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Driver Workload Comparisons among Road Sections of Automated Highway Systems

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목 차

요 약

The aim of this research was to compare driver's workload among AHS (Automate Highway Systems) road sections in a virtual AHS environment that is based on a re Korean expressway in order to predict and compare the workloads imposed by the change driver-vehicle interface and vehicle control authority. Road sections included the M (Manual Lane), TL1 (Transition Lane to enter the automated lane), AL (Automated Lane TL2 (Transition Lane to enter the manual lane after the end of automated driving), an post-AHS manual lane.

I. INTRODUCTION

The AHS is a newly developing human-machine interface system which enables 'hands-off' and 'foot-off' driving by supporting the automation and replacement of human functions, such as hand function (steering control), foot function (throttle and brake control), and eye function (information collection) [3]. However, carry-over effects and confusion brought about by the changes of vehicle control authority and driver-vehicle interfaces are therefore to be expected. How will the transfer of vehicle control authority and change of driver-vehicle interface when adapting to automated driving functions affect the driver's mental states and workloads among various AHS road sections including the manual lane, automated lane, and transition lanes? Is workload maintained at the same level while driving on the various road sections of AHS driving?

To predict the workload and AHS impacts, this research adopted the following measures:

- Vehicle speed to evaluate the carry-over effect as a performance measure
- Steering entropy
- Secondary task measure (reaction time)
- Subjective mental workload technique (RNASA-TLX : Revision of National Aeronautics Space Administration-Task Load Index)
- Psychophysiological parameters (EOG : Electrooculo-graphy, GSR : Galvanic Skin Response

The following data were collected on the following road sections:

- Vehicle speed and steering entropy data were collected on pre-AHS, TL1, and post-AHS.
- Reaction time, GSR and EOG were collected on all five sections.
- RNASA-TLX was collected on pre- and post-AHS driving sections.

A fixed-base AHS simulator was constructed for the experiments, and data were collected among the given road sections at 120kph, 140kph, and 160kph automated vehicle speed.

II. Experimental Driving Environment

1. AHS Simulator Description

The simulator was constructed on a half-sized real vehicle cockpit module (Verna automatic transmission mode, Hyundai Motor Company) with a 16degrees of freedom (d.o.f.) real vehicle dynamics model. The virtual driving environment was projected from a beam projector onto a 110-inch screen, which had a 45°~55° field of view. The distance from the projector to the screen was 3.6m thereby replicating the real-size road environment. It featured 800x600 32bits true color resolution with a 40~60Hz refresh rate. 3D vehicle sound was generated through four speakers located around the seating buck. A keyboard and mouse was connected to an integrated control box to specify the simulator settings.

2. Road Configuration

'Shared Space at-Grade Concept' was implemented as the AHS road configuration in a simulator that is suggested by PATH (Partnerships for Advanced Transit and Highways) [11]. This is one among four kinds of configurations - 'Shared Space at-Grade Concept', 'Dedicated Space at-Concept', 'Above-Grade AHS Concept', and 'Below-Grade AHS Concept' suggested by PATH. Transportation expert's review suggested that this concept requires a low-cost and minimum-changeable configuration for the implementation within the Korean road system. This concept also satisfies the following principles governing the configuration of the AHS and the maneuvers of vehicles [4].

- Vehicles are organized into closely spaced platoons, which have an inherently low casualty rate
- There is a barrier between the AL and ML on the rest of the right-of-way; vehicles must enter and exit through gates in the dividers
- Platoons do not join together (merge) at speed, either on the ALs or on the transition lane

Barriers designs were based on Korean road facility standards [8] - median barriers (drawing number: II-15-2), width was 3.5m which is the minimum requirement and AL-TL (drawing number: II-3-1) was used. The road specified in Korean regulations of road structure and facility [7]. This concept was implemented on the Osan to Cheonan part of Kyungbu expressway. The total length of the road was about 40km. Along this length, the pre- and post-AHS manual road sections were 6.5 km each (about 4 minutes driving),with the AL section accounting for 25km. Time on the AL driving section was about 12.5, 10.7, and 9.4 minutes at each AL speeds of 120 kph, 140 kph, and 160 kph. The lengths of the TL sections were 1.83km and 2.5km before and after the AL driving, respectively.

