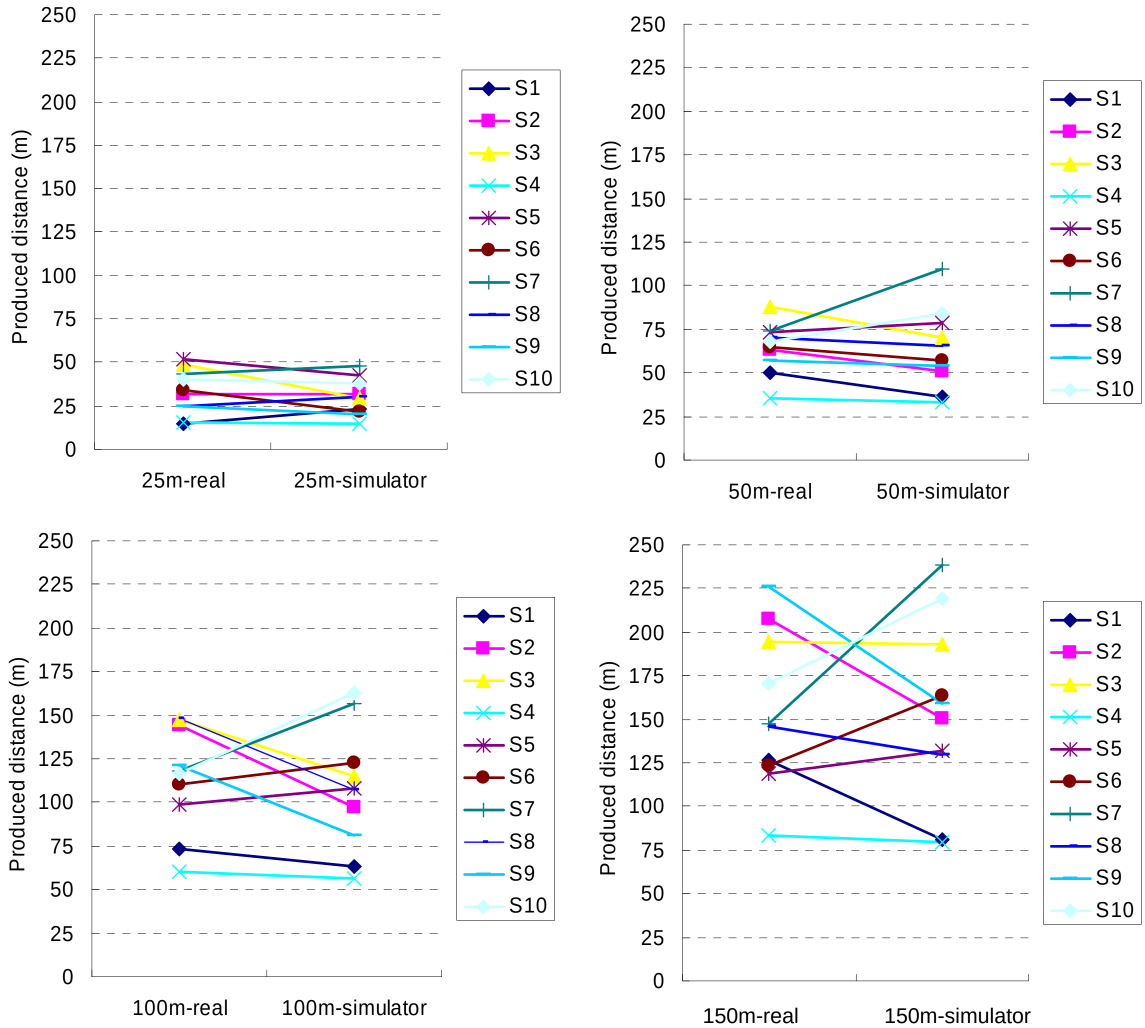


Figure 6-19 Produced distance under the required distanced (individual data)

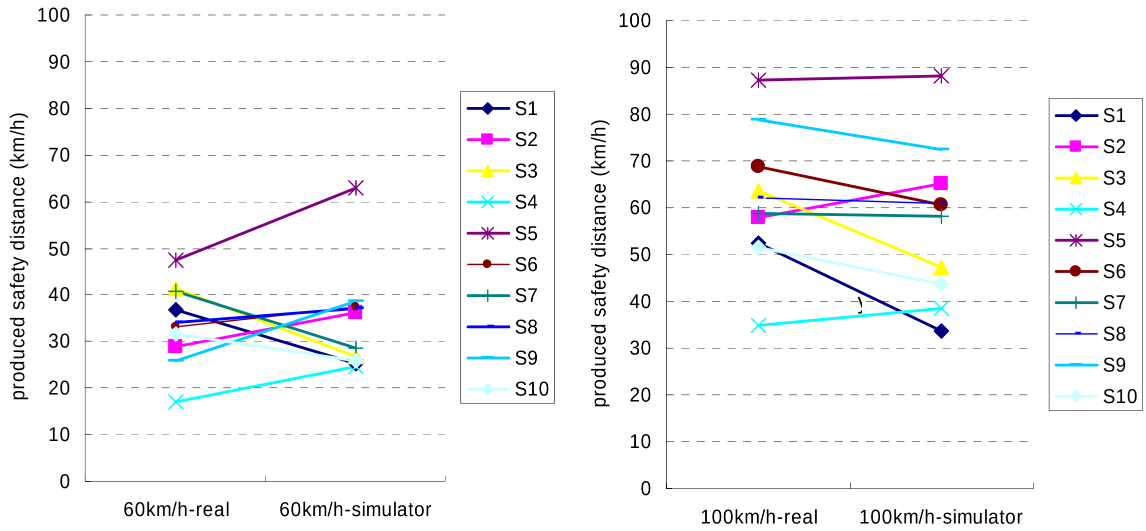


Figure 6-20 Produced safety distance under the required speed (individual data)

First, the data which can be explained by the hypothesis in Figure 6-13 are shown below. Figure 6-21 shows one example that the three validated driving data of a certain subject which supports the hypothesis. The shorter safety distance can be explained by: (1) the higher produced speed under required speed which means the decrease of perceived risk and (2) shorter produced distance under required distance which means the larger perceived distance (overestimation).

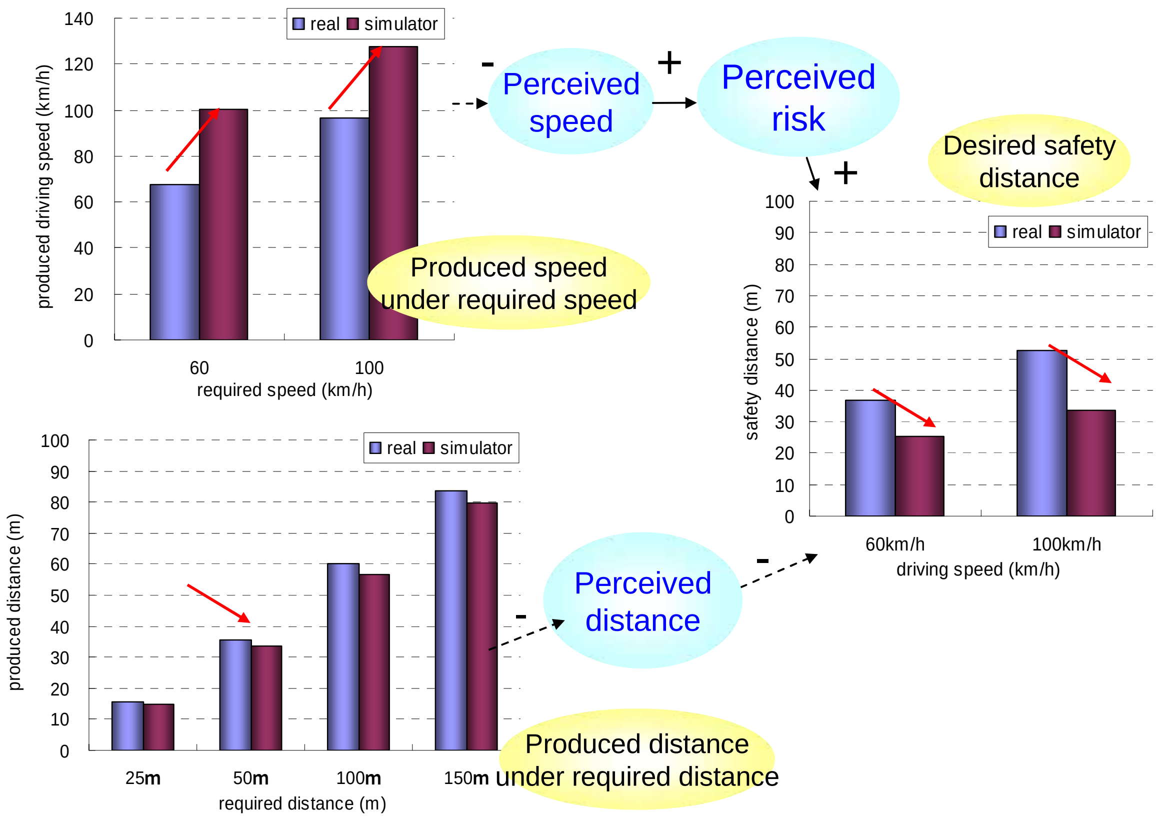


Figure 6-21 Example of the validated driving data which supports the hypothesis (1)

Figure 6-22 shows the other example. With this subject, the larger safety distance can be explained by: (1) the lower produced speed under required speed which means the increase of perceived risk and (2) larger produced distance under required distance which means the smaller perceived distance (underestimation).

