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Driving Simulator for Head-Up Display Evaluation: Driver's Response Time on Accident Simulation Cases

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Abstract

This paper introduces a novel automotive full-windshield Head-Up Display (HUD) interface, which aims to improve drivers' spatial awareness and response times under low visibility conditions. To evaluate the effectiveness of the proposed HUD system, a multidiscipline and multinational team of researchers built the driving simulator presented further on. Due to time and cost constraints, this simulator was assembled from off-the-shelf components and was based on an open-source code. This paper will discuss the HUD function, present the challenging construction process of the simulator and provide an analytical overview of the two accident scenarios. The evaluation outcomes of forty user tests conducted using this custom-built driving simulator will be demonstrated and the conclusions of this study will be discussed.

1. INTRODUCTION

The automotive industry, for many years, has been investigating systems that could increase drivers' spatial awareness and decrease their response times. Concentrated efforts have attempted to enrich the functionality of the contemporary instrument panels by integrating visual and audio warning cues (1). A particular area of increasing research interest has been the design and use of visual cues that could be superimposed on the vehicle's windshield, creating an automotive Head-Up Display (HUD) system. By adhering to the industry standards, we developed a driving simulator, which could be exploited as a test-bed simulation system for various HUD interfaces.

Subsequent discussion in this paper describes the issues surrounding the decision to implement the proposed driving simulator and outlines the research findings derived from user tests. The experimental trials have aimed to evaluate the effectiveness of the visual cues and quantify their usefulness in terms of response times and overall driving stability as mentioned in previous studies (2). Accident scenarios have been researched thoroughly and re-enacted according to guidance information and statistics provided by the traffic police department.

The successive section offers a rationale justifying the development of a prototype full-windshield HUD interface. The driving scenarios used in this study are presented in detail, and the decision to opt for an open-source code rather than an already existing driving simulator is discussed. An analytical account of the simulator's individual elements is offered, along with an explanatory presentation regarding the development process of the open-source software and hardware. Further on, the paper provides a description of the simulation methodology, as used in the experimental testing of the system, as well as an overview of the evaluation outcomes. In the final section, we present our conclusions and a tentative plan for future work.

2. HEAD-UP DISPLAY INTERFACE

Previous research (3) has suggested that driving is principally a visual task; thus, several research efforts have concentrated on exploiting visual signals to pass on useful information to the driver (4,5), although other (auditory and haptic) avenues have also been explored (1). The advantages of HUD systems compared to Head-Down Displays (HDDs) for such purposes have been well documented in the literature (6-8). To prevent from causing distraction, the majority of existing HUD designs fall into the small projection category, which means that they utilise only a small section of the vehicle's windshield and are usually well within the driver's central field of view. When an excessive amount of information is channelled via this method, occasionally drivers may fail to distinguish between the virtual visuals and the real-life environment. Hence, depending on the situation, only the fundamental and relevant information should be presented to avoid visual cluttering and distraction (2).

In this design, we have opted for a full-windshield HUD, which utilises a large section of the area viewed by the driver, as opposed to the small projection form described above. Our motivation for this decision stems from research in (7,8), where the full-windscreen form has been demonstrated to be a valid alternative to small HUDs with advantageous performance outcomes compared to classic HDD instrumentation. Taking into account the nature of the projected information of this prototype HUD, it was deemed more suitable to use the full windshield area.

The proposed interface intends to enhance human reactions during driving in low visibility conditions in a motorway environment. After analysis of statistics regarding accident data, four pieces of information were initially identified as the most vital for collision avoidance in motorways: lane recognition, lead vehicle detection, traffic warning and sharp turn notification. The lane recognition utility has a dual function since it can act as a lane departure warning as well as a side collision warning. These utilities have been visually represented in the HUD design by four colour-coded symbols. The symbols appear in context in Figure 1.

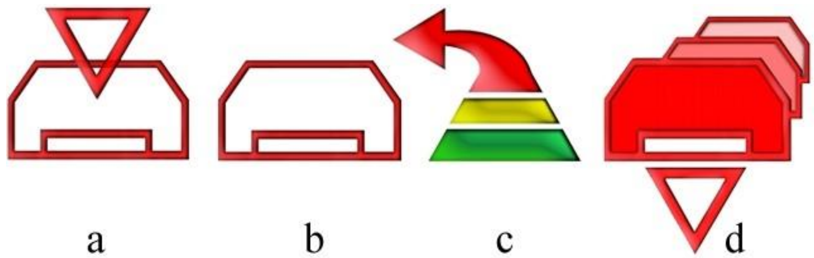

FIGURE 1: Symbols used in the full-windshield HUD.
Key: (a) lead vehicle on the same lane (b) lead vehicle on a different lane (c) traffic congestion in close proximity (d) road turn in close proximity.