3. Inter-Vehicle Gap

In general, it is best to have the smallest possible inter-vehicle gap between vehicles in an automated platoon in order to maximize the benefits of aerodynamics drag reduction and lane capacity increase as well as minimizing the risk of severe impact between vehicles when a failure occurs. However, there are practical limitations that make it impossible to make the gap as small as possible due to limitations of sensor noise and accuracy and variability of vehicle dynamics responses. If the vehicle gap is made to small, these imperfections would cause the vehicles to occasionally contact each other during normal driving, which is undesirable for both passengers and vehicles [9].

Many studies have investigated the inter-vehicle space problem in the platoon. For example, Castillo *et al* [2] used this parameter of 1m and 4m of inter-platoon distance at 30m/second vehicle speed to estimate the capacity of AHS. Leis [6] insisted that a tight platoon (inter-vehicle distance) is the desired condition and he set the 1.34m of inter-vehicle distance and 96.5-112.7 kph vehicle speed to investigate the minimum safe separation distance in various driving conditions.

The human factors design guideline of AHS [5] suggested the inter-vehicle distance guideline founded on the experiment of Bloomfield et al's [1]. These experiments were based on driver's preferences whereby if there is a string of vehicles in the automated lane, which has a design speed of, more than 104.7 kph (65 mph), gaps of greater than 0.0625 seconds should be provided between the vehicles within the string.

In this experiment, a 0.0625 second inter-vehicle gap is used which simultaneously fulfilled the human factors design guideline and development plan of PATH. Also, this is a widely used value to make it possible to compare the results with those of other studies. Therefore, the designed inter-vehicle gap was 2.08m, 2.43m, and 2.78m for 120 kph, 140 kph, 160 kph of AL speed, respectively.

III. Driver-Vehicle Interface and Driving Scenario

1. Driver-Vehicle Interface Design

A HUD (Head-Up Display) was transparently projected onto the screen, and the AHS information was displayed on the 7-inch LCD-based portable computer using IPX (Internetwork Packet eXchange) protocol for the synchronization between the vehicle parameters and the information presentation on the display. The HUD presented the current lane position, speed, driving mode (automated or manual driving), and the remaining time to the destination as well as the lane position. The AHS information display presented the remaining distance to the destination, inter-vehicle distance, destination name, and the driving mode and was located on the right-hand side of the cockpit.

Eight VMSs (Variable Message Signs) were implemented for the driver's rapid acquisition of roadside information 500m in front of each gate with young female voice instructions.

Five function keys were arranged on the center facia area for the calibration of vehicle control parameters (function key #1～#4), and for the start of automated driving (CCB : Cruise Control Button : function key #5).

Inter-vehicle gap was controlled from 1m to 30m distance and platoon speed was controlled from 100 to 200 kph through the use of the simulator administration program, which enabled convenient settings within advanced human factors experiments

2. Driving Scenario

Figure 1 shows the driver's maneuvering and vehicle operation procedure from the start to the finish of the automated driving. In this figure, EML (Entry Maneuvering Length) is the area in which the drivers should press the CCB to start the automated driving and to check the vehicle state, CCL (Control Change Length) refers to the transfer of driving authority from vehicle to driver and driver to vehicle on the TL. The FML (Failure Maneuvering Length) gate is the exiting area in case of CCB press failures or vehicle malfunctions. Among the road sections, the length of the CCL after exiting the AL is long, because there is the possibility that the driver had fallen asleep and is unprepared for the manual driving mode.