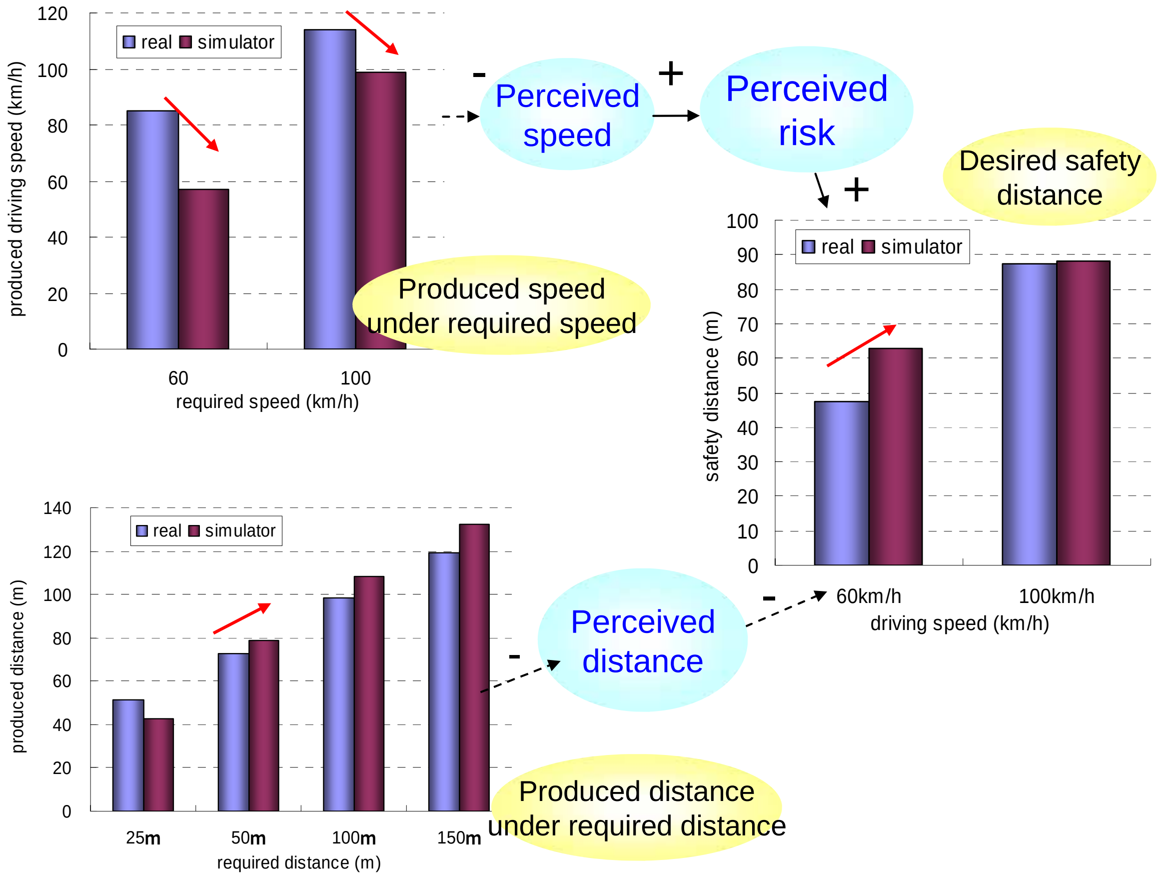


Figure 6-22 Example of the validated driving data which supports the hypothesis (2)

6.4.4. Analysis of physiological data

6.4.4.1 Skin potential level

In the experiment (4), subject followed the F-car which ran at the speed of 60 km/h in the left lane for the first 210 seconds. After 210 seconds, it ran at the speed of 100 km/h in the right lane for the 210 seconds. During this experiment, subject and experiment staffs were asked not to speak anything in order to exclude the disturbance in the physiological data. The physiological data of one subject was failed to record.

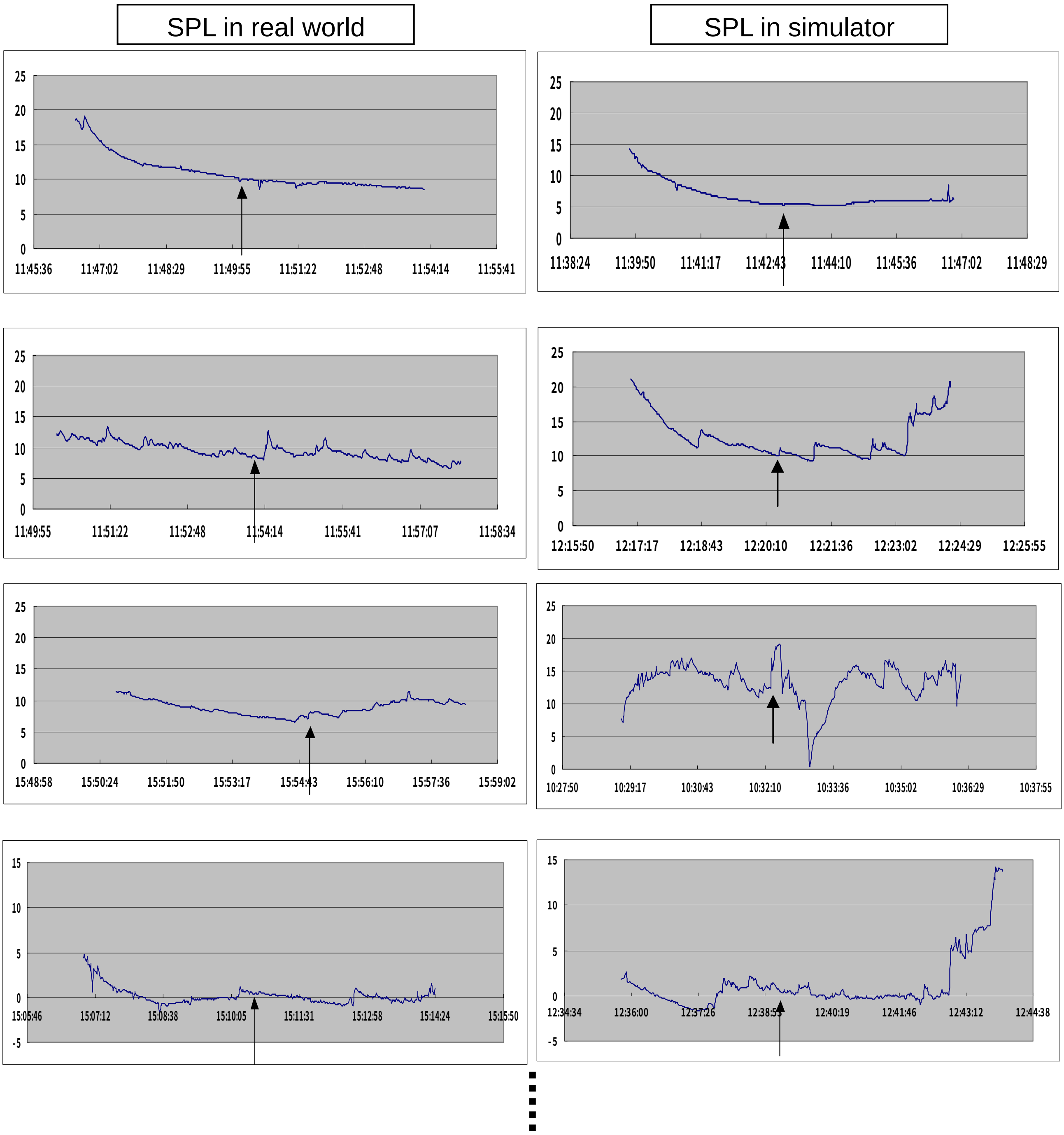
Figure 6-23 shows the skin potential level (SPL, awareness level index) of each subject in real and simulator. Therefore only the data trend which can be seen from the figure is discussed in this section. The lower SPL means the lower awareness level of subject. Roughly speaking, the SPL decreased monotonously at the first half seconds and maintained the same value at the latter half in real world. The same trend can be seen also in simulator. It is considered to be natural that the driver's awareness level tends to decrease more easily in simulator than in real due to the lack of risk of life, but can't flatly affirm in these results. One possible reason might be that the condition of the experiment for this analysis was relatively monotonous. The difference of skin potential response (SPR) which means the sudden increase of SPL cannot be seen clearly between in real and in simulator.

