DESIGN AND EVALUATION OF AUTOMOTIVE HEAD-UP DISPLAY INTERFACE FOR LOW VISIBILITY CONDITIONS

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ABSTRACT
This paper introduces a novel design approach for an automotive full-windshield Head-Up Display (HUD) interface which aims to improve the driver's spatial awareness and response times (RTs) under low visibility conditions. The proposed HUD design aims to enhance the quality and increase the quantity of information provided to the driver in such adverse circumstances, by utilising the vehicle's sensors. Further, the HUD interface elements are based on minimalist visual representations of real objects, which shortens the learning curve and offers a compact form of interactive guidance for motorway environments. This paper discusses the challenges involved in the HUD design, introduces the visual components of the interface and presents the outcome of a preliminary evaluation of the system on a group of forty users, as conducted using a driving simulator. The initial evaluation reveals great promise in the system with results indicating reduced RTs and greater driving stability.

KEYWORDS Head-Up Display, Automotive, Navigation system, Low visibility, HMI

1 Introduction

Automotive industry research has had a long focus on providing drivers with information to aid spatial awareness and decrease response times (RTs) while "on the road". Expressions of this effort range from improved dashboard (or instrument panel) design to audio warning cues from proximity systems [11]. A particular area of increasing research activity has been the design and utilisation of visual cues embedded in the vehicle's windshield, which becomes in effect a Head-Up Display (HUD), as facilitated by anticipated developments in windshield manufacturing and electronic technologies.

Traditionally, a wealth of information regarding the vehicle's operational and mobility status has been delivered to the driver through the instrument panel (IP) on the vehicle's dashboard. Recent research efforts have leaned in favour of superimposing, some (or all) of that information on the vehicle's windshield [7, 16], by demonstrating in trials that a fully operational HUD design results in decreased RTs and more stable driving reactions, compared to traditional IP or Head-Down Displays (HDDs) [9].

According to the amount and type of information made available to the driver, two categories of displays may be identified, namely the map-navigation and guidance-navigation varieties. The former embraces the vast majority of navigation systems commercially available and delivers information on various roads on a 2D or 3D map, typically using GPS, and suggests possible routes to a chosen destination. Such systems, clearly contribute to the driver's sense of orientation but concerns have been raised on issues of information overload and driver distraction. On the other hand, guidance-navigation systems mainly focus on enhancing the driver's realisation of the traffic conditions within a short proximity of the vehicle, as well as providing alert cues for changes along the vehicle's blind or oft-neglected spots. Such functionality becomes increasingly important in low visibility conditions where the driver's spatial awareness is reduced. In contrast to map-navigation systems, for such instances, the long term goal of reaching the destination is somewhat irrelevant; it is the "now" rather than the "later" that matters [9]. For the remainder of this paper the term navigation systems will refer to guidance-navigation systems.

Our proposed HUD is a full-windshield design, particularly aimed for use at low visibility conditions. Following the paradigm set by Steinfeld et al. [16], a traditional IP comprised of a tachometer and a speedometer is displayed on the windshield along with other visual cues (transient and permanent). Subsequent discussion in this paper, describes the issues surrounding the decision to implement each symbol in its final form and outlines the experimental results derived from user-tests on a driving simulator. The aim of the experimental trials has been to evaluate the effectiveness of the visual cues and quantify their usefulness in terms of response times and overall driving stability as used in previous work [9].

The rest of the paper is organised as follows. The next section offers rationale justifying a full-windshield oriented design and explains the decision to opt for symbolic (in the sense of icons) rather than alphanumeric representation of the visual cues. Each element of the interface design is presented in subsequent sections as well as details on the choice of positions of the symbols on the windshield grid. Then a description of the driving simulator is provided, as used in the experimental evaluation of the system. An overview of the evaluation results is also included in this work. Finally, we outline our conclusions and present a tentative plan for future work.

2 The case for HUD and iconic representation

An initial approach to the design of a HUD interface involves fundamental decisions with respect to positioning and size; these are reflected in the mantras of Head-Up vs Head-Down Displays and full vs small sized projection forms. The design decisions taken with respect to these two dimensions as well as a rationale for the iconic representation used in the final system are now outlined in turn.

2.1 Head-Up Display

Previous research [15] has suggested that driving is a task almost overwhelmingly visual in nature; thus, several research efforts have concentrated on exploiting visual signals to pass on useful information to the driver [7,9,16,20], although other (auditory) avenues have also been explored [11]. The advantages of HUD systems compared to Head-Down Displays (HDDs) for such purposes have been well documented in the literature [7, 9, 16]. To avoid being distractive the majority of existing HUD designs fall into the small projection category, which means they employ little estate on the windshield (a few square centimetre's worth) and usually well within the driver's central field of view. Although HUDs may be utilised for the depiction of a wealth of information on a larger surface, it may be the case that the driver fails to distinguish between the artificial visuals and the real-life environment when an excessive amount of information is provided.

