■ 論 文 ■

Effects of a Hand-Free Cellular Phone Use on Driver's Mental Workload and Performance in an Urban Area

도시부 핸드프리 휴대폰 사용이 운전자 부하 및 수행도에 미치는 영향 연구

CHA, Doo Won
(Ph. D. Candidate, Industrial Engineering Department, Ajou University)

Nobuyuki, Uchida
(Researcher, Transportation Research Division, Japan Automobile Research Institute)

Tsuyoshi, Katayama
(Deputy Director, Transportation Research Division, Japan Automobile Research Institute)

PARK, Peom
(Professor, Industrial Engineering Department, Ajou University)

목 차

요 약

근래 폭발적인 휴대폰 사용자의 증가와 비례한 운전 중 휴대폰 사용에 의한 교통사고 빈도 및 상해정도의 증가는 운전 중 휴대폰 사용을 새로운 주요한 교통사고의 요인으로 떠오르게 하고 있다. 이는 휴대폰 사용에 의한 운전자의 조정 및 감시, 경계 행위의 방해, 인지 및 정신적 부하의 증가에 의한 '부적합한 경계 (improper lookout)'와 '부주의 (inattention)' 상태 발생에서 유발되며, 현재 많은 국가들이 법제정을 통한 운전 중 휴대폰 사용금지를 실행중이거나 고려하고 있는 실정이다.

이에 본 연구는 현재 대부분의 국가에서 실질적 규제 대상에서 제외되어 있는 운전 중 핸드프리 휴대폰의 사용이 운전자의 부하 및 수행도에 미치는 영향을 시각분석, 정신적 부하, 부가작업 수행도, 스티어링 엔트로피의 측정을 통하여 실시하였다. 실험은 일본 도시 중심부에서 실시되었으며, 결과는 부가작업의 형태에 따른 4가지의 실험상황과 시험구간의 직선부와 곡선부 (우회전) 사이의 비교분석 통하여 제시하였다. 또한, 실험설계, 적용 평가방법, 및 실시과정에서의 문제점을 바탕으로 핸드폰관련 실제 도로시험을 위한 가이드라인을 제시한다.

Ⅰ. Introduction

These days, cellular phone becomes a basic in-vehicle communication tool for publics not only for the personal use but also for the ITS (Intelligent Transport Systems) two-way communication domain to supply the traffic and road information. However, cellular phone use in a vehicle is regarded a new contributor of traffic accidents and disasters by arousing the 'improper lookout' and 'inattention' state as referred by Treat et al. (1977) such as turning the radio, talking with others in the vehicle, distraction from children, daydreaming, and so on (John and James, 1996).

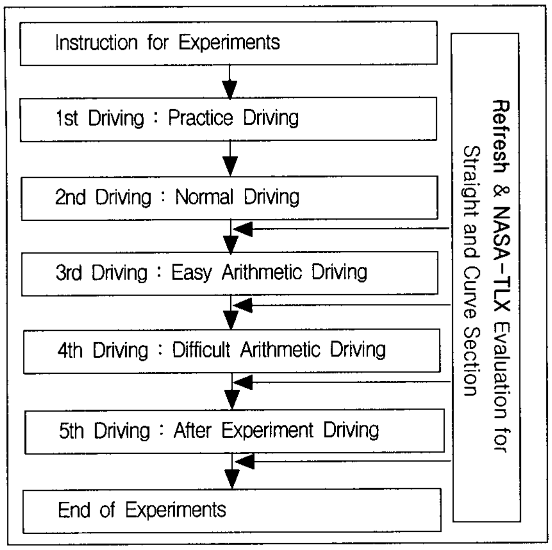
Three epidemiological studies have concluded that drivers, who regularly use a cellular phone in their vehicle including hands-free phones, have an increased risk of having a road crash including fatal crash involvement compared to drivers who do not use cellular phone (Violanti, 1998). Then, many studies have indicated the negative impacts of cellular phone use while driving that decline the ability to stay in a traffic lane (Stein, Parseghain and Allen, 1987), decrease the drivers' eye tracking movements (Iida and Ito, 1993), disturb the driver's behavior (Macnight, 1993; Kawano, Nishida, Hashimoto, and Moriwaki, 1998), affect the perceptual and motor skill (Stein et al., 1987; Alm and Nilsson, 1990; McKnight and McKnight, 1991, 1993; Zwahlen, Adams, and Schwartz, 1998). Specifically, when drivers attempted to maintain a constant headway to a vehicle ahead and were engaged in a cellular phone conversation, their reactions to headway changes were somewhat delayed (Brookhuis, Gerbrand, and De Waard, 1991; Brookhuis and De Waared, 1994). Also, when considering the vehicle performance aspects, on-road studies have shown that hands-free phones cause less interference to the driver's handling of the vehicle than hand-held phones, however, hands-free phones still impair some aspects of driving performance (Brookhuis et al., 1991). See Lamble et al and Viloanti's paper in reference for more previous research results.