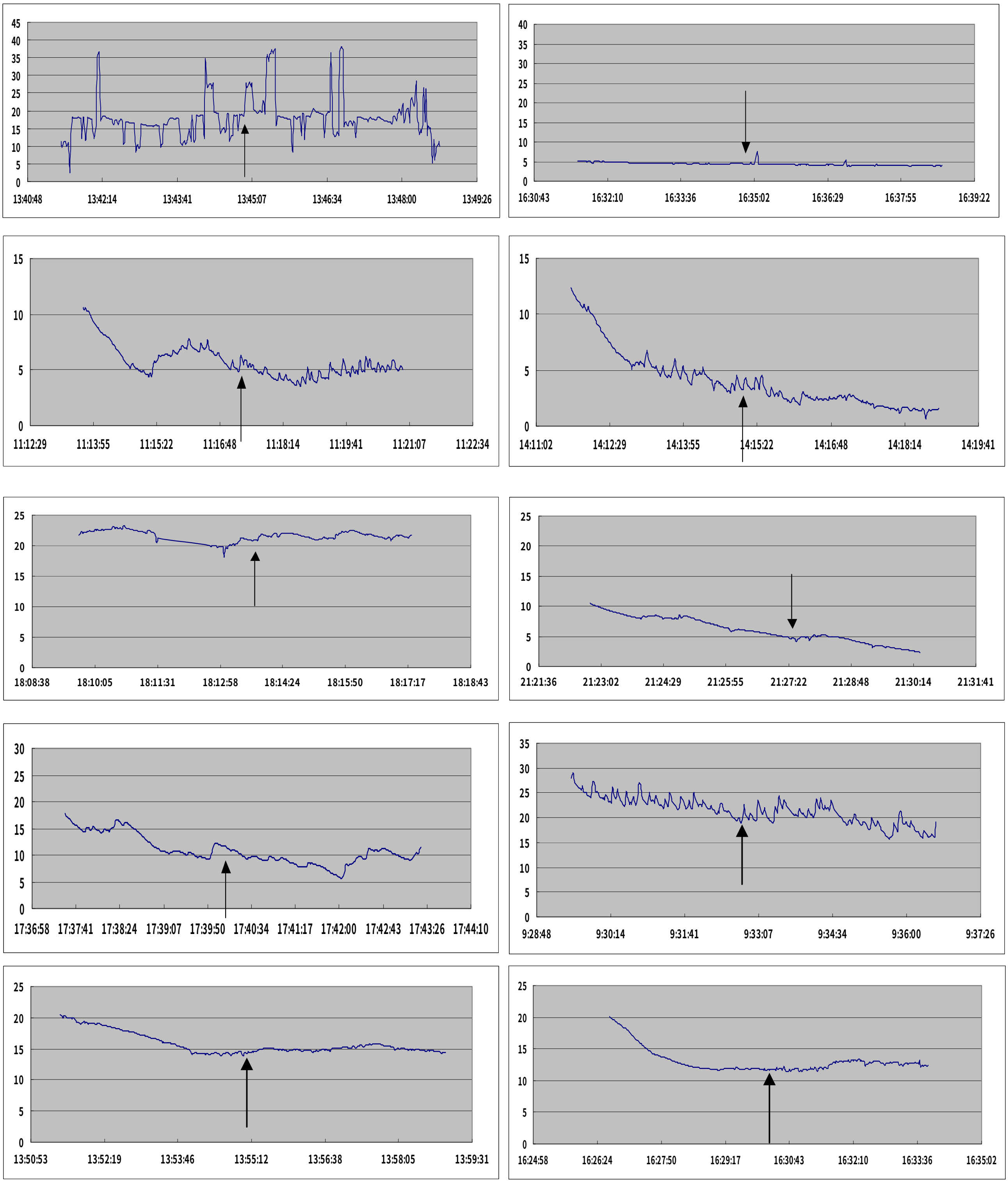
Skin potential level is difficult to compare its absolute value because the absolute value changes depend on the several conditions such as the detailed position of the electrodes, atmospheric temperature and humidity and so on. In addition, the difference among individuals is not small. Therefore the normalizing the SPL data is needed to eliminate the difference among individuals and data. In order to obtain the SPL data for normalizing, the SPL data while doing exercise and bed resting was measured for each subject (see Figure 6-24). Normalizing the SPL data is conducted through subtracting the minimum value of SPL while bed resting and divided by the range between the maximum value while exercising and minimum value while bed resting. Accordingly, the normalized data takes the value from 0 to 1.

Figure 6-25 shows the time series of 1 minute average value of normalized SPL in real and simulator experiment. As seen in the figure, the trends of two conditions are so similar. And the interaction effect of "time*condition" on SPL is not significant

(F=0.75, P=0.61: test by Repeated measures ANOVA), that means both of the pattern of SPL change with time are same. SPL (awareness) in simulator seems to be generally lower than that in real, but the result shows the opposite trend in terms of normalized SPL. Though the clear reason for this trend cannot be said, one possible reason might be the difference of minimum and maximum value of SPL for normalizing (see Figure 6-24). For example, the minimum value of SPL in simulator is lower than that in real, which induces the higher normalized SPL. And this lower minimum SPL in simulator might be attained because subjects could calm down easier in simulator experiment room due to little disturbance while there are more disturbance in real road experiment site such as surrounding vehicle's noise and existence of other people. Actually the SPL data in simulator is lower than that in real which is not normalized value.

The physiological data is generally difficult to validate because many factors can affect its change the understanding of the relationships between such measures and driving are still incomplete (Blaauw, 1982). However the comparative results indicated that the data trend of SPL don't have large difference between in real and simulator.


SPL in real world
SPL in simulator
25 20 15 10 5 0
11:45:36 11:47:02 11:48:29 11:49:55 11:51:22 11:52:48 11:54:14 11:55:41
11:38:24 11:39:50 11:41:17 11:42:43 11:44:10 11:45:36 11:47:02 11:48:29
11:49:55 11:51:22 11:52:48 11:54:14 11:55:41 11:57:07 11:58:34
12:15:50 12:17:17 12:18:43 12:20:10 12:21:36 12:23:02 12:24:29 12:25:55
15:48:58 15:50:24 15:51:50 15:53:17 15:54:43 15:56:10 15:57:36 15:59:02
10:27:50 10:29:17 10:30:43 10:32:10 10:33:36 10:35:02 10:36:29 10:37:55
15 10 5 0 -5
15:05:46 15:07:12 15:08:38 15:10:05 15:11:31 15:12:58 15:14:24 15:15:50
12:34:34 12:36:00 12:37:26 12:38:53 12:40:19 12:41:46 12:43:12 12:44:38



* The allow in the figure points out the time when the speed change from 60 to 100km/h

Figure 6-23 Skin potential level in real (left) and simulator (right)