In this design, we have opted for a *full-windshield* HUD which utilises a large portion 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 [7,16], where the full-windscreen form has been demonstrated to be a valid alternative to small HUDs with comparable performance gains compared to classic HDD instrumentation. Even though we have experimented extensively with small form designs, it is unclear how such a small estate could comfortably accommodate the amount of information of traffic conditions surrounding the vehicle, therefore, it was deemed more suitable to use a full form design.

2.2 Symbols versus alphanumeric representation

Alphanumeric interfaces have been widely used as symbology for real-time navigation, especially with respect to military applications (use in aircraft being a particularly notable example). However, previous research has shown that

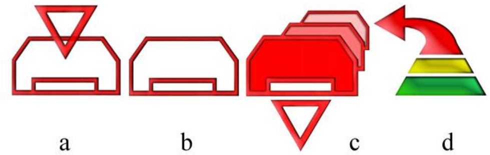


Figure 1. Symbols used in the full-windshield HUD. Key: (a) lead vehicle on the same lane (b) lead vehicle on a different lane (c) traffic congestion in close proximity (d) road turn in close proximity

without extensive training, alphanumeric representations may significantly add to HUD clutter, leading to "cognitive capture" [17]. The term describes the event of sideband information swamping the main signal, i.e. when an attention seeking HUD prevent the user from focusing on the main task. For a moving vehicle setting, this may mean that drivers would exhibit substantially less attention to the driving activity, leading to increased delays in response times and even to a collision incident. Further note that previous comparative studies of symbols and alphanumeric data in HUDs has demonstrated that iconic representation results in faster human reaction [13].

Towards reducing visual clutter, this design opts for the conformal type of symbology for navigation information, as examined in [6]. In broad terms, conformal symbology simulates the visual transformations of external objects to give observers the perception that the symbology is part of the external scene [8]. In order to satisfy the requirement of both alleviating visual clutter and minimising contrast interference (seamless integration of virtual and real-life visual stimuli [8]), the proposed interface utilises simple geometric shapes as symbols.

3 Interface Design

The main use case examined and intended for the proposed interface is driving on a motorway in low visibility conditions (weather conditions such as fog, rain or some other visual impairment factor). As in other work [4], 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; these can cause greater speed variance, which increases crash risk.

Towards designing the HUD display, four pieces of information were initially identified as the most vital for collision avoidance in motorways, namely lane recognition, lead vehicle detection, traffic warning and sharp turn notification. These were visually represented in the HUD design by four symbols. Prior to commencing the design and modelling of these four symbols, valuable comments had been gathered from drivers during informal interviews.

To achieve the goal of designing attention-seeking symbols, it was decided to create colourful visual cues with

Figure 2. Colour coding of the lane symbols. Key: (a) no obstacles on either side of the vehicle (b) obstructed left side (c) obstructed right side (d) obstacles on both sides of the vehicle

possibly changing dimensions or visual intensity. Specifically, depending on the situation, a series of effects have been developed for each symbol. The primary challenge was to provide auxiliary information to the driver without diverting significant mind-share from the primary task. At the same time, the visual cueing effects may have ended being subtle enough to go unnoticed. To avoid such an eventuality, the appearance of each traffic symbol, is accompanied by an auxiliary consideration, namely the relatively sharp transition in colour states for each symbol (drawing inspiration from the concept of an "abrupt stimulus onset" as described in [19]). Specifically, as the sudden induction of any element in the driver's field of view could cause unexpected reactions, the symbols were chosen to appear through a sequence of gradual (but distinct) changes with regard to their colour-changing pattern [2]. Generally, symbols as used in this design appear in light blue and then change to green, yellow and finally to red as the events they refer to come closer to the moving vehicle. The symbols appear in their entirety in Figure 1 and are described in turn below.

3.1 Lane Symbols

Bascuñana [1] identifies three levels of lane-change countermeasure systems. The first level informs the driver about targets in blind spots, the second provides a warning when an unsafe lane change is being initiated and the third, augments level two by introducing automatic control for avoiding collisions. Such lane identification and warning system was identified as an integral component for a HUD interface and was targeted for implementation. Notably, the feature was deemed especially useful in low visibility conditions. It was decided that this symbol would facilitate an easily identifiable "virtual pathway" that the driver could follow in order to move within a road lane.

The "pathway" display concept had been designed and developed for aviation HUDs in the early 1950s as part of the US Army-Navy Instrumentation Program [18]. Our simplified version is exhibited in Figure 2 and is a simple composition of converging lines, superimposed on the real road lane markings. The constant presence of these lines aims to prevent the driver from an accidental lane departure by providing a point of reference for the car's position with respect to the road.

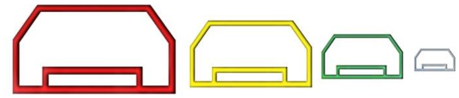


Figure 3. Size and colour coding of the vehicle symbol

Additionally, the lane ("pathway") icon also serves as an obstacle warning system. This is achieved through a colour coding sequence where a green lane strip indicates absence of a vehicle (or obstacle) on that side of the vehicle (potentially including the blind spot at the rear end of the vehicle). Note that such a system provides warning on vehicles overtaking or hard shoulder lanes and lane barriers. This functionality is expected to be achievable through the use of object detecting sensors in real configurations.