This study carried out the experiment to investigate the impacts of hands-free cellular phone use on driver's mental workload and performance in an urban road situation with two different secondary mental arithmetic tasks. Results were compared in terms of eye movement, subjective mental workload, secondary task performance, and driving behavior using steering entropy technique between straight and curve road sections among four kinds of experimental driving situations for each road section.

Ⅱ. Experiment Conditions and Procedures

Field experiments were carried out in an urban area of Japan on a dry road surface condition at daylight. Four male subjects participated in the experiment. Their ages were from 28 to 37 years old (average : 31.5, S.D. : 3.35) with 11.25 years average actual driving experiences (S.D. : 5.67). Their both eye acuity were higher than 1.5 without wearing glasses and eye-related disease. Experiment route was about 2 kilometers course (about 4 minutes driving distance), and its alignment was almost flat including two times of curves (right turn) and three times of straight road sections. This route was a familiar road for all participants for their commuting and usual driving.

To estimate the impacts of hands-free cellular phone use while driving, subjects were required five times of experimental driving like ⟨Figure 1⟩ including two times of secondary task driving on the same route. As a matter of fact, it is desirable to use the natural conversation contents and questions to evaluate the cellular phone impacts and interferences for driving. However, to standardize and to differentiate the conversation contents and the level of difficulty of them



〈Figure 1〉 Experiment Procedure

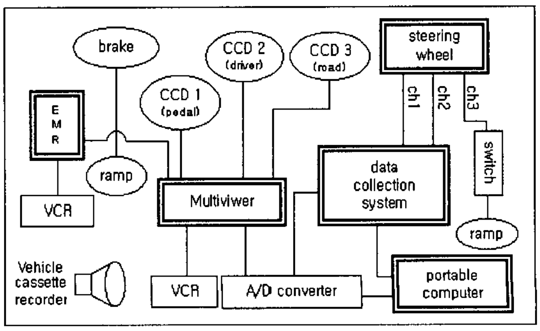
quantitatively, this study used two kinds of secondary arithmetic tasks that enable to analyze the impacts of hands-free cellular phone by the change of required mental workloads degree. And, use of standardized secondary tasks is helpful to keep the subject's safety to the highest degree for on-road experiment.

First driving was the practice driving to make aware of the exact experimental route and calculation methods of secondary mental arithmetic tasks, and the second driving was the common driving (zero workload) without any secondary task (Normal Driving). Then, the third was the low mental workload required secondary task driving that asked the subjects to calculate the minuend of one point (Easy Arithmetic Task), and the fourth was the high mental workload demanded secondary task driving using PASAT (PAced Serial Addition Task) method (Difficult Arithmetic Task) (Gronwall and Sampson, 1974). PASAT is a fairly hard combination of a memory test and an addition test, sensitive to external influences. This test, although rather inappropriate for the subject matter itself (communication), allow the experimenter to impose a fixed mental load and study the subject's tradeoff between primary and secondary task (Brookhuis et al., 1991). Vehicle cassette recorder suggested the Arabic numerals as the stimulus for two arithmetic tasks about two seconds delay through whole experimental routes. Finally, the fifth driving was the refresh driving without any secondary task like a normal driving to investigate the recovery of mental workload and to verify the required workloads among situations (After Experiment Driving).