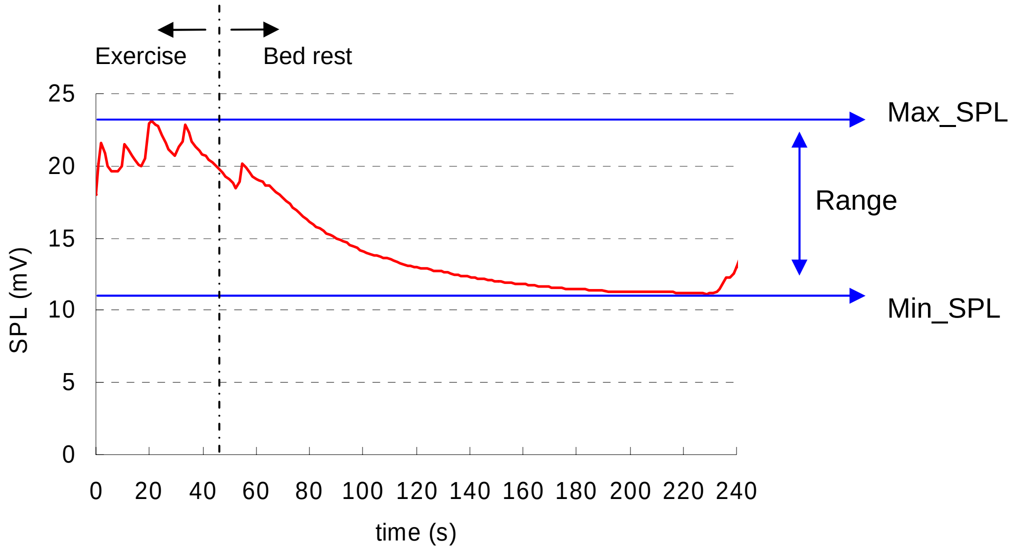


Figure 6-24 Maximum and Minimum SPL value for normalizing SPL data

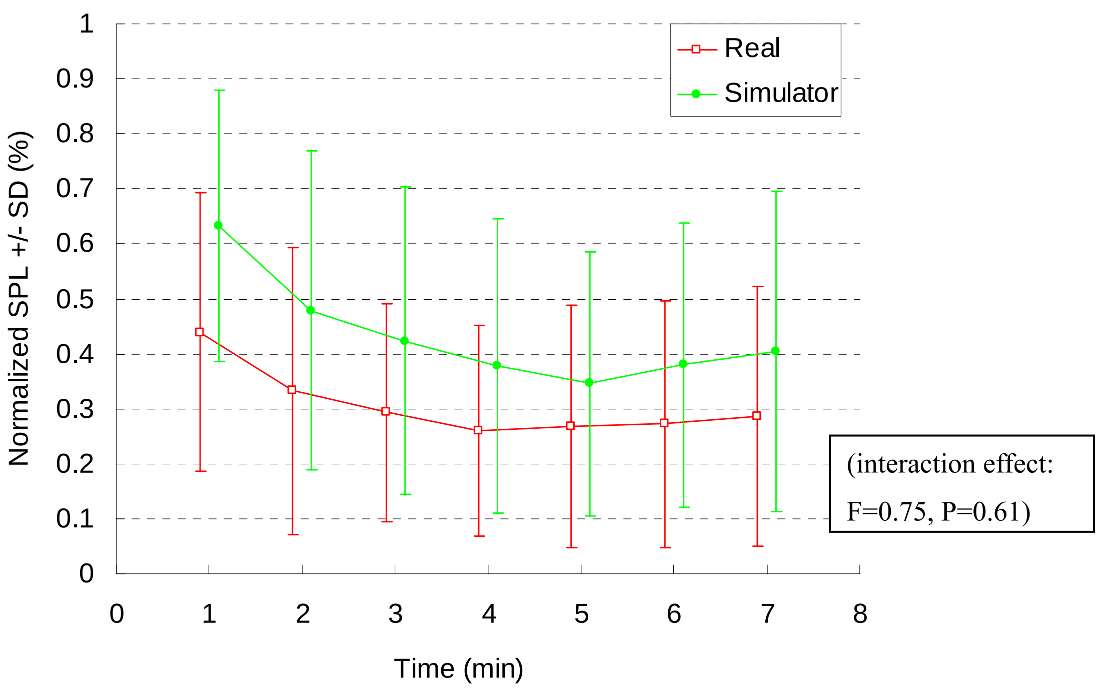


Figure 6-25 Comparison of mean normalized skin potential level in real and simulator

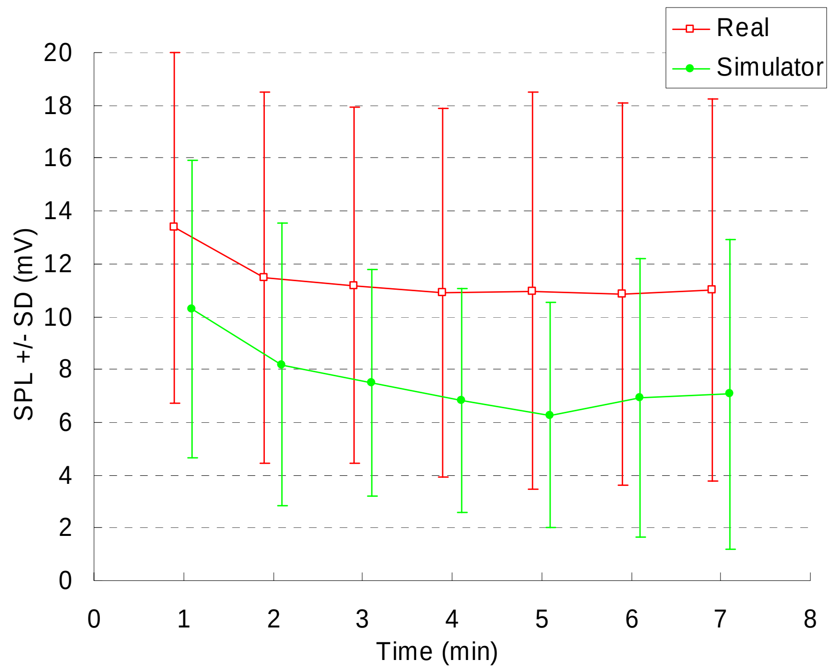
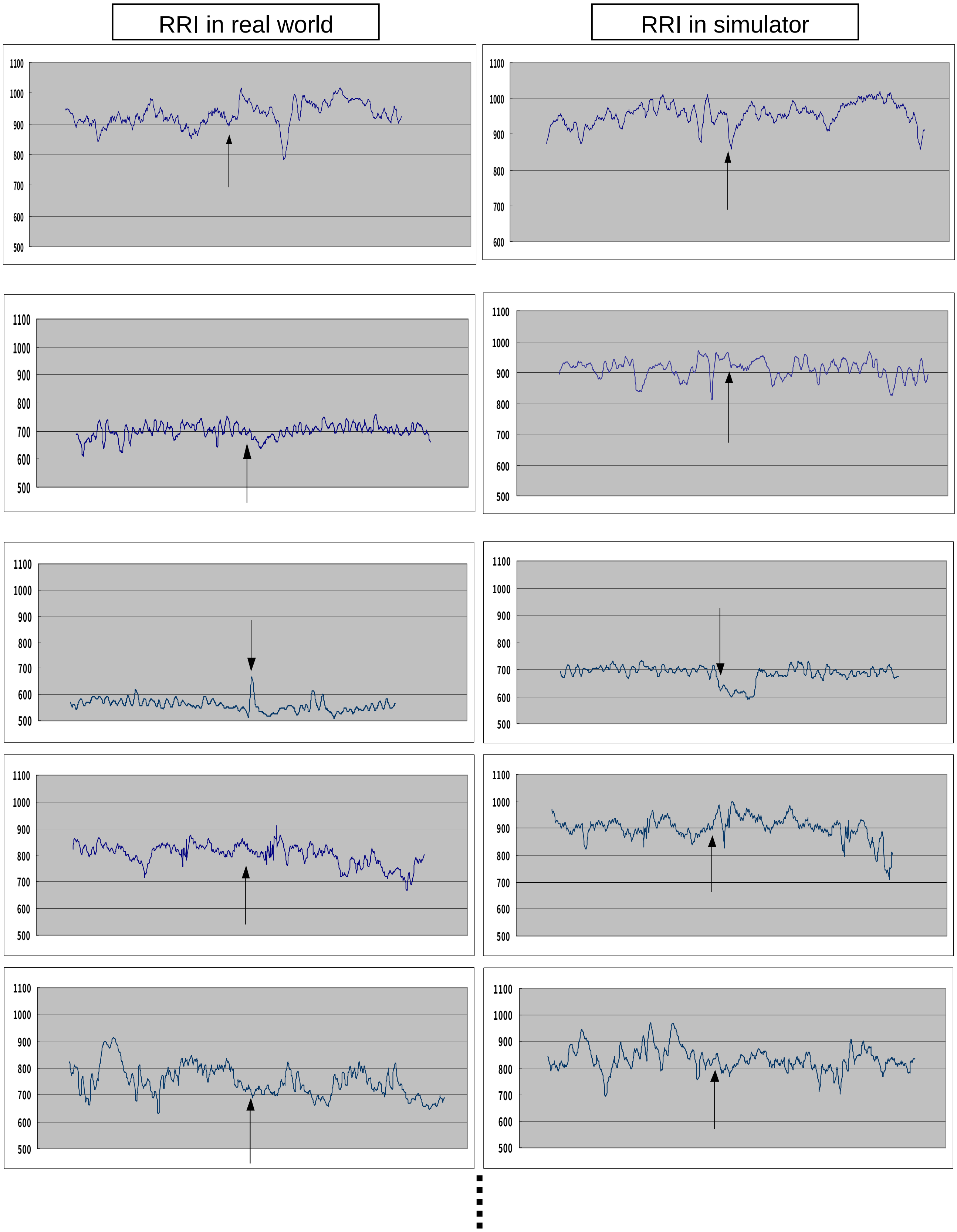


Figure 6-26 Comparison of mean skin potential level in real and simulator (not normalized)

6.4.4.2 RR-interval

Figure 6-27 shows the RR-interval (mental load index) of each subject in real and simulator. Lower RRI means higher mental load. For almost all subjects, the RRI is higher in simulator than in real, that is, subject felt less nervous in simulator than in real (the difference of mean value is significant: t=3.3, P=0.00). This might be due to the lack of the life risk in simulator. Figure 6-28, Figure 6-29, Figure 6-30 and Figure 6-31 shows the comparison of time series of 1 minute average value respectively of RRI, HF, LF/HF ratio and CV-RR between in real and simulator. HF is the power for high frequency band (0.15-0.40 Hz) calculated by FFT (Fast Fourier Transform) result of RRI, and lower HF means higher mental load. LF/HF ratio is the ratio of the power for low frequency band (0.04-0.15 Hz) and high frequency band calculated by FFT (Fast Fourier Transform) result of RRI, and higher LF/HF ratio means higher mental load. CV-RR is coefficient of variance of RRI, and higher CV-RR means higher mental load. For all of them, the value were not change with time significantly both in real and simulator (no main effect of time on the value) and accordingly the interaction effect of “time*condition” are also not significant. This means the time series trend of each index didn’t differ significantly between in real and simulator. However these results cannot support the validity of mental load indices strongly because the value was not change with time due to the relatively monotonous traffic condition.