3. ACCIDENT SCENARIOS

Prior to constructing the simulator, a significant decision had to be taken regarding the most appropriate driving scenario, given that the primary aim of this study was to evaluate the proposed HUD interface. The car-following scenario was considered to be the most suitable for the experiment. Applying this scenario on a driving simulator offered the ability to control the driver's behaviour, especially with regard to the preceding vehicle in the same lane. The user's vehicle could be considered as following when it is constrained by a preceding vehicle. By positioning the preceding vehicles deliberately in all three lanes, we could hinder the user and create possible accident events.

A number of car-following scenarios had been discussed in detail with experienced traffic police officers (Strathclyde Police Department). In particular, motorway driving under low visibility conditions is a scenario that generates a substantial number of accidents. These circumstances are the cause of approximately 3.500 accidents per year within the Strathclyde region alone and more than 196.000 in Britain (9). The scenarios considered as the most accident-prone are: (a) sudden braking of the lead vehicle and (b) traffic congestion formed behind obstacles such as blind spots, bridges, buildings, trees and sharp turns. Both accident scenarios presented below have been tested in low visibility conditions, with and without the HUD interface.

Accident Scenario 1
The first scenario was a variation of the main car-following model. As the user was driving along the motorway, the lead vehicles were suddenly braking creating a chain reaction of rapidly decelerating vehicles. As anticipated, this event increased substantially the chances of a vehicle collision. The user was forced to respond instantly, by either manoeuvring around the accident

area or by braking. The scenario was programmed to minimise the possibility of accident avoidance since we were particularly interested in measuring drivers' reaction times and distance from the lead vehicle.

Accident Scenario 2

The second event was also based on the car-following concept. Initially, the user had to drive for 5km following the lead vehicles' group, without any major events. After the 5km, the motorway formed a junction with bridges obscuring the driver's field of view. Underneath the bridges, the motorway led to a sharp turn (120 degrees). To increase the difficulty of the simulation, very slow-moving traffic congestion was positioned at the exit of the turn (5,8). In the second accident scenario, we utilised the traffic symbol and the sharp turn warning.

4. OPEN SOURCE DRIVING SIMULATOR

In the last years, driving simulators are an affordable solution for industry and academic research and evaluation. Nevertheless, the cost of acquiring, supporting and servicing such equipment is forbidding for most academic institutions. Frequently, to conduct an evaluation experiment on an automotive topic, academic researchers have to rent the facilities of traffic research centres or automotive industry studios. These specialised driving simulators provide the ideal environment for testing various automotive systems and devices (10).
However, in some cases, financial limitations may require an alternative solution. In particular, the proposed HUD is part of doctoral research, consequently, funding, dedicated to equipment, was inefficient to cover the expenses of a professional driving simulator. Thus, the most cost-efficient and flexible solution was to construct a custom-made driving simulator by purchasing off the shelf components and developing the code on The Open-Source Racing Car Simulator (TORCS) software. The idea of a custom driving simulator project was the initiative that brought together a multidiscipline group of researchers from different Scottish and other European universities. A screenshot of the simulator in action is shown in Figure 2.