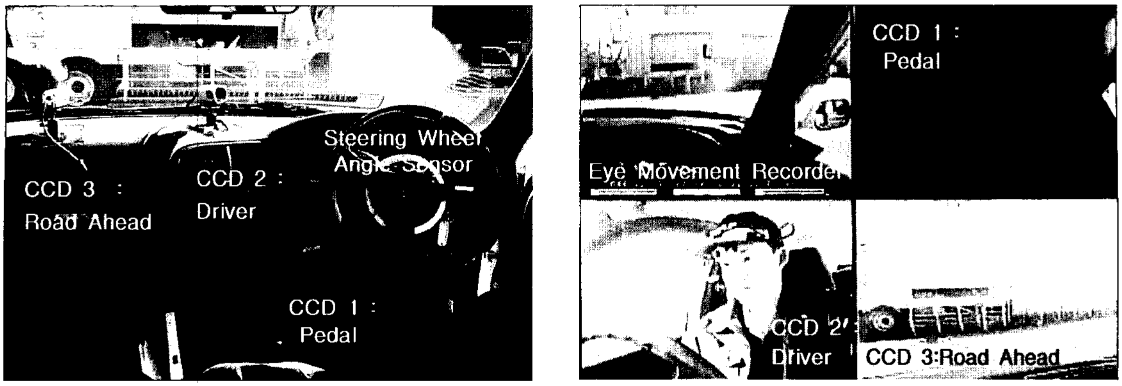
Results were analyzed from the second to the fifth experimental driving conditions excluding the first practice driving. After each experimental driving, subjects were asked to evaluate the subjective mental workload using NASA-TLX (National Aeronautics and Space Administration-Task Load Index) evaluation sheet during about 10 minutes refresh time. Other evaluation parameters automatically recorded using VCR and portable computer.

III. Measurements and Apparatus Configuration

To analyze the suggested four measurements, various experiment apparatus were equipped in an experimental vehicle (automatic transmission) that is illustrated in 〈Figure 2〉. 〈Figure 3〉 shows, (a) the inside of experimental vehicle and equipped apparatus, and (b) the sample picture of recorded video for analysis. Descriptions of detailed measurements and system configurations are as follows.



〈Figure 2〉 System Configuration



(a) Inside of Experimental Vehicle (b) Recorded EMR and CCD Images

⟨Figure 3⟩ Inside of Experimental Vehicle and Sample Image of Recorded Video Data

1. Driver Eye Movement

This parameter is widely used and adapted measurement to evaluate the mental workload of the driver. Because this is regarded one of the most effective index of mental workload, and recently received a great deal of attention involves the measure of a driver's field of view (James et al., 1990). Subjects were wearing the EMR (Eye Movement Recorder, Model : NAC-8) through all experimental driving conditions, and their eye movements had been recorded in conjunction with a VCR. For the data reliability, calibration was performed under dark laboratory area, and threshold was rearranged under the same condition of experiment (on the road) for each subject.

Then, duration fixations were evaluated from the divided visual sources of straight and curve road sections.

2. Subjective Mental Workload

NASA-TLX was used as the subjective mental workload assessment technique in this study, because the subjective mental workload assessment can suggest a comparative safety, subjective preference and usability results among target systems or information displays, and then provide an appropriate tool to draw out the human-machine interface design guidelines and evaluation standards that other objective evaluation techniques cannot suggest. NASA-TLX was firstly developed by the Human Performance Group at NASA Ames Research Center, and has been used for broad samples of people in various situations, and more recently, used for the driving and ITS environments (Cha and Park, 2000).

NASA-TLX has the multidimensional rating scale procedure that uses six dimensions to assess the subjective mental workload : mental workload, physical demand, temporal demand, performance, effort, and frustration level. The overall workload score for the condition is obtained by multiplying the ratings by dimension weights and divided the sum by 15. The higher this score means the higher mental workload required situation from the subjects (Hart and Staveland, 1988).

3. Secondary Task Performance

It is certain that the driving with a cellular phone use is a dual task: adding a secondary task raises questions about the driver choice in terms of priority, which task is considered the main one. Thus, dual task interference provides an index of the workload demands placed on driver's attentional resources between primary and secondary tasks (Procter and Zandt, 1994).

Applied secondary mental arithmetic tasks (Easy and Difficult Arithmetic Tasks) for this experiment enable to measure the workload at the low and high mental workload required conditions because these two conditions are undoubtedly basic conditions for human errors. Also, since the mental workload and the interface are external factors which may influence the mental strain experienced by the driver, it is necessary to change the level of mental workload quantitatively by changing the content of the stimuli that require information processing, and it is also necessary to assign the content of the secondary task and the level of mental workload through both a visual and auditory channels and the level of mental workload can be changed by changing the number of terms in the equation (James, Robert, Mary, William and Julli, 1990). Secondary tasks performance of this experiment was evaluated in terms of error rate. This error rate was measured as the ratio of incorrect responses to the total arithmetic stimuli of easy and difficult arithmetic task driving conditions between curve and straight road sections. This data was collected directly during experimental driving by the experimenter, and then rechecked using recorded videotapes after experiments.