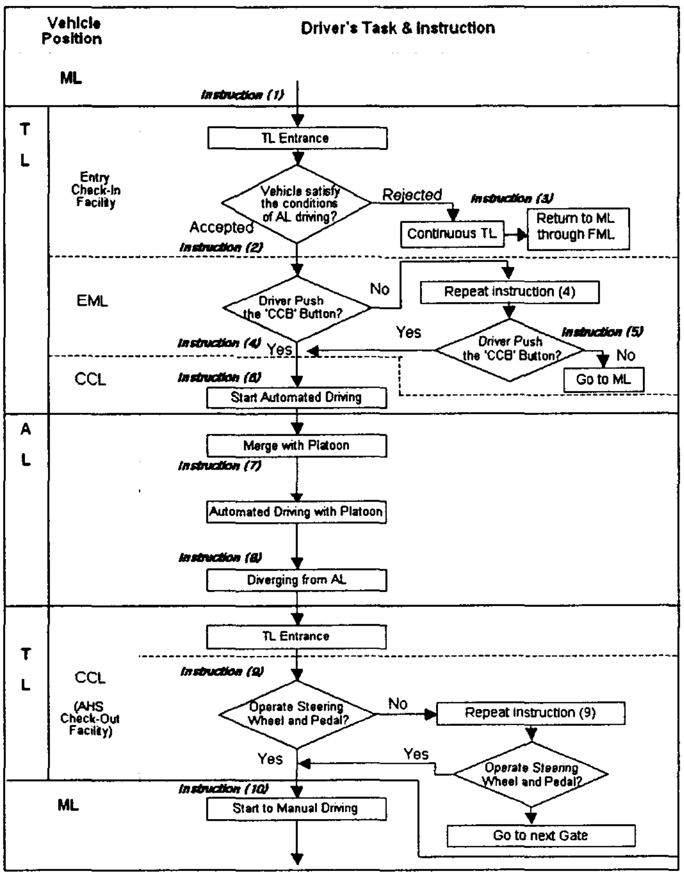

Figure 1. Driver's Maneuvering and Instructions for Entry and Exit of AL

To complete a session of driving, the driver should drive the vehicle in the following order ML→TL→AL→TL→ ML. After the success of the vehicle check-in process for entering the AL, the vehicle automatically enters the AL increasing in velocity until predetermined automated driving speed of the platoon is reached. In cases where the driver fails to push the CCB or vehicle check-in process, they should drive the vehicle through the FML. To finish the automated driving, the vehicle automatically moves to the gate at the end of the TL by transferring the control authority to the driver. Ten kinds of voice instructions were presented when the road sections changed and the driver's operation was required.

IV. EXPERIMENT DESIGN

1. Subject

32 graduate and undergraduate male students were recruited through postal and web advertisements. All subjects had no past history of psychiatric or physical disease and they had normal (corrected) vision and normal hearing. They all also had no vehicle accident history. Three of these subjects were used for a pilot experiment to predict the required experiment time and any unexpected problems with the experimental apparatus and procedure. Data from 4 of the 29 subjects were discarded from the analysis because of excessive EOG artifact, excessive blinking, and exceeded vehicle speed. Thus, 25 subjects data were analyzed for this experiment. Their age range was 23 to 33 years (mean : 26.44, s.d. : 2.87), with a mean of 4.68 year's driving experience (s.d. : 1.504). GSR finger electrodes and EOG electrodes were attached throughout all of the experiment.

2. Experimental Protocol

Four parts to the experiment were performed using the constructed AHS simulator. Since the AHS is not yet implemented in the real world, the experimenter explained the detailed concepts of the AHS including development objectives, AHS vehicle structure and operation, road configuration, and the development trends within other countries. The dependent measures used to measure workloads were explained to each subject. Opportunities to practice vehicle operation and driving were supplied on the simulated driving route until the subjects' could satisfactorily operate the simulator and were accustomed to the route. Then, three sessions of experiment were executed on the same route. 120kph, 140kph, and 160kph of AHS driving speed were set for each session of experiment to investigate the effect of AHS speed and automated driving among five road sections. The driving environment was daylight and dry road conditions. The traffic density was 5 vehicles/km/lane, and a platoon was composed of passenger vehicles only, because a mixed flow with trucks or buses could arouse another human factors problem of driver's field of view. A break of about 20 minutes was allowed among the sessions to permit refreshment and enable completion of the RNASA-TLX questionnaire. All subjects were required to wear the seat belt, and there was no passenger beside the subject. During manual control driving, subjects were required to try to keep within the upper speed limits of the highway regulation of 100kph. Before the experiment, the camera module of the simulator screen was calibrated for each subject to coincide with their eye position and road scenes. Figure 2 shows the experiment scene.