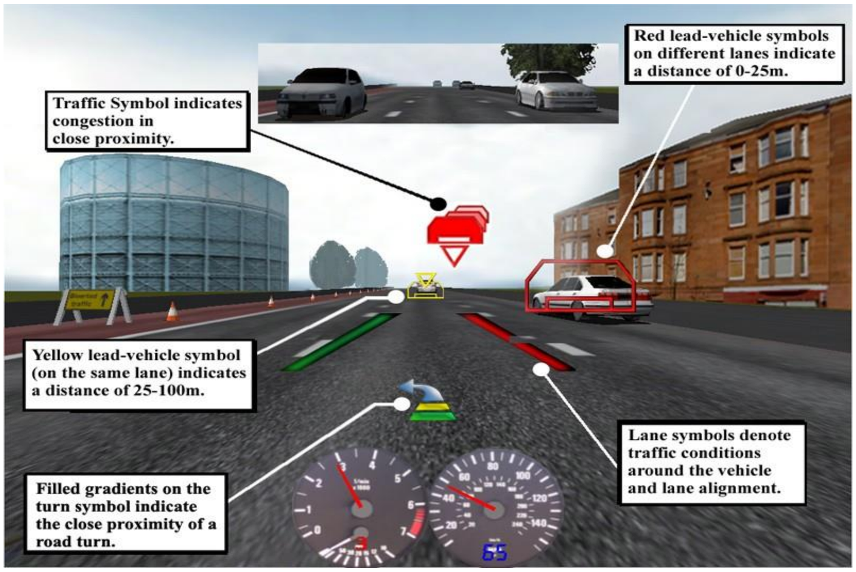

FIGURE 2: Screenshot of the driving simulator with the HUD interface.

a. Accident Pre-Programming and Randomness

As mentioned previously, two scenarios were analysed thoroughly, designed and tested. To create such events, vehicles with predetermined behaviour (robot vehicles) had to be added to the track along with the testing vehicle. Since the initial open-source programme had been designed for racing purposes only, a part of the code had to be re-compiled to embed the robot vehicles in the traffic flow. Initially, the racing vehicles were utilising the full width of the road, as lane-keeping restraints are not applicable in a racing environment. Therefore, the behaviour of 20 robot vehicles had to be pre-programmed according to the Highway Code.

For the implementation of the first scenario (sudden braking of the lead vehicles), the robot vehicles had been divided into 3 groups which we named "traffic waves". The purpose of these groups was to replicate the real-life traffic flow on motorways. Apart from enhancing realism, these waves were intentionally constraining the participants from exceeding the speed limit and consequently implicating them in a car following accident events (11). At the beginning of the simulation, the user's car was positioned amongst the third wave of vehicles. Having two waves of vehicles driving in front ensures that the driver would be accompanied at all times during the simulation thus augmenting the sense of realism. At a predetermined point of the road, the leading vehicles of the second wave were scheduled to rapidly brake, causing the accident scenario 1. The succeeding vehicles were responding randomly to this event either by braking on time or by colliding with the preceding vehicles. Due to low visibility conditions, the driver had little time to decide what action to perform, for instance, harsh braking or manoeuvring around the stopped vehicles by using the hard shoulder lane. If a collision with the second wave had been circumvented, the first wave of vehicles was repeating the scenario, 300 meters ahead, hence minimising the possibilities of avoiding accident involvement.

For the second scenario, the traffic formation had been divided into two groups; the accompanying group and the congestion group. The accompanying vehicles followed similar patterns as in scenario 1. The congestion group had been allocated virtually motionless in an area after a sharp left turn, under a complex of bridges. Early identification of the sharp turn and traffic congestion, especially under low visibility, was proven to be a difficult task.

The comparative study between HUD and HDD demonstrated that the integration of the HUD system had substantially enhanced drivers' reactions by providing them useful information about the surrounding vehicles and possible traffic congestions. Apart from improving their response times, the HUD also increased their confidence and lowered their stress level.

b. Simulation of Low Visibility Conditions

Given that the primary aim of the study was to measure and compare drivers' reaction times in contrary weather conditions, such conditions had to be replicated accordingly. As in other work (12), zero visibility conditions are defined here when objects come into clear view in less than 100m distance. Similarly, low visibility conditions, are set at below the 250m viewing distance mark. Heavy fog, of 5% visibility, was assimilated in four of the driving simulations. The visibility percentage could be adjusted through the initial software, achieving a satisfactory fog quality. Furthermore, specific parts of the code had been improved to simulate the desired fog conditions and realistic depth of field. Time limitations strained the further development of the fog visualisation, which we consider as an area for future experimentation.

c. 3D Visualisation

For validity purposes, the testing track was designed and modelled based on a section of the M8 motorway outside Glasgow, Scotland as depicted in Figure 3. The simulation model has been delimited to deal only with motorways with three lanes in each direction and one hard-shoulder lane. To reduce the amount of 3D geometry, the track had been simplified to only one direction, in this case, the route from Glasgow to Edinburgh.