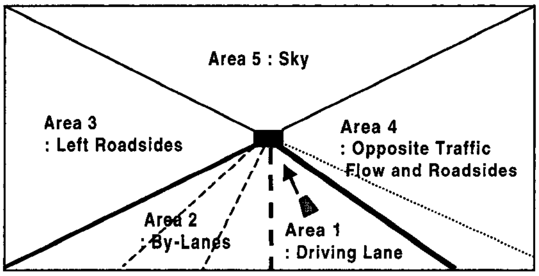
4. Steering Entropy

Steering wheel of experimental vehicle was replaced with a steering wheel angle sensor to collect the trace of steering wheel angle data that was sampled by 100ms rate. These data were automatically recorded to the portable computer. Then, these collected data were analyzed using steering entropy method developed by Nakayama et al (1999). This technique has an assumption that the driver's steering behavior tends to become more discontinuous while performing an activity in addition to driving task. To quantify these discontinuities, steering entropy values are obtained from a time series history of steering angle data, and this make it possible to quantify accurately and easily the workload imposed on drivers by any activity other than the action of driving itself (Nakayama, Futami, Naamura, and Erwin, 1999).

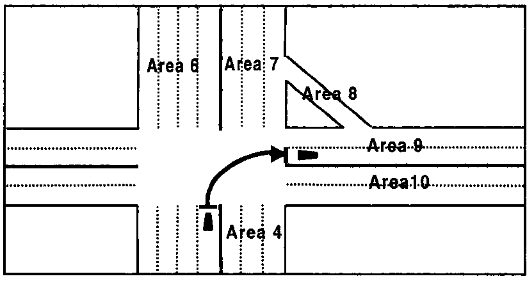
Ⅳ. Experiment Results

1. Driver Eye Movement Analysis

Recorded EMR data were analyzed among interesting visual demand sources (boxed areas of ⟨Figure 5⟩ and ⟨Figure 6⟩) of the first straight and right turn section that was about 200m distances with 30 seconds driving time (average time of straight section was 21.34 seconds, and that of curve section was 5.7 seconds). ⟨Figure 4⟩ (a) shows the classified areas of visual activity demands of straight road section, and (b) does the classified areas of curve road section for analysis. Results were derived from calculating the relative fixation duration percents(%) of visual demand sources.