Next, the change of these mental load indices before and after speed change from 60km/h to 100km/h was analyzed. Figure 6-32 and Table 6-5 shows the mean of RRI for 30 seconds before and after speed change. Regarding the change of RRI before and after the driving speed change, RRI significantly decreased after the speed change from 60 km/h to 100 km/h in real road. Although the difference is not significant in simulator, mean RRI decreased after the speed change from 60 km/h to 100 km/h also in simulator. Table 6-6 and Figure 6-33 shows the mean of HF, LF/HF, and CV-RR for 30 seconds before and after speed change and its statistical test results of interaction effect of condition (real or simulator) and time (60km/h or 100km/h). Regarding these mental load indices, there is no clear trend. Sometimes the direction of change differs between in real and simulator. Roughly speaking, the original RRI data have validity to some extent, however the mental load indices which are calculated by frequency analysis such as FFT don’t always have validity. Those frequency-based indices might have to be used for longer analytical period.


RRI in real world
RRI in simulator

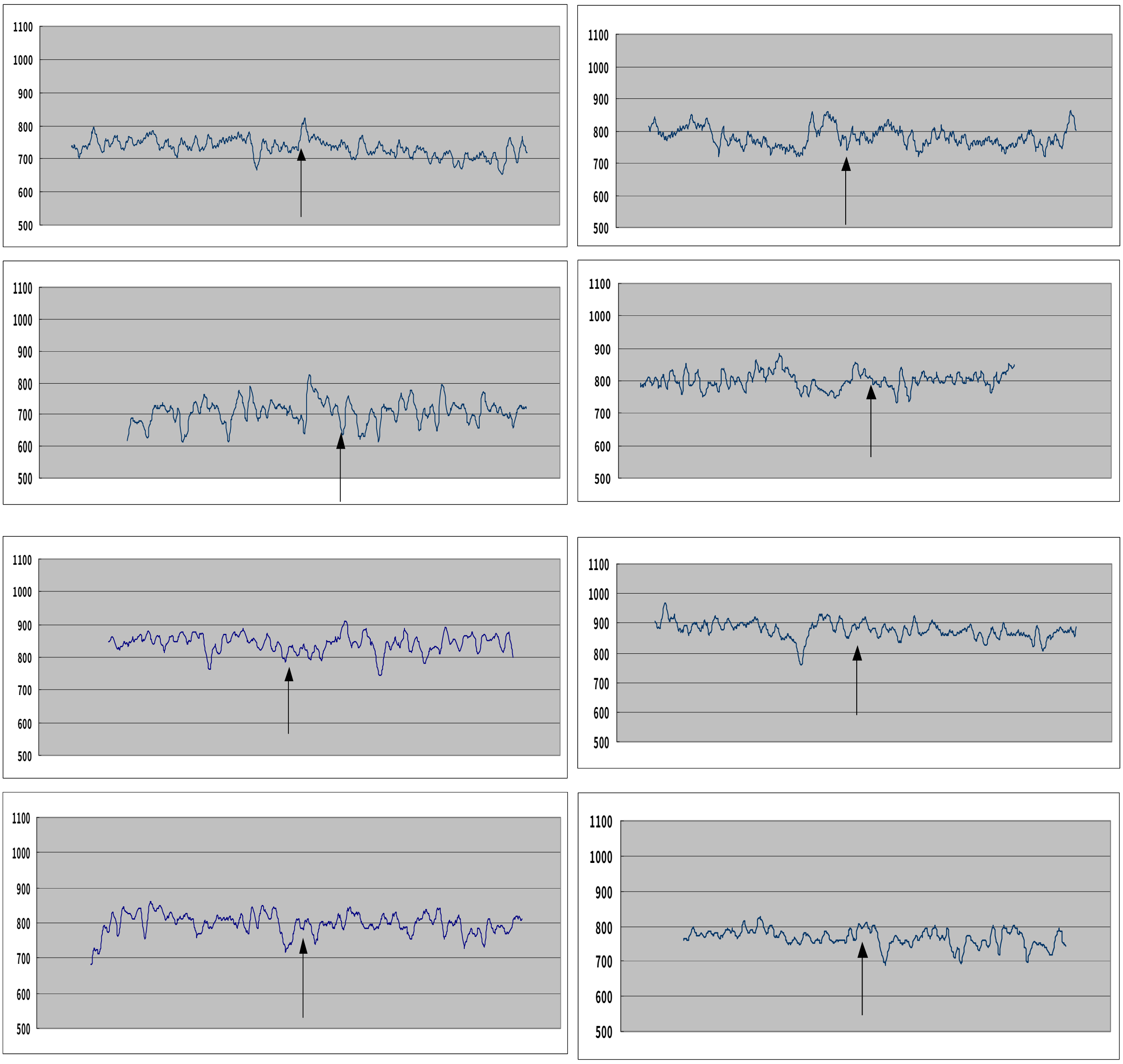


Figure 6-27 RR-intervals in real (left) and simulator (right)

