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SIMULATION STUDY OF THE EFFECT OF FOUR ROUTE GUIDANCE SYSTEMS ON DRIVER DISTRACTION

Raghavan Srinivasan, Research Assistant
Paul P. Jovanis, Professor
Chun-Zin Yang, Research Assistant
Ryuichi Kitamura, Professor
Institute of Transportation Studies
University of California, Davis

Cheryl Hein
Francine Landau
Hughes Aircraft Company

ABSTRACT

A series of realistic experiments have been conducted using a driving simulator developed by Hughes Aircraft Corporation, in order to examine the implications of different types of route guidance systems on driving performance. The focus of the experiments was on en route guidance over predescribed and planned routes. Drivers were asked to follow a predetermined route to the destination. Four types of route guidance systems were tested: (i) Paper Map, (ii) Heads Down Electronic Map, (iii) Heads Up Display (HUD) in combination with Heads Down Electronic Map, and (iv) Voice Guidance in combination with Heads Down Electronic Map.

The experiments were designed so that all subjects were tested using all route guidance systems, using a within subject design. Subjects, recruited by a market research firm, included nine males and nine females.

User perceptions and preferences for the devices and the subjects' subjective assessment of workload were measured using a variety of measuring scales. Reaction times were measured whenever the subject had to react to an external event to avoid a collision. External events included: pedestrians crossing in front of the subject, left turning vehicles, crossing vehicles, obstacles, and changes in traffic signal indication from green to amber. The NASA TLX method was used to measure subjective workload immediately after completing two driving trials with each of the four route guidance systems. Driver preferences of each system were also measured at this time using five dimensions: ease of use, clarity of information, quantity of information, preparation for turns and levels of distraction.

A variety of statistical methods have been applied to the performance measures including analysis of variance, linear regression and logit models. Among the findings are:

1) Subjective workload, user perceptions and number of errors all indicated that the voice guidance/electronic map combination performed the best, and the paper map to be the worst. Somewhat surprisingly, the HUD/electronic map combination performed worse than the electronic map is the case of workload.

2) The reaction time modeling yielded slightly different device performance depending on the event being reacted to. In general, the paper map was associated with largest reaction times.

INTRODUCTION

Application of advanced technology has been prescribed as one of the possible solutions to continuing urban congestion. In-vehicle route guidance systems consist of display devices in the car which obtain information about the network and real time traffic conditions. This information is used to influence drivers to choose routes which will be not only be beneficial to them individually, but also to the system. If these systems are not designed with care, then their presence might lead to distraction from the driving task. This might lead to an increase in the number of accidents, especially under high demand conditions. The experiments conducted in this study attempted to address this problem.

The main objective of this study is find out how the characteristics of route guidance systems affect the safety and efficiency of the driving task. Specifically, this study seeks to understand how drivers react to relatively complex route guidance systems under increased driving demand conditions. The results of the study will help in identifying the advantages and disadvantages of different types of route guidance systems.

The study was conducted using a driving simulator that has been developed by the Hughes Aircraft Corporation. The simulator is a fixed base simulator equipped with three screens which result in a total field of view of 170 degrees. Computer generated images, such as roadway segments, traffic control devices, roadway traffic, etc. are projected on the screens. The movement of these objects is synchronized with the vehicle movement generated by the driver as in a typical car. More details about the driving simulator can be found in a recent report.(1)

The focus of the experiments were on route following using four different route guidance systems. Subjects were asked to drive from an origin to a destination using a pre-determined route. A "within subject" experimental design was adopted, i.e., each subject who participated in the study drove with all the four route guidance systems.

EXPERIMENTAL DESIGN

The independent variables used in this study can be divided into three categories: type of route guidance system, driving environment and subject characteristics. Dependent variables include measures of safety (reaction time to external events), navigational performance (number of navigational errors), device perceptions and workload.

Driving Environment

The basic study area was a 2 mile x 2 mile section of Los Angeles. Each trial that a subject performed corresponded to a different route in the network. In addition, each trial had a different set of street names.

The network consisted of three types of roadway segments. They were: (i) Parkways -- 4-lane divided with 12 feet lanes and 55 mph speed limit, and limited access. (ii) 4 lane urban undivided arterials -- 12-feet lanes and 40 mph speed limits. (iii) 2 lane urban undivided roads -- 10-feet lanes and 30 mph speed limits. Each intersection in the network was controlled either by a traffic signal or a stop sign for the minor road.