A closed-circuit was created by connecting seamlessly three main motorways thus forming a triangular track shape. This model does not incorporate ramps on motorways or intersections on rural roads. A 3D visualisation of the important intersections and most recognisable landmarks was incorporated in the final model. Such visual cues improved sufficiently drivers' familiarisation with the environment. To populate the track, the twenty most popular vehicles, as seen on British roads, had been modelled in low polygons geometry (gaming quality).

Although the original programme offered a wide choice of vehicles, the majority of them were inappropriate for this experiment as they were mostly racing cars. The 3D objects and track had been modelled with Alias Maya 6.5 and imported into the simulator, after a distilling process of exports in various formats using Track Editor and AC3D software. Additional alterations to the XML code were needed to allow compatibility with the Windows XP environment.

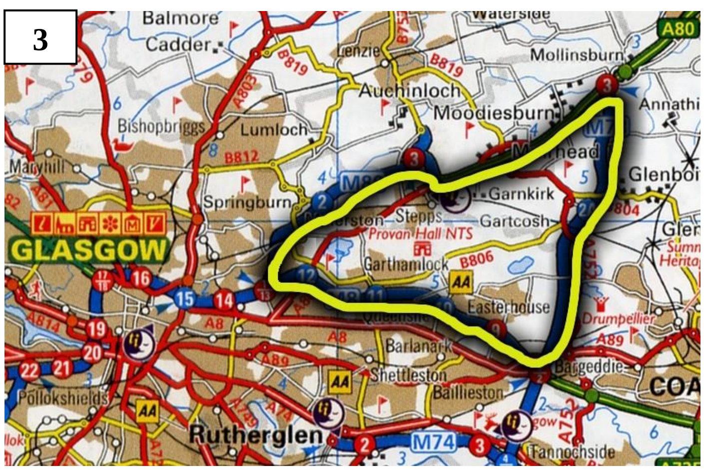

FIGURE 3: Simulation track based on real motorway routes.
FIGURE 4: Driving simulator set-up.

d. Equipment

This section of the paper describes the off-the-shelf hardware acquired for constructing the simulator. The acquisition of the components had been carefully thought through to accomplish cost-efficiency, effectiveness and portability. The system set-up involved a driver's seat with a metallic frame, which was hosting the steering wheel, gear stick and pedals as depicted in Figure

4. A custom PC was built based on dual processors (AMD Opteron-242) and a Quadro FX1100 graphics card. The computer was running the simulation with a frame rate of 60-90 fps. Even though the simulator could efficiently perform on a low specification laptop, this powerful dual-processor system was built with the view to accommodate simultaneously more than one driver for future experiments.

Since the driving simulator was accommodated at the E-motion Lab of Glasgow Caledonian University, the custom PC had been connected to other additional equipment. Sophisticated devices such as the Tobii x50 Eye tracking system and a pulse-measuring system were recording the driver's eye fixations and stress level respectively. Two high-definition cameras were providing real-time streaming video to the control room capturing both user and screen.

5. METHODOLOGY

a. Subjects

To evaluate the effectiveness of the proposed HUD system, we performed trials using participants of varying driving experiences. Forty licensed drivers representing both genders and three age groups (18-30, 30-50, 50 or above) were recruited through personal contacts and user databases.

b. Procedure

Before the test, every participant was handed documentation describing the test and one experimenter provided a brief explanation of the driving simulator system. Users were instructed to drive, as they would normally do under these conditions, respecting the speed limits. Every participant drove six different simulations.

The first two involved driving under light traffic and clear weather conditions to enable the users to familiarise themselves with the simulator and the controls. During these two laps, the participants had the opportunity to drive for approximately 10-15 minutes, covering more than 25km, depending on their speed. The following two driving scenarios (accident scenarios 1 and 2) were driven under low visibility conditions without the HUD. Dense fog conditions were simulated restricting visibility to below 50m (zero visibility). These two scenarios were repeated with the HUD under the same weather conditions. After the conclusion of all 6 trials, participants were completing a post-test questionnaire concerning the HUD interface and the driving simulator experience. A short informal discussion provided additional information regarding possible issues, comments and suggestions for further development.

6. EVALUATION RESULTS

The metrics used in assessing the system's effectiveness were reaction time and error occurrences. In particular, the driver was faced with several challenging situations per trial in which the proper response would be to break or change lanes. The reaction time was defined as the time difference between the appearance of the event and the driver's response to it (either breaking or changing lanes as appropriate). If the driver's failure to take action resulted in a (mild or otherwise,) collision, a driver's error event was recorded. Data about the driver’s speed, lane position, elapsed time and distance from the front vehicle were recorded every 0.05 seconds.