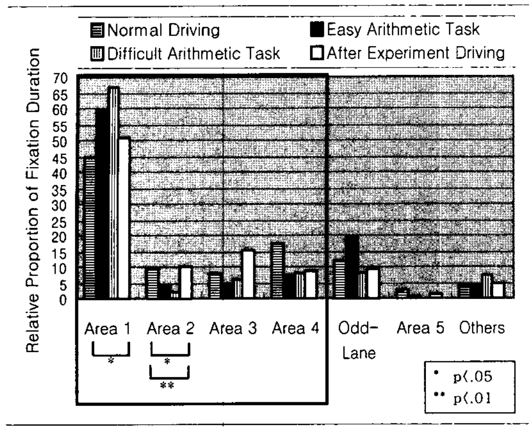


(a) Straight Road Section

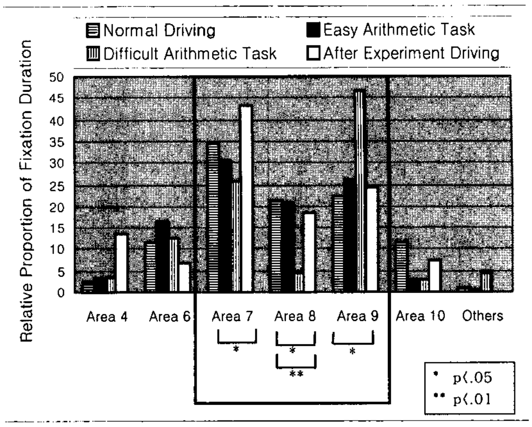


(b) Right Turn Section

⟨Figure 4⟩ Classification of Interesting Eye Activity Demand Sources



〈Figure 5〉 Relative Proportion of Fixation Duration of Straight Section



〈Figure 6〉 Relative Proportion of Fixation Duration of Right Turn Section

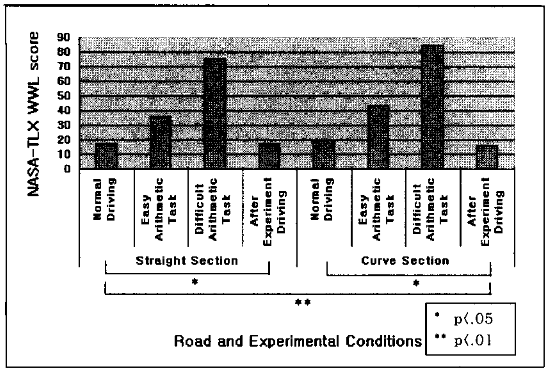
Thus, the total percents of classified areas in 〈Figure 5〉 and 〈Figure 6〉 are 100%. These data were calculated using recorded timer of EMR system that supports the 1/60 second time unit by manual frame analysis using jog shuttle VCR. During data analysis, unnecessary data were eliminated such as eye movement among visual demand sources and visual activities during stoppage for right turn, and so on. There were no congestions though whole experimental driving sessions. 〈Figure 5〉 and 〈Figure 6〉 shows the distribution of fixation durations by the visual activity demand sources and tasks of the straight and curve road sections, respectively.

The result of straight road section that can be seen in 〈Figure 5〉, the visual demand of area 1 (road ahead) was increased whereas that of area 2 (by-lane) was decreased by the increase of task difficulty level. Then, that of area 3 and 4 (left and right roadsides) was decreased under secondary task driving conditions. ANOVA (Analysis of Variance) results of these visual resources showed the significant differences in area 1 ($F(3,12)=5.9$, p-value=0.0114) and area 2 ($F(3,12)=32$, p-value=0.000005), besides area 3 ($F(3,12)=3.4$, p-value=0.0517) and area 4 ($F(3,12)=2.1$, p-value=0.1509) did not show the significant differences among experimental driving conditions.

This result explains that subjects tend to concentrate their visual activities on the road ahead by the increase of secondary task difficulty on the straight lane, whereas the monitoring ability of by-lane and roadsides were reduced. However, the visual activities of these areas are important ones to monitor the lane change, collision and traffic situations during driving that should be considered. Then, concerning the result of curve section in 〈Figure 6〉, visual activity demand of area 9 (direction that subject should drive) was increased, whereas that of area 7 (straight lane toward area 4 direction) and 8 (entrance lane toward area 9 from 7 area) was decreased by the increase of task difficulty. ANOVA results of these three areas showed the significant differences (area 7 : $F(3,12)=3.52$, p-value=0.0488, area 8 : $F(3,12)=6.3$, p-value=0.0082, area 9 : $F(3,12)=3.88$, p-value=0.0391) among experiment driving conditions. Like the visual activity pattern of straight section, subjects tend to concentrate their visual activities on the direction that they should drive.

2. Subjective Mental Workload Analysis

Before conducting experiment, subjects were instructed to remember the imposed workload between straight and curve sections, and evalua-



〈Figure 7〉 Results of NASA-TLX

tions were performed for these two sections during refresh times just after finishing each experimental driving condition.

〈Figure 7〉 is the results of subjective mental workload assessment using NASA-TLX between straight and curve section of four experimental driving conditions.

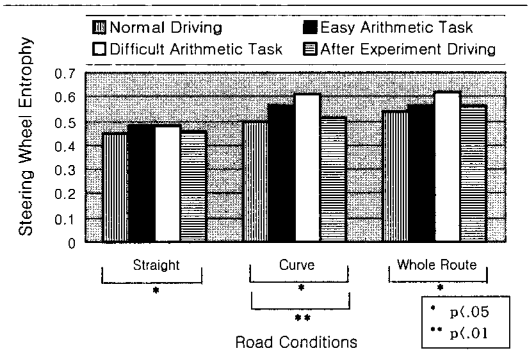
Result indicates that the subjective mental workload increased as the secondary task difficulty did. And, the higher subjective mental workload was required on the curve section than the straight one in each normal and secondary task situation. Then, the required workload after experiment driving was recovered at the similar level of normal driving. ANOVA result supported this fact that workloads among driving conditions were significantly increased by the improvement of secondary task difficulty in both road sections (straight section : $F(3,12)=7.450$, p-value=0.0045, curve section : $F(3,12)=7.568$, p-value=0.0042).