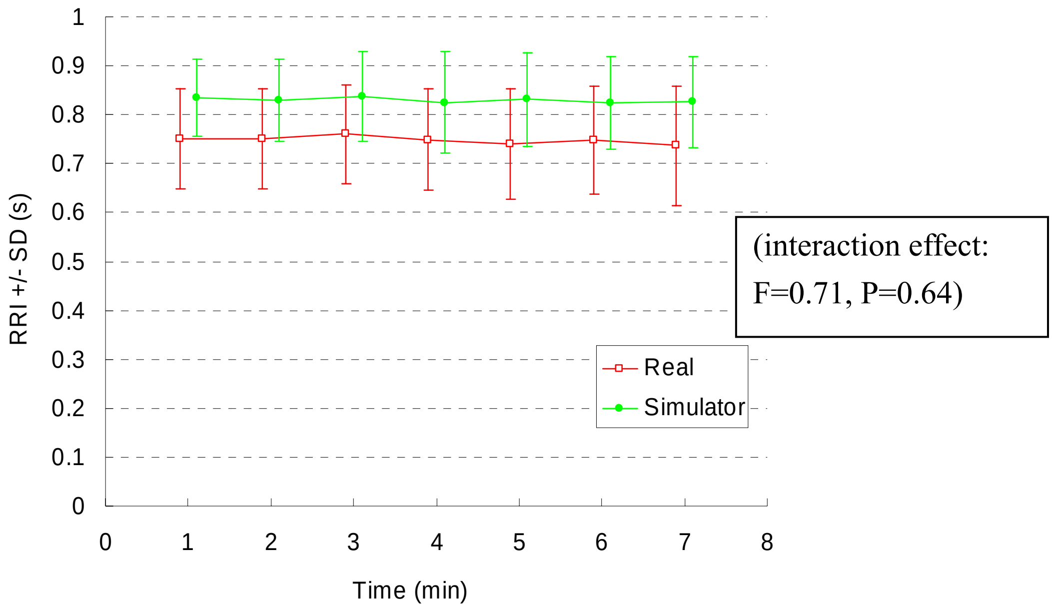


Figure 6-28 Comparison of mean RR-interval in real and simulator

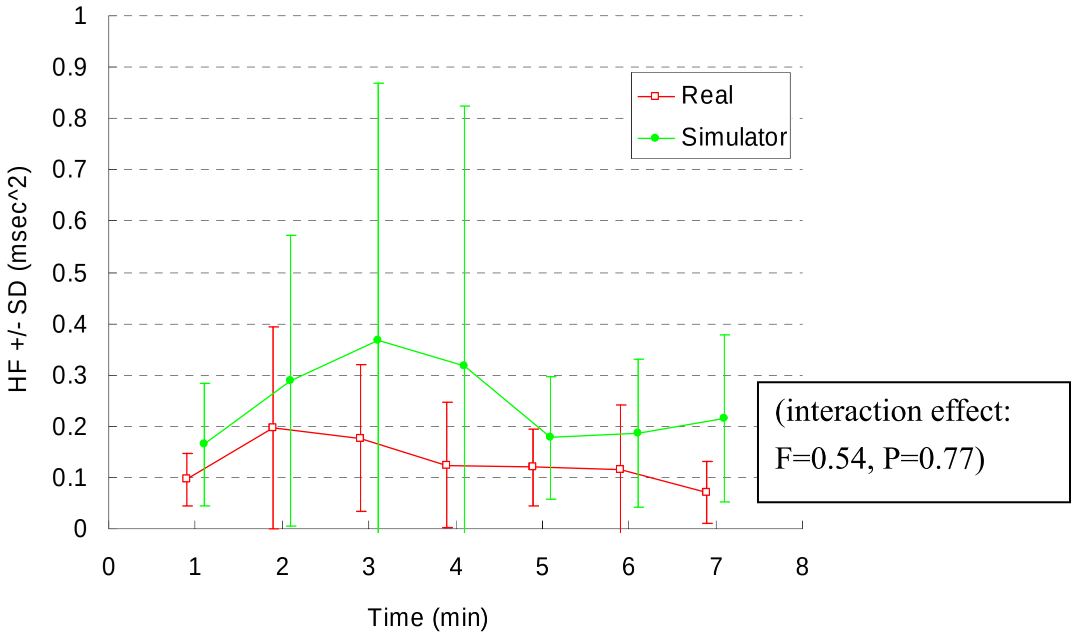


Figure 6-29 Comparison of mean HF (the power for high frequency band) in real and simulator

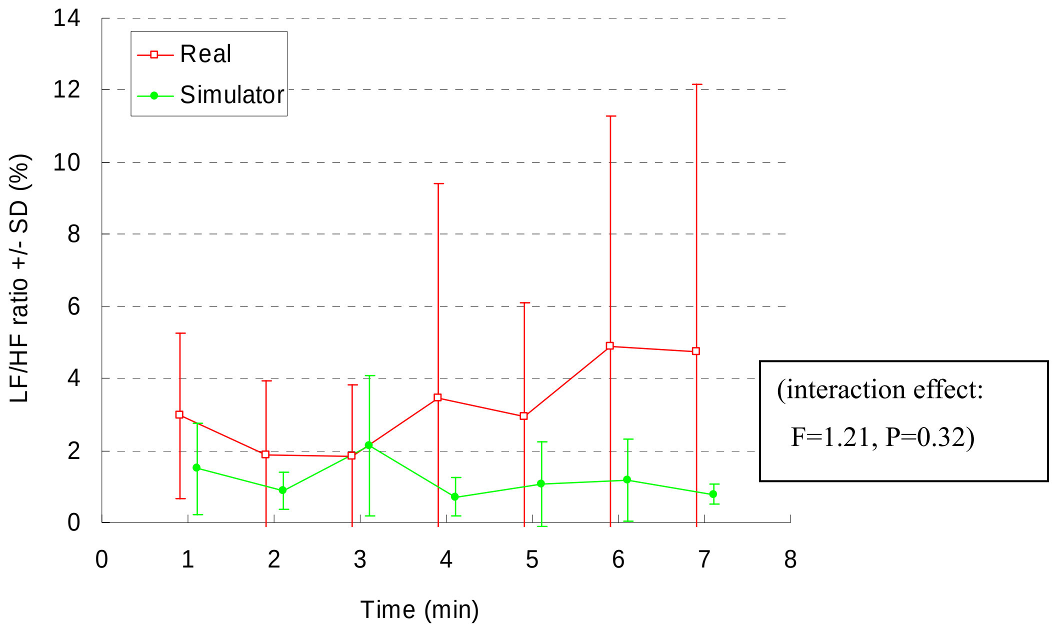


Figure 6-30 Comparison of mean LF/HF ratio (the ratio of the power for low frequency band and the power for high frequency band) in real and simulator

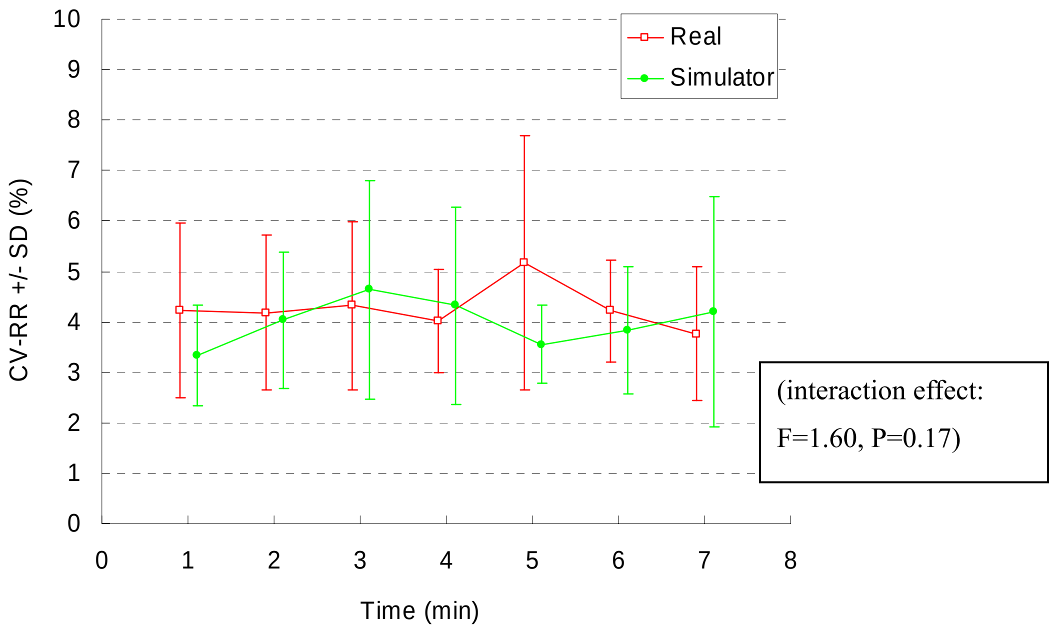


Figure 6-31 Comparison of mean CV-RR (coefficient of variance of RRI) in real and simulator

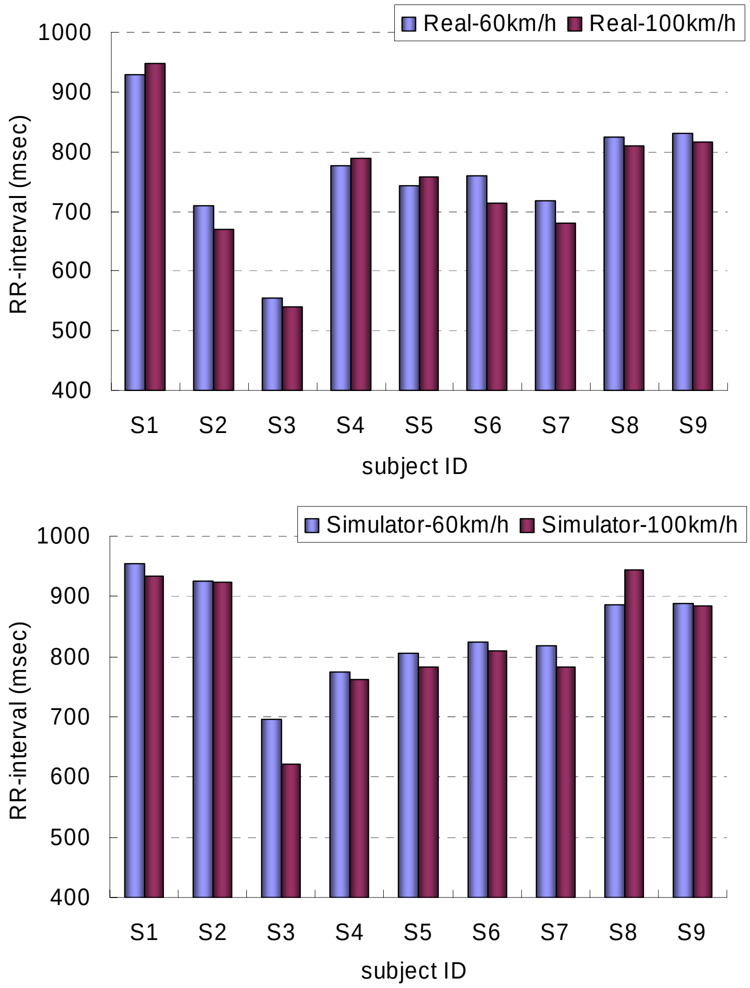


Figure 6-32 Comparison of RRIs for 30 seconds before and after speed change

Table 6-5 Statistical test of the mean RRI difference between at the speed of 60 km/h and 100km/h