Each trial had five types of external events that the subjects encountered. These events were introduced to study the reaction times of subjects to unanticipated events. They were: (i) pedestrians crossing the road (ii) crossing vehicles crossing the driver's path at intersections (iii) left turning vehicles turning in front of the driver (iv) change of signal from green to amber (v) obstacles appearing in the parkway. The events were designed in such a way that the subjects had to react to them as long as they were traveling near the speed limit.

Route Guidance Devices

Four route guidance systems were tested. They are described in the following paragraphs.

Heads Down Electronic Map

The electronic map was a 6 inch x 6 inch liquid crystal display located in the instrument panel to the right of the driver. The streets in the electronic map were shown in green and the route to be followed by the driver was shown in red. The thickness of the lines (showing the streets) depended on the roadway type: parkways thickest; 4 lane urban roads less thick; and, 2 lane urban roads the thinnest. The top of the electronic map showed the distance to the destination and the distance to the turn. The position of the vehicle was shown by an arrow head which was used to track the driver' s position along the route. The destination was indicated by a star. The map was configured to display direction up, that is, when the driver made a turn, the map rotated to preserve the vehicle up configuration.

Before the beginning of the trip, the driver was shown the complete network (the electronic map was in full scale), and the route to follow to reach the destination. After the driver started to drive, the electronic map was changed to half a mile scale, showing the area in the immediate vicinity of the driver (Figure 1). The driver was not given any option to go back to the full scale map once he/she started driving.

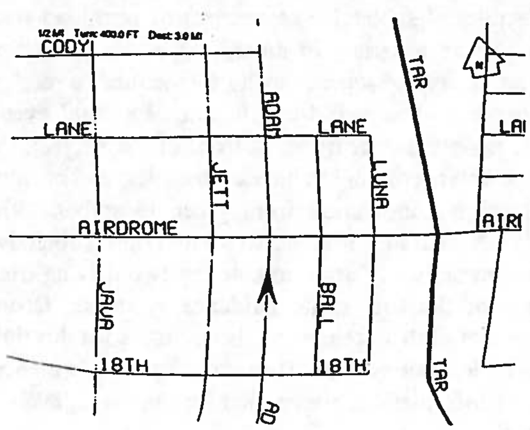

Figure 1. Electronic Map (Half-Mile Scale)

Heads Up Guidance Screen (HUD) with Heads Down Electronic Map

The guidance screen (Figure 2) consisted of a vertical line which indicated the street upon which the driver is traveling, and a horizontal line which indicated the street onto which the driver had to make a turn and the direction of turn. The arrow at the top showed whether the driver had to make a left or right turn and the distance to the decision point (shown in miles till the driver is 500 feet from the intersection after which it is shown in feet). The bottom of the display showed the distance to the destination. The left side of the display showed the speed of the vehicle.

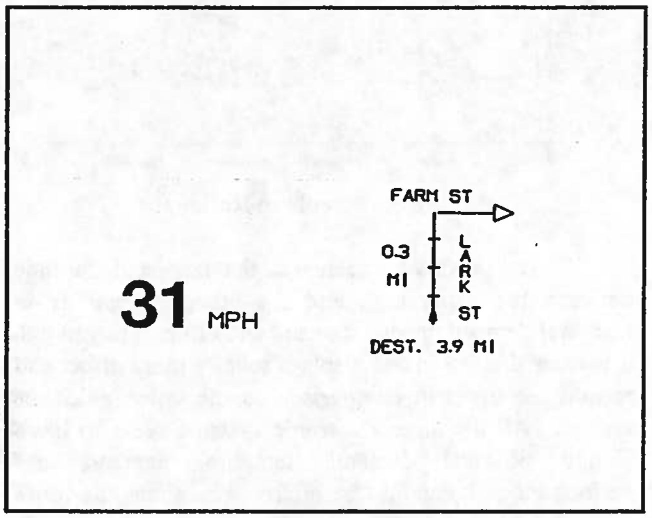

Figure 2. Heads Up Display

The horizontal bars on the vertical line also indicates the distance to the decision point. The distance between two consecutive bars represents 25 percent of the distance between the decision point and the previous turn. Each of these bars disappear after the driver crosses that particular point on the roadway.