3. Secondary Task Performance Analysis

〈Table 1〉 shows the results of secondary tasks between easy and difficult arithmetic tasks. Result indicates that subjects were required more cognitive workload on the curve section by the increase of secondary task difficulty. Statistical test results showed the significant differences in both road sections (p-value (two-sided)=0).

〈Table 1〉 Results of Secondary Tasks

	Easy Arithmetic Task		Difficulty Arithmetic Task	
Road Situation	Straight	Curve	Straight	Curve
Error Rate (%)	0.94	1.55	26.33	46.49



〈Figure 8〉 Results of Steering Entropy

4. Steering Entropy Analysis

Result in 〈Figure 8〉 indicates that steering entropy among driving conditions was significantly increased by the improvement of task difficulty, and then the required workload level of after experiment driving was recovered at the normal driving level in both road sections (straight section : $F(3,12)=4.489$, p-value=0.0240), curve section : $F(3,12)=6.44$, p-value=0.0075). Also, steering entropy of total route showed the significant differences among situations ($F(3,12)=3.767$, p-value=0.040). However, dissimilar from the tendency of other measurement results, required entropy of curve section was lower than that of straight one. Because the straight lane of analyzed experimental route included two intersections to be go straight. In practice, it is possible to calculate the exact steering entropy of straight and curve road by cutting the collected data between intersections or curves. However, in this case, it is impossible to reflect the real urban traffic situations that are very changeable and much traffic volumes with interferences of other vehicles.

V. Findings and Conclusions

This paper compared four mental workload measurements such as normal driving, easy and difficult arithmetic driving, and after experiment driving conditions with hands-free cellular phone use.

Results of eye movement analysis indicate that as the secondary task difficulty level start to increases, the visual activities tend to focus on the primary task operation (task for lane keeping and advancing). It means that the drivers tend to concentrate their visual activities on the area that they should drive to, so that the inspection ability of circumference visual field for monitoring other lanes and traffic situations become reduced.

The subjective mental workload and the secondary task performance evaluation support this result that more workloads are required to maintain the primary driving task by the increase of secondary task difficulty. Also, this result supports the fact that more workload is required on the curve section than that of straight section. It means that the hands-free cellular phone use on a curve section can make more dangerous situation than on a straight section when the driver having or holding a conversation demanding a high workload such as negotiation, calculation, quarrel, and so on. However, more examination of steering entropy method is required to adapt the specific road and driving conditions as a new mental workload index.

Initially, this experiment was designed to estimate the reaction time between the brake light of fore-vehicle and the start time of subject accelerator release using CCD 1 by experimental driving situations. However, it was very difficult to estimate by VCR analysis using the recorded data of ⟨Figure 3⟩ (b), because of sunlight interference and variable traffic situations, and this kind of analysis method requires much experimenter's time and labor load for result derivation. Therefore, for more exact experimental results, it is recommendable to use a leading vehicle (another experimental vehicle) and multi-beam laser radar device to estimate the accurate reaction time and headway distribution that are also regarded as important driver's performance measurements. This way also could diminish the experiment result analysis time and, could improve the data accuracy.

Nowadays, governments in many countries are trying to prohibit the cellular phone use while driving by the law. However, most of them only restrict the use of hand-held types. Based upon the results of current study, the hands-free cellular phone use while driving can make a serious traffic situation depending on the difficulty of convertsation. It means that hands-free cellular phone use could arouse the negative effects to the driver's performance and workload that is one of the major causes of traffic accident. However, to investigate farther impacts of hands-free cellular phone use on drivers, additional experiments with various demographic groups in various driving situations are strongly recommended.