	60km/h	100km/h	t-test result
Real	760.4 (102.7)	746.9 (114.8)	t=1.62, P=0.07
Simulator	841.3 (80.4)	827.0 (105.0)	t=1.24, P=0.13

*Mean (SD)

Table 6-6 Statistical test of the mean HF, LF/HF, CV-RR difference between at the speed of 60 km/h and 100km/h

		Mean (SD)		t-test
		60km/h	100km/h	
HF	Real	33.16 (24.62)	21.76 (19.94)	t=3.03, P=0.01
	DS	27.40 (15.75)	57.19 (71.11)	t=1.48, P=0.09
LF/HF	Real	2.93 (3.62)	4.38 (5.15)	t=1.71, P=0.06
	DS	1.70 (1.14)	1.21 (1.00)	t=1.36, P=0.11
CV-RR	Real	4.46 (0.11)	4.51 (0.12)	t=0.15, P=0.44
	DS	4.11 (0.12)	4.13 (0.13)	t=0.06, P=0.48

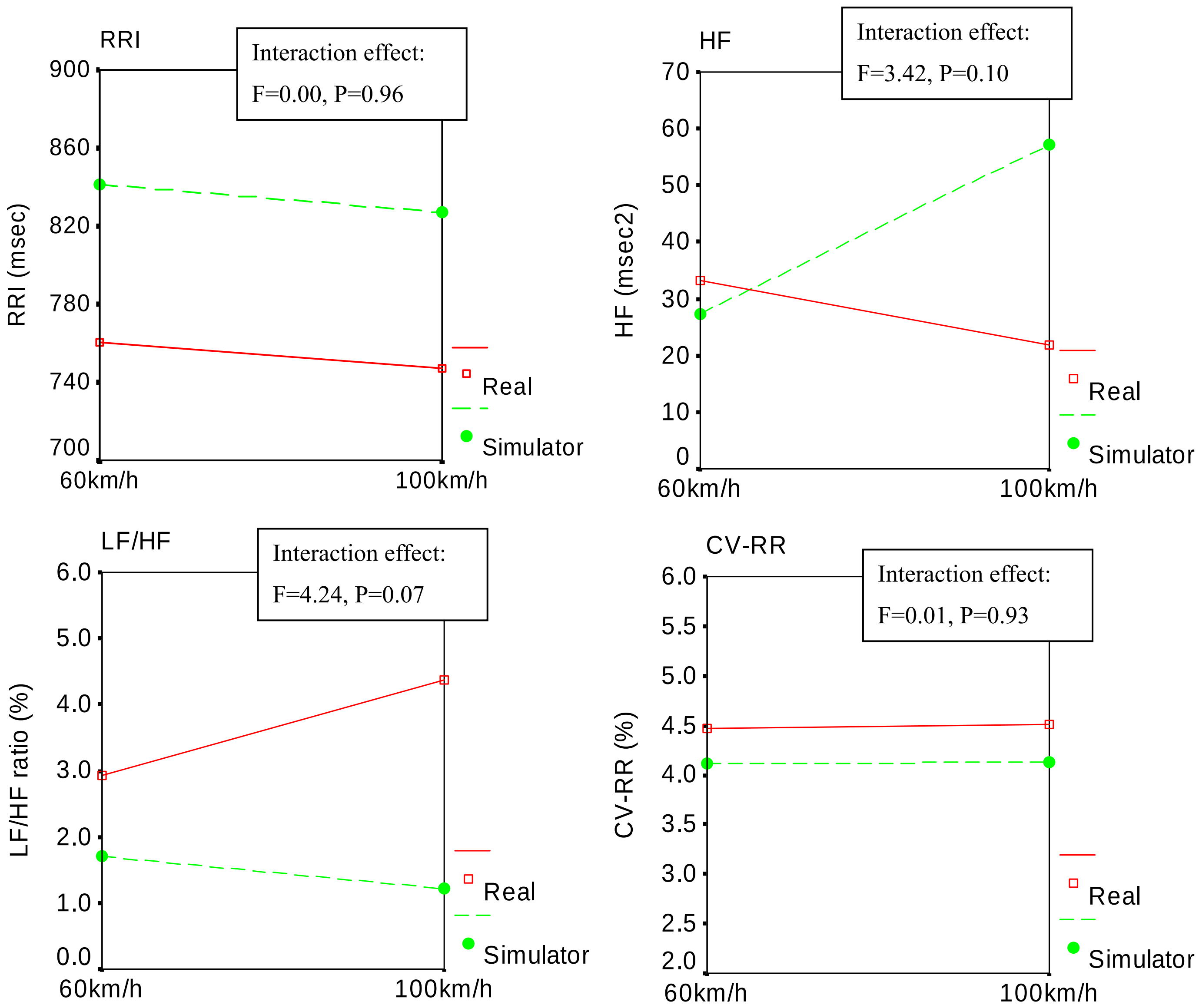


Figure 6-33 Interaction effect in HF, LF/HF, CV-RR change

6.4.5. Analysis of the decelerating behavior

The validity of the decelerating behavior is important when the experiment where researcher want to analyze the collision avoidance behaviors such as a rear-end collision. Visual presentation in a simulator is monoscopic with limited depth cues and perception of distance and/or velocity is often reported to be biased (Panerai et al. 2001). Therefore the deceleration behavior in MOVIC-T4 was validated.

Deceleration experiment was conducted at a straight section of local road. The subjects were asked to decelerate from first sign post set along the road and stop as close as the second sign post. The subjects were also required not to release the brake pedal (adjusting the deceleration was allowed) after starting deceleration.

Figure 6-34 shows the deceleration profile in real road. The deceleration transition in real road is moderate and maximum value is less than 0.4-0.6 G. In addition, the trends were almost consistent among the repetitions. Braking to a complete stop often involves high deceleration amplitudes of the order of 0.3-0.4 G, and 0.6 G or more when it is an emergency braking (Siegler et al, 2001). And Figure 6-35 shows the deceleration profiles in simulator whose motion is ON. The deceleration transition in simulator is not moderate and maximum value is over 0.4-0.6 G. Simulated deceleration G-force must be scaled smaller than that in real world due to the limitation of motion-base movements. So the over-deceleration might be unavoidable in the simulator experiments. However the deceleration was considered to be too large by comparing the other 6 DOF simulators. This might occur because the motion-base of MOVIC-T4 has only 2 DOF whose acceleration cueing to be duplicated may be smaller than that of 6 DOF simulator. But the maximum deceleration can be a little bit reduced significantly by this motion-base (t=1.58, P=0.06, see Table 6-7). And the overestimation of distance might also cause this over-deceleration and immoderate transition of deceleration. The stop position from the sign post in simulator is also biased from that in real world (see Table 6-8). This might be induced by the visual problem that is the biased distance perception and the abovementioned deceleration cueing problem.

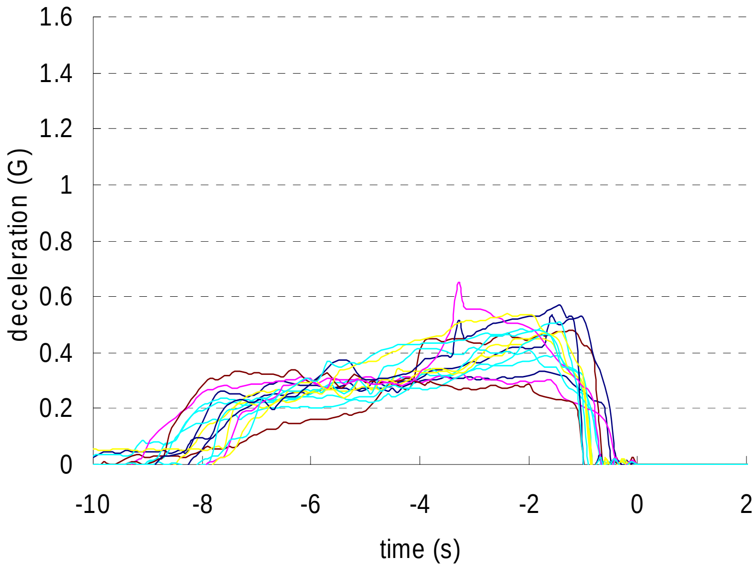


Figure 6-34　Deceleration in real world

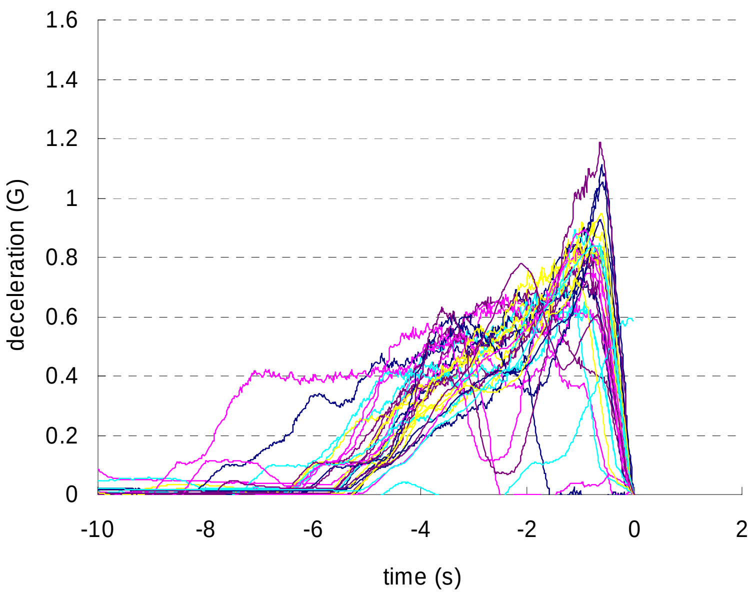


Figure 6-35　Deceleration in simulator (Motion-ON)