The guidance screen was projected directly in front of the driver just above the hood line at approximately eight feet from the driver (heads up). This heads up guidance screen was used in combination with the heads down electronic map.

Audio Guidance System with Heads Down Electronic Map

A pre-recorded female's voice was used for guidance information. Two messages were provided for each turn. The distance from the decision point at which the first message was given, depended on the type of road: on parkways, at 1,200 feet; on 4-lane urban roads, at 700 feet; and, on 2-lane roads, at 400 ft before the turn. These distances were based on estimates of the time taken to perceive and react to the messages. The second message (in all the three types of roads) was given just before the turn. An example of an audio message is:

"IN 400 FEET, TURN RIGHT ONTO ZUMA"

The audio guidance system was used in combination with the heads down electronic map.

Paper Map

The basic design of the paper map was similar to that of the full scale electronic map, with the obvious difference being that the position of the driver was not tracked. The size of the paper map was 11" x 17".

Dependent Variables

A variety of performance measures were collected during the study. They were:

i) Number of Navigation Errors: Defined as the number of times the subject deviated from the intended route either by making a wrong turn or by missing a turn.

ii) Reaction Times: Reaction times to external events in the simulator (e.g., pedestrians, crossing vehicles, change in traffic signal) were recorded whenever an event occurred in the simulator.

iii) Workload: The NASA TLX subjective workload test[2] was used to obtain to ratings on workload. This test assumes workload to be a function of six factors, namely: Mental Demand, Physical Demand, Temporal Demand, Performance, Frustration Level and Effort. The first step in this method involved rating each route guidance system on these dimensions on a scale of 0 to 100. The second step involved a weighting procedure which consisted of assigning weights to the different dimensions based on their importance to the route following task.

iv) Perception Ratings: After completing trials with each route guidance system, subjects were asked to rate the devices on a scale of 1 to 5 for the following attributes: clarity of information, quantity of information, preparation for turns and distraction from the driving task.

Subjects

Subjects were recruited by a market research firm to satisfy experimental and subject adequacy criteria. Subjects with prior experience with motion sickness, individuals wearing bifocal lenses (due to difficulties in eye tracking), and older subjects (age greater than 40) were screened out due to an increased propensity for motion sickness in the simulator. The sample that was recruited was restricted between the ages of 30 and 40. Eighteen subjects completed the experiments. There were an equal number of males and females. Half of the subjects were in the high experience group (driving more than 1,5000 miles a year) and half were in the low experience group (driving less than 12,000 miles a year).

Experimental Procedure

The experimental procedure included the following steps:

Step 1: The subjects were asked to complete an informed consent form which gave a description of the study, the risks associated with it and how the subjects would be compensated if they drop out of the study before completing all the trials. The subjects completed a pre-test questionnaire followed by the subjective workload test.

Step 2: Subjects were trained in using the simulator.[1,3] This session determined if the subjects were comfortable enough to continue the study. Subjects not comfortable in driving the simulator were simply excused from the rest of the study.

Step 3: Simulator experiments: Each subject drove two trials with each of the route guidance systems, the order of presentation being counter-balanced across subjects. After completing two trials, the subjects filled out ratings for the subjective workload test and answered questions regarding their perceptions of the devices.[1,3]

Step 4: After completing all the trials of the experiment, the subjects were asked to fill out additional subjective questionnaires concerning preferences and ease of use.

ANALYSIS AND RESULTS

A variety of statistical techniques were used to analyze the experimental data. The following paragraphs describe the analysis procedure and the results that were obtained.

Workload

Figure 3 is a plot between workload rating and workload dimension for all the four route guidance systems. This plot was obtained by taking an average of the workload load ratings over all the 18 subjects. It is very clear from the plot that the paper map is associated with the highest workload in all the six dimensions. The voice guidance/electronic map combination, has the lowest workload rating in all the dimensions except in the case of frustration level for which the electronic map has slightly lower (some of the subjects commented that although the voice guidance system is easy to use, it is annoying, and that they would like to have the option of shutting it off). The heads up display/electronic map combination was associated with higher workload in comparison with the electronic map.