References

1. Alm, H., Nilsson, L. (1990), Changes in driver behavior as a function of hands free mobile telephones : A simulator study, In Drive Project V1017, Report NO. 47, Linkoping Sweden, Swedish Road and Traffic Research Institute.
2. Brookhuis, K., Gerbrand de Vries, Dick de Waard. (1991), The Effects of Mobile Telephoning on Driving Performance, Accident Analysis and Prevention, Vol. 23, No. 4, pp.309~ 317.
3. Brookhuis, K., De Waard, D. (1994), Measuring Driving Performance by Car-Following in Traffic, Ergonomics, Vol. 37, pp.427~434.
4. Cha, D. W., Park, P. (2000), Comparative Research of Subjective Mental Workload assessment Techniques for the Application of

Human-Machine Interface Evaluation of ITS-oriented Information Systems, IE-Interfaces, (in press).

5. Daimon, T., Usuki, D., Kawashima, H. (1999), A Study on Drivers' Characteristics based on the Mental Stress When using the Communication Services on In-Vehicle Information Systems, CD-ROM Proceeding of 6th World congress of Intelligent Transport Systems.
6. Gronwall, D. M. A., Sampson, H. (1974), The Psychological Effects of Concussion, Auckland, New Zealand, Auckland University Press.
7. Hart, S.G., AND Staveland, L. (1988), Development of NASA-TLX (Task Load Index) : Results of Empirical and Theoretical Research, In P. A. Hancock and N. Meshtati (Eds.), Human mental workload, Amsterdam, Elsevier.
8. Iida, T., Ito, T. (1998), Influence on thought when Trying to Obtain Visual Information While Driving, Journal of the Traffic Science Society of Osaka, Vol. 28, No. 1-2, pp.60~65.
9. James, G. M., Robert, S. K., Mary, C. W., William, P. D., Julie, R. B. (1990), Eye Movement Indices of Mental Workload, Acta Psychologica, Vol. 75, pp.75~89.
10. John, M. V., James, R. M. (1996), Cellular Phone and Traffic Accidents : An Epidemiological Approach, Accident Analysis and Prevention, Vol. 28, No. 2, pp.265~270.
11. Kawano, T., Nishida, S., Hashimoto, M., Moriwaki, T. (1998), A Study on Driving Performance, Conversion Result and Reaction to Avoid Car Crash when using a Portable Phone during Driving, Journal of the Traffic Science Society of Osaka, Vol. 28, No. 1-2, pp.66~70.
12. Lamble, D., Kauranen, T. M., Laakso, H. (1999), Cognitive Load and Detection Thresholds in Car Following Situations : Safety Implications for using Mobile (Cellular) Telephone while Driving, Accident Analysis and Prevention, No. 31, pp.617~623.
13. McKnight, J. A. (1991), McKnight, S. A., The Effect of Cellular Phone Use upon Driver Attention, National Public Services Research Institute, Landover MD.
14. Macnight, A. J. (1993), The Effect of Cellular Phone Use upon Driver Attention, Accident Analysis and Prevention, Vol. 25, No. 3, pp.259~265.
15. Nakayama, O., Futami, T., Nakamura, T., Erwin, R. B. (1999), Development of a Steering Entropy Method for Evaluating Driver Workload, SAE Paper Number 1999-01-0891.
16. Procter, R. W., Zandt, T. V. (1994), Human Factors in Simple and Complex Systems, Allyn and Bacon.
17. Stein, A. C., Parseghain, Z. Allen, R. A. (1987), A Simulator Study of Safety Implications of Cellular Mobile Phone Use, 31st Annual Proceedings of the American Association for Automotive Medicine, Des Plains, IL, American Association for Automotive Medicine, pp.181~120.
18. Tokunaga, R., Hagiwara, T., Takagi, H., Shimojo, A. (1998), Effect of Cellular Telephone Use on Driver's Reaction Time and Subjective Mental Workload, CD-ROM proceedings on 5th World Congress of Intelligent Transports Systems.
19. Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., Stansifer, R. L., Castellan, N J. (1977), Tri-Level Study of the Causes of Traffic Accidents, Final Report on U.S. Department of Transportation, Indiana University, Institute for Research in Public Safety, Washington, DC : Government Printing Office.
20. Violanti, J. M. (1998), Cellular Telephone Use and Fatal Traffic Collisions, Accident and Prevention, Vol. 30, No. 4, pp.519~524.
21. Zwahlen, H. T., Adams, C. C., Schwartz, P. Z. (1998), Safety Aspects of Cellular Telephone in Automobiles, Reference No. 88058, Proceedings of the 18th International Symposium on Automotive Technology and Automation.