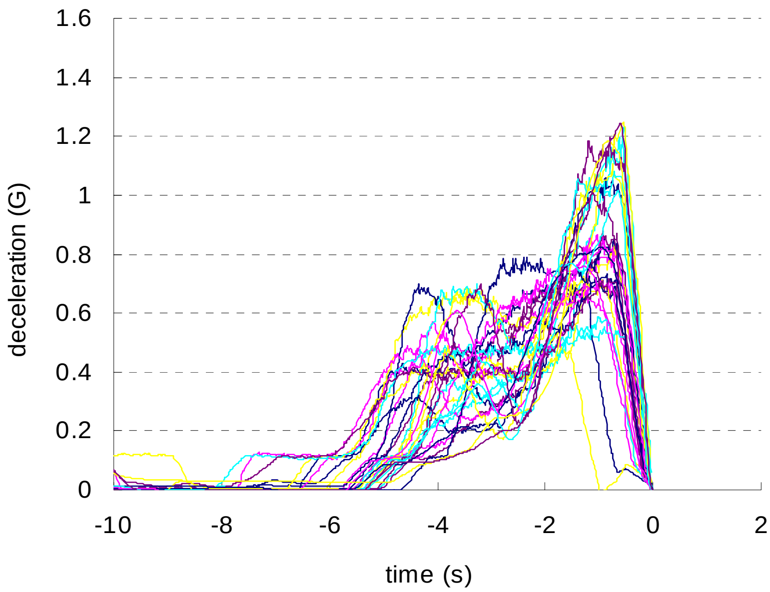


Figure 6-36 Deceleration in simulator (Motion-OFF)

Table 6-7 Comparison of maximum deceleration

	Real	Simlator (Motion-ON)	Simlator (Motion-OFF)
Mean of Max Deceleration (G)	0.46 (0.09)	0.83 (0.21)	0.90 (0.17)

* Mean (SD)

Table 6-8 Comparison of stop position from the sign post

	Real	Simlator (Motion-ON)	Simlator (Motion-OFF)
Stop position from the sign post (m)	1.4 (1.6)	5.6 (3.6)	5.0 (3.1)

* Mean (SD)

6.4.6. Summary

In this chapter, the basic driving data which are necessary to assess the traffic safety are validated using the field driving data. The experiment site was the long tunnel expressway, Aqualine, because MOVIC-T4 will be used mainly for the analysis of traffic safety in underground expressways. In this study, the analysis of validity was conducted by incorporating the two kinds of driving data, perception and action data. The results indicated that the perceived driving speed in simulator is almost same as that in real world. And the perceived distance headway in simulator is slightly larger than that in real world (overestimation), but the difference is not so large comparing the other simulator presented in the other papers. This might be caused by that the roadway which is the target of MOVIC-T4 is inside tunnel. And the chosen safety distance in simulator is shorter than that in real world especially at the speed of higher speed. This phenomenon can be explained by the overestimation of distance in simulator. Of course there is possibility that the other factors also affect the safety distance. Regarding the physiological data such as RRI and SPL, these data averagely behaved similarly to that in real world. However the frequency-based indices such as HF and LF/HF ratio calculated by FFT don't necessarily have validity. Decelerating behavior in simulator was relatively highly different from that in real world, that is, larger deceleration was tend to produced in simulator. However the experiment with and without motion cueing indicated that the motion cueing can reduce the deceleration slightly.

These results of validation implies that when usual driving experiments, following distance can be produced slightly short, therefore the safety indices become slightly riskier. And when analyzing the response to the incident, behavioral data after starting deceleration must be modified (larger deceleration may induce the collision avoidance which is impossible in real world).

Chapter7. Conclusion

7.1. Conclusion

This study develops a driving simulation system for the traffic safety analysis in an underground urban expressway, and conducts a validation study of a newly developed driving simulation system using the field driving data. And this study also conducts an analysis of the traffic safety related driver's awareness level deterioration induced by the monotonous visual stimulus in a tunnel.

First, the classical-style driving simulation system 'DS1' is developed using the existing hardware systems. In this development, the algorithm for driving vehicle control and surrounding vehicle control are mainly described. The developed surrounding vehicle control scenario might well allow us to produce flexible traffic conditions. And the simple validation of DS1 regarding the difference of perceived driving speed and mental load between inside and outside tunnel is also conducted.

By using the developed DS1, the research proceeds with the analysis of traffic safety regarding the driver's awareness level in an underground urban expressway. In this analysis, the relatively monotonous traffic conditions are assumed where the driver's awareness level can deteriorate even in underground urban expressway which may give high mental load to the drivers. Deterioration of driver's awareness level is analyzed through the simulator experiments conducted on elderly drivers and taxi drivers. Results of analyses indicated that at basic segment between merging/diverging sections in underground urban expressway, the driver's awareness level could significantly deteriorate, especially for elderly drivers as compared to taxi drivers. It was also shown that an audio information system that gives warning on approaching merging and diverging sections could prevent deterioration of the driver's awareness level. This study was not able to clarify the differences of awareness level between an underground and aboveground expressway. However, the audio information system is considered to be effective against the deterioration of the awareness level prior to merging diverging sections.

To overcome the limitation of the classical driving simulation system 'DS1', an original driving simulation system named MOVIC-T4 (Moving Virtual Cockpit) is newly developed which have higher performance for analyzing the traffic safety on the higher risk traffic conditions and have portability and low-cost for using communication tool with public. The new system consists of Head Mounted Display (HMD) for the visual system and the small-sized motion-base with 2 degree of freedom, pitch and roll. In this development, the algorithm to control the motion-base to duplicating the acceleration cueing and vehicle vibration while driving is mainly discussed. The scale of acceleration cueing was investigated by the subjective evaluation of its realism considering the trade-off relationship between the perceived acceleration cueing and the odd feeling induced by the tilt movement. The vibration of vehicle was measured in a real highway, and frequency analysis of the vehicle vibration was conducted. The characteristics of perception of vibration in simulator were also investigated by the subjective evaluations.

In the validation study of newly developed driving simulation system MOVIC-T4, the field driving experiment and the simulator experiment were conducted on the same conditions, and the driving behavioral data and the physiological data in both experiments were compared in order to show the performance of this system. The results showed that the perceived driving speed in simulator is almost same as that in real world. And the perceived distance headway in simulator is slightly larger than that in real world (overestimation), but the difference is not so large comparing the other simulator presented in the other papers. This might be caused by that the roadway which is the target of MOVIC-T4 is inside tunnel. And the chosen safety distance in simulator is shorter than that in real world especially at the speed of higher speed. This phenomenon can be explained by the overestimation of distance in simulator. Of course there is possibility that the other factors also affect the safety distance. Regarding the physiological data such as RRI and SPL, these data averagely behaved similarly to that in real world. Decelerating behavior in simulator was relatively highly different from that in real world, that is, larger deceleration was tend to produced in simulator. However the experiment with and without motion cueing indicated that the motion cueing can reduce the deceleration slightly. These results of validation implies that when usual driving experiments, following distance can be produced slightly short, therefore the safety indices become to be computed as slightly risky. And when analyzing the response to the incident, behavioral data after starting deceleration must be modified (larger deceleration may induce the collision avoidance which is impossible in real world).

7.2. Future directions

With further improvement, the future applications of the driving simulation system may include (1) traffic safety and comfort analysis of an underground urban expressway in more complicated traffic conditions which may give drivers higher mental workload, and (2) analysis of safety mitigation countermeasures with the results from the traffic safety analysis.

Some other possible future directions include:

- Validation of the driving data in MOVIC-T4 in more complicated driving experimental conditions including the interactions with surrounding vehicles at merging sections
- Consideration of another utilization method as a communication tool in the process of infrastructure planning; including the data collection and analysis method in such a communication stage.

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