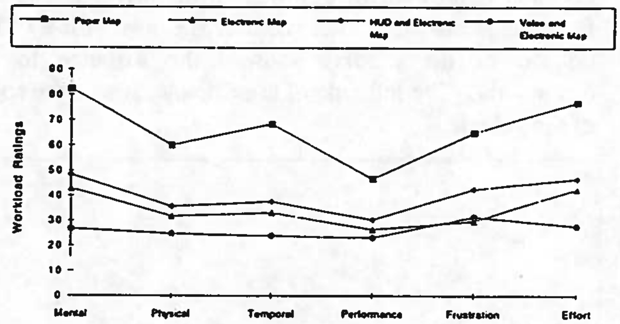

Figure 3. Workload Ratings

It can also be seen that the largest difference between the paper map and the other systems is in temporal demand, mental demand and effort. In general, it is clear that the visual displays require more effort and mental resources in comparison to the voice guidance system. All the three electronic systems seem to have similar physical demand, temporal demand and performance. It can also be inferred that since, the route following task requires less physical resources in comparison to mental and cognitive resources, the differences between the systems in the physical component of the workload is smaller than in the other components. The difference between the heads up display/electronic map combination and the voice guidance/electronic map combination is smallest in the case of performance, even though the heads up display/electronic map combination has higher workload on mental and effort dimensions.

In order to test for the differences between the route guidance systems statistically, linear regression models were developed for each of the six dimensions and for *weighted workload* as the dependent variable.[1,3] The results from the regression models confirmed the qualitative observations based on the figure.

The difference between the paper map and the voice guidance/electronic map combination was statistically significant (p value less than 0.10), for all the dimensions except performance. The difference between the paper map and the electronic map was statistically significant for all dimensions except performance and physical component. The difference between the paper map and the heads up display/electronic map combination was significant for mental component, and marginal for temporal demand, frustration level and effort (p values between 0.10 and 0.20). Other comparisons yielded insignificant results.

The model developed for the weighted workload indicated the voice guidance/electronic map combination and the electronic map to be associated with significantly lower workload in comparison with the paper map (p values are 0.01 and 0.08), and the heads up display/electronic map combination and the paper map to have a marginal difference (p value = 0.16). Comparisons were also made between the three electronic map systems. The difference between voice guidance/electronic map combination and heads up display/electronic map combination was significant (p value = 0.05). The other comparisons did not yield any significant results.

Perception Ratings

The average ratings (over 18 subjects) for 5 system attributes have been shown in Figure 4. In this figure, a low value represents better performance and a high value represents worse performance. In the plot for "Quantity of Information," a value of 5 represents too much information and a value of 1 represents too little information. The figure clearly indicates that the paper map has the worst rating among all the four systems. The voice guidance/electronic map combination has the best ratings except in the case of "preparation for turns" where the electronic map seems to be slightly better.

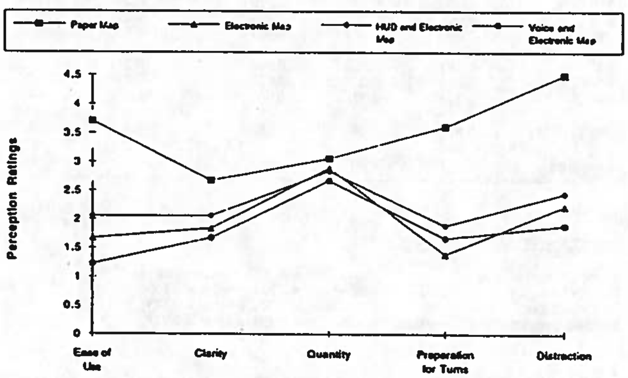

Figure 4. Perception Ratings

Number of Navigation Errors

Figure 5 shows a plot between the number of navigation errors per trial and the type of route guidance system. It can be seen that the paper map was associated with the largest number of navigation errors and the voice guidance/electronic map combination, was associated with the least number or errors. A logistic regression model was developed in order to test the statistical significance of the differences between the systems. In the development of the logistic regression model, the dependent variable was coded as 1, if the number of errors in that particular trial was 1 or greater, and was coded as 0, otherwise. The results from the statistical models confirmed the observations made based on the figure. The paper map had significantly more errors per trial than the voice/electronic map combination and the electronic map alone option (p values < 0.10). However, the differences between the heads up display/electronic map combination and the paper map were not significant (p = 0.24).