Figure 2. Experiment Driving Scene

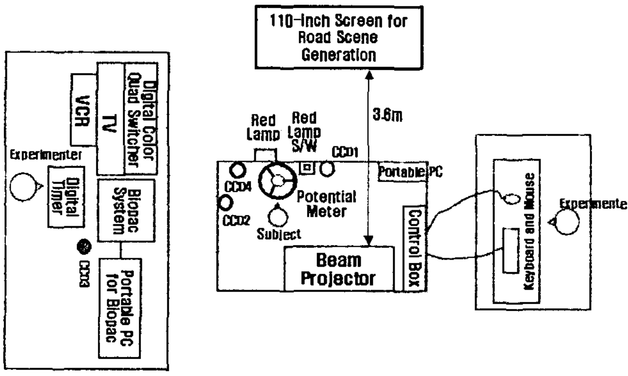

Figure 3. Experiment Chamber and Apparatus Settings

3. Apparatus

The driver's behavior monitoring system, the psycho-physiological parameters measurement system, secondary task generation, and the steering behavior data collection systems were positioned around the simulator as shown in Figure 3. The Biopac^{TM} system was established to measure the driver's psychophysiological workloads. A red lamp was set up on the dashboard and a push switch was placed on the air conditioner register. This lamp was connected with the digital time on the experimenter's space to estimate the reaction time among various driving conditions. Steering angle meter was installed on the steering wheel, and then vehicle speed and steering angle data were automatically logged in the host computer as well as the brake and accelerator control behavior.

Four CCDs (Charge Coupled Devices) were positioned around the simulator. CCD1 recorded the driving scenes including frame numbers, and CCD2 monitored the driver's foot behavior to investigate the driver's authority transfer behavior. CCD2 was installed in front of subject to monitor their behavior. CCD3 recorded the reaction time of the digital timer and the processing time of BiopacTM system, whilst CCD4 was installed in front of the subject to monitor the driver's state and steering behaviors. All video data were recorded in videotape using digital color quad switcher.

V. EXPERIMENT RESULTS

Among the dependent measures of workloads, EOG and GSR were evaluated for one minute's duration on each road section, whilst steering entropy and vehicle speed were evaluated on TL1, pre- and post-AHS road sections during the same time period. Data on pre- and post-AHS section was evaluated for the minute duration just prior to entering TL1 and just after exiting TL2 in order to investigate the effects of automated driving exactly. On TL1 and TL2, data were evaluated during the overall driving time. One minute data, sampled at the middle of driving time was analyzed on the AL to estimate the driver's workload in a stable condition.

For the data analysis, a two-way ANOVA and Duncan's multiple range tests were adapted for post hoc analysis of the means. This method tests the observed ranges between means, beginning with the least significant range R. N ext, the range of the largest and the second smallest is computed and compared with the least significant range R-1. These comparisons are continued until all means have been compared with the largest mean. The primary focus of the ANOVA was to test the interaction between AL speeds and road sections on the five kinds of mental workload measures and vehicle speed.

Table 1 shows the summary of evaluated data for each measure, and Table 2 displays the results of the ANOVA. Vehicle speed significantly increased on TL1 and post-AHS manual driving period compared to pre-AHS driving road section. This result explains that there existed a carry-over effect when performing the manual driving after automated driving. Even though, steering entropy between pre- and post-AHS manual driving did not exhibit significant differences, post-AHS manual driving required more steering entropy than pre-AHS manual driving situations. TL1 required lower steering entropy compared with the other two conditions. Because the TL1 was surrounded with barriers on both right and left sides, subjects tried to keep in the lane in order not to crash into them.

GSR result supported this result since the average GSR value for TL1 was 9.51 higher than AL and pre-AHS driving. The GSR value for post-AHS driving was the highest value among five road sections, and TL1 and TL2 followed by the same Duncan group.

Reaction times among the five road sections were classified into three groups. Subjects responded in shortest times when manually driving on the pre-AHS section, followed by TL1, post-AHS, and TL2 that belonged in the same Duncan group. The AL required the longest reaction time among the road sections; many subjects complained of drowsiness on this section, and three subjects crashed into the barrier just after entry into the ML, which was the driving control authority change area.