Although the evaluation of the experiment is ongoing, early analysis of the collected data indicates that the proposed HUD design significantly reduces the chances of an accident in the presence of perfect information (the simulation system did not at the time entertain the possibility of false-positive indication), as shown in Figure 5. In particular, the average response time with the use of the HUD was 1.1 seconds as opposed to 1.7 seconds measured without the HUD. Since the HUD was presenting the warning 250m before reaching the event, the driver was provided with approximately 4 seconds extra time to react, when travelling with 100km/h. As illustrated on the chart in Figure 5 the majority of users exploited this time sensibly and avoided collision with the front vehicles. Further, through questionnaires, we documented the participants' preferences and feedback regarding the visual elements. The HUD interface was specifically evaluated and compared against contemporary dashboard dials with favourable results.

The driving simulator was evaluated according to the Task Load Index Form. Essentially, users were asked to evaluate the driving simulator's features on a scale of 1 to 10. Figure 6 depicts the average rates for Mental Demand, Physical Demand, Effort Expended, Performance Level and Annoyance Experienced. The results were in agreement with users’ comments, which were recorded during the informal interview.

The component that gathered the most contradictory feedback was the steering wheel. Although its rotation was closely replicating real steering wheels, most of the participants encountered difficulties aligning the car within the traffic lanes, possibly due to the sensitivity of the hardware. After the preliminary trials, the problem was resolved to a degree by recalibration, yet in the future, we are considering the construction of a custom-made steering wheel.

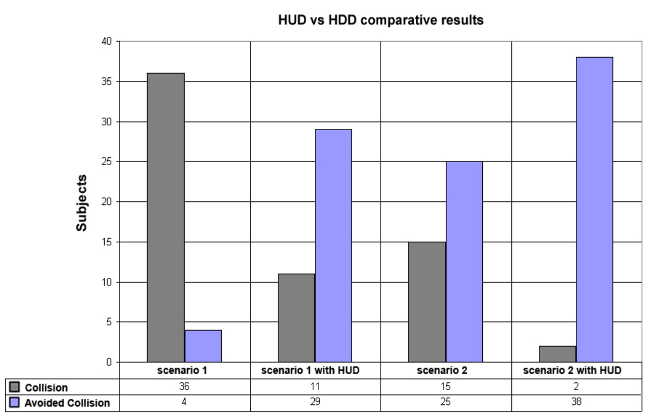

FIGURE 5: Response results on accident scenarios 1 & 2, with and without HUD.

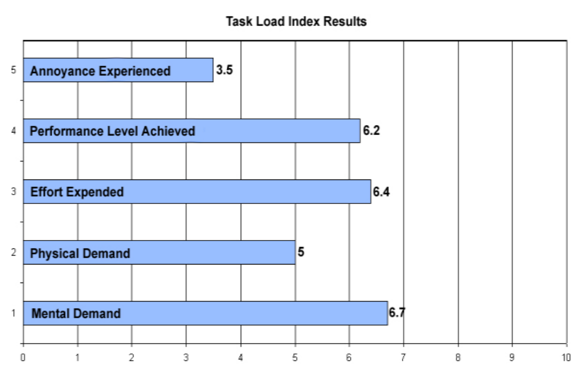

FIGURE 6: Task load chart for the driving simulator.

7. CONCLUSIONS

This paper has presented the evaluation process of a prototype HUD interface and outlined the development stages of a custom-made and open-source code based driving simulator. For the experiment, two accident scenarios had been re-enacted, based on actual traffic police data. The trials demonstrated that the proposed full-windshield HUD interface could operate sufficiently, providing the user with the necessary information for navigation under low visibility conditions. The experiment has also highlighted some problems stemming from the initial driving simulator set-up, which could be refined by reviewing the participants' suggestions and preferences. In the future, we aim to measure variations of the HUD interface performance, in an upgraded version of our driving simulator. It is our intention to explore additional driving scenarios and incorporate errors, or false feedback to the driver, to access the system in a more realistic setting. Hence, we have embarked on a project to build a HUD prototype system in a real vehicle that would embrace intra-vehicle interactions and different road and traffic conditions.

8. ACKNOWLEDGEMENTS

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