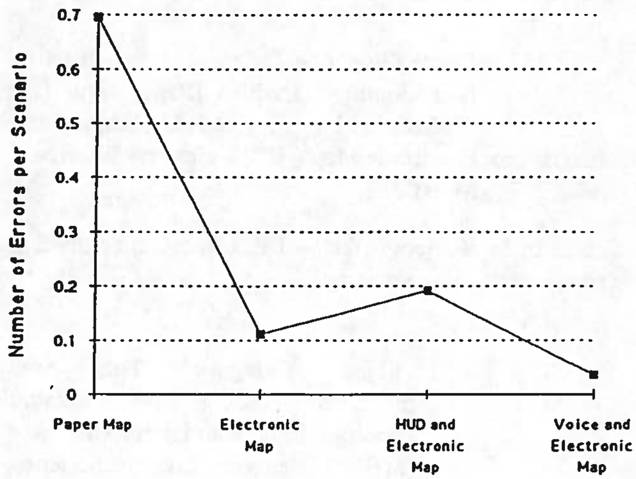

Figure 5. Number of Navigation Errors

Reaction Times

The first step in the analysis of the reaction time data was to select valid reaction times that could be used for developing the statistical models. This step was necessary in order to eliminate/reduce the consideration of reaction times that were obtained when there was a suspicion that the driver had already anticipated the occurrence of the events. After a lot of deliberation, it was decided to use the brake reaction times as reaction time data. Only those events which occurred with a foot on the accelerator were considered.

The analysis was conducted by considering each traffic event separately (see categories in Table 1). Originally, there was a plan to combine the reaction time data from the different events and analyze them as one set. Differences in the mean and variances of reaction times led to a decision to analyze the events separately.

Type of Event	Mean	Standard Deviation	Number of usable observations
Pedestrians	1.159	0.685	248
Crossing Vehicles	1.753	0.647	136
Turning Vehicles	3.626	0.680	103
Traffic Signal Events	1.996	1.001	109
Obstacles	1.334	0.772	108

Table 1. Mean and Variance of the Reaction Times to Different Types of External Events

Modeling of pedestrian and obstacle events appear to have been anticipated by some subjects, leading to significant period effects in the models.[1] Models for traffic signal, crossing and turning vehicle events are the clearest and most consistent, so they are reported here.

Analysis Procedure

Independent Variables: The following independent variables were considered:

a) Route Guidance Type: Represented using four dummy variables [Paper Map (P), Electronic Map (E), Heads Up Display and Electronic Map (HE), Voice and Electronic Map (VE)].

b) Subject Effect -- This effect can be divided into two parts:

   (i) Subject Category: This was represented using four dummy variables; Male with High Experience (MH), Male with Low Experience (ML), Female with Low Experience (FL) and Female with High Experience (FH).

   (ii) The random effect of the subject within each of the four subject categories (denoted by Subj(Cat)). This variable accounts for individual differences in driving style between the different subjects, within the subject categories.

c) Period Effect -- This factor is included to indicate when exactly a particular route guidance system was tested for each of the subjects. This effect represents a combination of effects such as, fatigue and practice (or getting used) in the simulator. Four dummy variables were included: [P1 -- period 1, P2 -- period 2, P3 -- period 3, P4 -- period 4].

Statistical Procedure: A mixed ANOVA model was estimated using the 3V procedure in the BMDP statistical procedure. The assumptions of the ANOVA procedure were tested by plotting the residuals against the predicted value of the reaction time and also the independent variables. If the residual plots showed any evidence of violation of the assumptions of the ANOVA procedure, then a Box-Cox power transformation[4] was applied to the dependent variable and the model was re-estimated.

Results

Crossing Vehicle Events: Table 2 shows the results of the ANOVA modeling. Route guidance type is highly significant (p value = 0.018). Subject category and period effects are also marginally significant (p values are 0.150 and 0.125, respectively). The dependent variable in this case is equal to (reaction time)$^{-0.75}$, hence, a relatively low parameter estimate implies longer reaction times, a high estimate shorter reaction times. Statistical comparisons were made between the parameter estimates. The table clearly indicates that there is hardly any difference between the parameter estimates of the paper map (base case), voice guidance/electronic map combination (VE), and the heads up display/electronic map combination (HE) (p values are 0.973 and 0.851). However, the electronic map (E) is associated with significantly shorter reaction time compared to the other three systems. In fact, the difference between the electronic map and the paper map was highly significant (p value = 0.005).