EOG (eyeblink frequency) values of post-AHS and TLs were higher than in the pre-AHS conditions. However, this value of the AL was the highest of the road sections, which means that the subjects continuously monitored the road environment even if undertaking AL driving.

Finally, the RNASA-TLX explained the subjective mental workloads between pre- and post-AHS manual driving sessions. Of its six scales, only 'Mental Workload', 'Visual Demand', 'Temporal Demand', and 'Difficulty in Driving' showed statistically significant differences between pre- and post-AHS manual driving, - 'Auditory Demand' and 'Difficulty in Understanding Information' did not show significant differences. Visual demand supported the result of the EOG that post-AHS driving required a higher mental workload than pre-AHS driving. Weighted workload as an overall index of the RNASA-TLX six scales, indicated that the subjects required higher workloads than pre-AHS manual driving conditions. Results of other measurements supported the existence of this effect on AHS driving. However, this applied not only to the post-AHS driving, but also to the TLs where the same effect existed. Reaction time, GSR values and EOG results were higher than those of pre-AHS manual driving conditions, and the vehicle speed of TL1 was faster than that of the pre-AHS driving condition. Between TL1 and TL2, TL2 necessitated higher reaction times, GSR, and EOG than those of TL1.

VI. Conclusion and Discussions

For simulated driving at three different AL speeds:

- Reaction time, GSR, and EOG were compared among the pre-AHS, post-AHS, TL1, TL2, AL.
- Steering entropy and vehicle speed were compared on the pre- and post-AHS, TL1.
- RNASA-TLX scales were compared on pre- and post-AHS manual driving conditions.

Table 1. Results of Six Dependent Measures among AHS Speeds and Road Sections

	120kph					140kph					160kph				
	Pre-AHS	TL1	AL	TL2	Post-AHS	Pre-AHS	TL1	AL	TL2	Post-AHS	Pre-AHS	TL1	AL	TL2	Post-AHS
Vehicle Speed (kph)	108.25	112.50	N/A	N/A	112.19	109.50	112.47	N/A	N/A	114.86	109.65	115.12	N/A	N/A	113.19
Steering Entropy	0.77	0.66	N/A	N/A	0.82	0.75	0.61	N/A	N/A	0.80	0.74	0.60	N/A	N/A	0.80
Reaction Time (ms)	995	1091	1425	1183	1157	997	1072	1886	1171	1111	998	1127	1890	1116	1115
GSR (μmho)	8.50	9.38	8.59	10.28	10.80	8.99	9.60	8.92	9.93	10.19	8.49	9.55	7.84	9.40	10.39
EOG	13.1	13.2	18.3	15.3	14.2	12.6	16.0	20.0	17.8	16.3	13.5	14.1	19.0	16.4	15.6
R-TLX	7.0	N/A	N/A	N/A	8.51	6.77	8.45	N/A	N/A	N/A	6.67	N/A	N/A	N/A	8.48

Table 2. ANOVA Results of Dependent Measures

	Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Vehicle Speed	Road Sections	2	905.97	452.98	4.93	0.0081***
Steering Entropy	Road Sections	2	1.319	0.660	9.41	0.0001****
Reaction Time	Road Sections	4	6715165.957	1678791.50	20.58	0.0001 ****
GSR	Road Sections	4	210.36	52.60	2.50	0.0425 **
EOG	Road Sections	4	2187.06	546.77	7.46	0.0001****
R-TLX	Road Sections	1	48.85	48.85	4.69	0.0320**

(* : α=0.1, ** : α=0.05, *** : α=0.01, **** : α=0.001)

The results of this research indicated changes in driver's workloads brought about by automated driving in various road sections. On one hand, AL speeds did not affect the subject's workloads among road sections. This means that the increased reaction time, GSR, EOG, steering entropy, RNASA-TLX, vehicle speeds were affected by the control authority changes of AHS driving. On the other hand, the TLs design should be cautiously considered in an effort to increase driver safety and comfort through the reduction of driver's workload and speed, since it was shown that driver's workloads significantly increased in the TL compared to the AHS road sections. These results could help to design the human-machine interface of AHS, for instance at what time should warning information be presented. This research could also contribute to the AHS and human factors-related research programme for future development of a basic network in Korea.

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