Dependent Variable = (Reaction Time)$^{-0.75}$

PARAMETER#	ESTIMATE	STANDARD ERROR	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
E	0.099	0.036	2.780	0.005
HE	-0.001	0.036	-0.034	0.973
VE	-0.007	0.037	-0.188	0.851
MH	0.090	0.046	1.976	0.048
ML	0.085	0.043	1.947	0.052
FH	0.090	0.047	1.909	0.056
P2	0.033	0.035	0.942	0.346
P3	0.089	0.037	2.397	0.017
P4	0.037	0.038	0.962	0.336
CONSTANT	0.578	0.045	12.916	0.000
Subj(Cat)	0.001	0.001		

RESULTS OF CHISQUARE TEST

Route Guidance Type	(Chi square = 10.068, p value = 0.018)
Subject Category	(Chi square = 5.321, p value = 0.150)
Period Effects	(Chi square = 5.743, p value = 0.125)
Random Subject Effect (Subj(Cat))	(Chi square = 1.459, p value = 0.227)

\#
E, HE and VE represent dummy variables corresponding to the 3 electronic devices. Paper map taken as base case.
MH, ML, FH are dummy variables for 3 subject categories. Female with low experience (FL) is taken as the base case.
P2, P3, and P4 correspond to dummy variables for the periods 2, 3, and 4 respectively. Period 1 (P1) is taken as the base case.

Table 2. ANOVA Model for Reaction Times to Crossing Vehicles

Comparisons between the different subject categories indicated hardly any difference between the parameter estimates of high experience males (MH), high experience females (FH) and low experience males (ML). Low experience females (FL) were associated with significantly longer reaction times in comparison to the other 3 groups (p values are 0.048, 0.052 and 0.056).

Turning Vehicle Events: Table 3 presents the results of the ANOVA modeling for turning vehicle events. It is clear that route guidance type and subject category are significant (p values are 0.104 and 0.100, respectively). The dependent variable in this case is (reaction time).[2] Hence, a relatively high parameter estimate implies longer reaction times and a relatively low parameter estimate implies shorter reaction times. The heads up display/electronic map combination (HE) is associated with the shortest reaction time. However, the difference between the heads up display/electronic map combination and paper map (P) was marginal (p value = 0.19). Other comparisons did not yield significant effects.

Dependent Variable = $(\text{Reaction Time})^2$

PARAMETER#	ESTIMATE	STANDARD ERROR	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
E	-0.889	1.210	-0.734	0.463
HE	-1.760	1.342	-1.312	0.190
VE	1.142	1.190	0.959	0.337
MH	-2.848	1.271	-2.241	0.025
ML	-2.661	1.223	-2.176	0.030
FH	1.561	1.190	-1.311	0.190
P2	0.112	1.173	0.095	0.924
P3	0.700	1.187	0.590	0.555
P4	0.058	1.373	0.042	0.966
CONSTANT	15.269	1.255	12.170	0.000
Subj(Cat)	0.000	0.000		

RESULTS OF CHISQUARE TEST

Route Guidance Type	(Chi square = 6.171, p value = 0.104)
Subject Category	(Chi square = 6.248, p value = 0.100)
Period Effects	(Chi square = 0.461, p value = 0.927)
Random Subject Effect (Subj(Cat))	(Chi square = 0.000, p value = 0.997)

#
E, HE and VE represent dummy variables corresponding to the 3 electronic devices. Paper map taken as base case.
MH, ML, FH are dummy variables for 3 subject categories. Female with low experience (FL) is taken as the base case.
P2, P3, and P4 correspond to dummy variables for the periods 2, 3, and 4 respectively. Period 1 (P1) is taken as the base case.

Table 3. ANOVA Model for Reaction Times to Turning Vehicles

The comparison between the parameter estimates of the different subject categories indicated that high experience males (MH) have the shortest reaction times and low experience females (FL) have the longest reaction times. The difference between low experience females and the male groups was highly significant (p value less than 0.03). High experience females (FH) have shorter reaction times than low experience females (base case) but longer reaction times than low experience males (ML). The difference between high experience and low experience females is marginal (p value = 0.19). However, the difference between high experience males and high experience females is not very significant (p value = 0.327).

Traffic Signal Events: Table 4 presents the results of the ANOVA modeling for traffic signal events. The chi-square tests indicated that, only the route guidance type is significant (p value = 0.111). Hence, further analysis was conducted only on this factor.

Dependent Variable = $(\text{Reaction Time})^{-0.25}$

PARAMETER#	ESTIMATE	STANDARD ERROR	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
E	0.040	0.028	1.439	0.150
HE	0.065	0.029	2.230	0.026
VE	0.061	0.029	2.108	0.035
MH	0.031	0.031	1.003	0.316
ML	0.012	0.028	0.435	0.664
FH	-0.014	0.032	-0.420	0.674
P2	-0.004	0.027	-0.141	0.888
P3	-0.031	0.026	-1.201	0.230
P4	-0.020	0.030	-0.671	0.502
CONSTANT	0.836	0.033	25.674	0.000
Subj(Cat)	0.000	0.001		

RESULTS OF CHISQUARE TEST

Route Guidance Type	(Chi square = 6.008, p value = 0.111)
Subject Category	(Chi square = 1.[illegible]2, p value = 0.614)
Period Effects	(Chi square = 1.702, p value = 0.636)
Random Subject Effect (Subj(Cat))	(Chi square = 0.1[illegible]8, p value = 0.665)

#
E, HE and VE represent dummy variables corresponding to the 3 electronic devices. Paper map taken as base case.
MH, ML, FH are dummy variables for 3 subject categories. Female with low experience (FL) is taken as the base case.
P2, P3, and P4 correspond to dummy variables for the periods 2, 3, and 4 respectively. Period 1 (P1) is taken as the base case.

Table 4. ANOVA Model for Reaction Times to Traffic Signal Events

The dependent variable in this case is equal to $(\text{reaction time})^{-0.25}$, hence, a relatively low or negative parameter estimate implies longer reaction times and a relatively high or positive parameter estimate implies shorter reaction times. The parameter estimates indicate that the heads up display/electronic map combination (HE) and the voice guidance/electronic map combination (VE), have the shortest reaction time, whereas, the paper map (base case) has the longest reaction time. The differences were found to be statistically significant (p values are 0.026 and 0.035). The electronic map also (E) has shorter reaction times compared to the paper map but the difference is only marginal (p value = 0.15). Other comparisons did not yield significant results.

Summary of Results from the Reaction Time Models

The models indicate that the paper map is associated with the longest reaction times. However, it is not very clear which system is associated with the shortest reaction times. In the case of crossing vehicles, the electronic map comes out the best. In the case of turning vehicles, the heads up display/electronic map combination comes out the best. In the case of traffic signal events, the heads up display/electronic map combination and the voice guidance/electronic map combination come out the best. With respect to subject category, it is clear, that more experienced drivers are associated with shorter reaction times. This effect is more pronounced in the case of females than males.

CONCLUSIONS

The analysis has clearly demonstrated the inferiority of the paper map in comparison to the other systems. However, at the same time, there is no clear consensus on which is most superior to the paper map among the three systems considered.

The results from workload, user perceptions and number of errors are quite consistent. In general, analysis of these performance measures indicated the voice guidance/electronic map combination to be the best, and the paper map to be the worst. The electronic map was found to be the second best. Surprisingly, the heads up display/electronic map combination, performed worse than the electronic map, in the case of workload.

The poor performance of the heads up display/electronic map combination (relative to the electronic map) could be due to different reasons. One possible reason for this could be the way this HUD was designed. Comments given by the subjects on the different route guidance systems clearly revealed problems with two aspects of the HUD. The count down bars indicated 25 percent of the distance between the decision point and the previous turn. This variable distance between bars was confusing for some. Secondly, the top of the cursor in the heads up display, was a fraction of an inch below the actual location of the intersection in the HUD. This turned out to be irritating for some. Follow up studies using a different HUD design have yielded more favorable results.[5]

The results of the reaction time modeling are not completely consistent. The Heads up display/electronic map combination performs much better than with other performance measures, but the voice device also does well. In general, the paper map is the worst even in the reaction time data. The analysis of the subject effects indicated that drivers with higher experience perform better than drivers with lower experience. This effect was more prominent among females than males.

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