3.2 Lead Vehicles Symbols

The stated goal of enhancing driving quality in low visibility conditions necessitated the addition of a leading vehicle warning system. The symbol used for this purpose is a miniature representation of the outline of a car, as shown in Figure 3. Initially, the symbol had been superimposed over all the vehicles in a distance of less 250m (low visibility threshold). This setup worked well in low traffic but led to visual clutter in denser configurations. To overcome this, the symbol is only used on the first row of leading vehicles, which are of the highest interest to the driver. Depending on the lead vehicles distance, the symbols adjust their colour and size in four stages. During these stages the colour changes in the $blue \rightarrow green \rightarrow yellow \rightarrow red$ pattern denoting low risk, conflict, near crash and crash imminent states respectively, as examined in [14].

During on-going trials it was noted that most motorway accidents would involve the first leading vehicle. Therefore the first leading vehicle is denoted by a special leading vehicle symbol (depicted in Figure 1) featuring an inverted triangle in its design. The triangle pointing downwards was adopted as it generally denotes a negative spectrum of meanings such as danger [5]. Note that this interpretation is already used in automotive road signalling, signifying the passive yield or give way to crossing traffic [12].

3.3 Traffic Symbol

A common cause of accidents in motorways occurs when leading vehicles rapidly decelerate perhaps as a response to traffic congestion along the road. Note that in such circumstances traffic congestion might be a cause for alarm for an approaching vehicle other than the one directly in view of the congestion event. This can create a "domino" effect

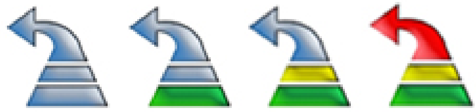


Figure 4. Turn symbol as used in the simulator; the colour gradients indicate degrees of distance from the actual road turn

of slowing vehicles, which is due to affect several links in the traffic flow chain. Traffic notification would be helpful in those cases and especially useful for traffic congestion around corners or otherwise areas hidden from view (due to low visibility conditions).

The traffic symbol as used in this design was created as a miniature of overlapping lead vehicle symbols so as to convey the meaning of multiple slowed down or stopped vehicles. Before deciding upon the final symbol, different versions of it were tested, such as a "hollow" traffic symbol, which was deemed to be too hard to notice for users, or a more "full" version which effectively enhanced the presence of the symbol, but added to the visual clutter as it was often confused with the lead vehicle symbols. Eventually, the design was settled in the form shown in Figure 1 (item C), which includes a reversed triangle that further emphasises its importance and makes it sharply distinguishable.

3.4 Turn Symbols

Certain parts of the motorway, such as junctions, intersections and hairpin turns, can be particularly tricky to traverse especially in view of low visibility conditions. A notification system of the proximity of such road conditions, the existence of which may be realised through GPS and road mapping software, was also deemed a useful addition to the HUD design.

Realising that dictating a dichotomy in the driver's attention between the road and a projected map can be distracting, a turn symbol was introduced in the proposed interface in the form of an arrow as shown in Figure 4. Consistent with the other three symbols, the colour of the symbol initially appears in light blue colour and adds distinct stripes of green yellow and red as the distance to the potentially tricky road turn decreases. As expected, the arrow points in the direction of the upcoming road turn.

4 Symbols Positioning

Previous research has given rise to much argumentation regarding the type and positioning of symbols HUD interfaces. According to Inuzuka et al. [10] any icon placed within a 5 degrees radius of the driver's field of view could be "annoying". Gish and Staplin [8] have asserted that the reason for the findings in [10] was the fact that speed information had been centrally projected on the HUD in those series of experiments; hence icon placement well within that range could be acceptable. Finally, in the work of Yoo et al. [20] an interface symbol positioning experiment proves that superimposed symbols in front of the driver's field of view have no significant difference in response times, although user interviews confirmed the preference bias of the driver as reported by Inuzuka [10]. As a superposition of these findings we applied the mantra of deploying symbols well within the driver's field of view but as sparingly as possible. Note that our proposed interface does not provide extraneous information apart from the necessary speedometer and tachometer indicators. Naturally, all other relevant symbols (on battery power, oil levels etc.) can still be included on the traditional dashboard.

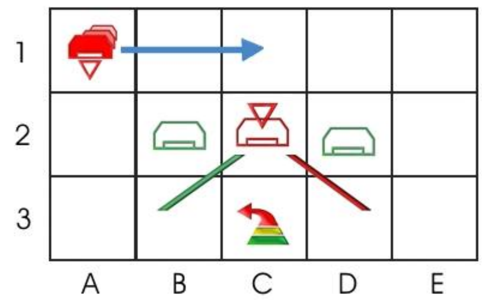
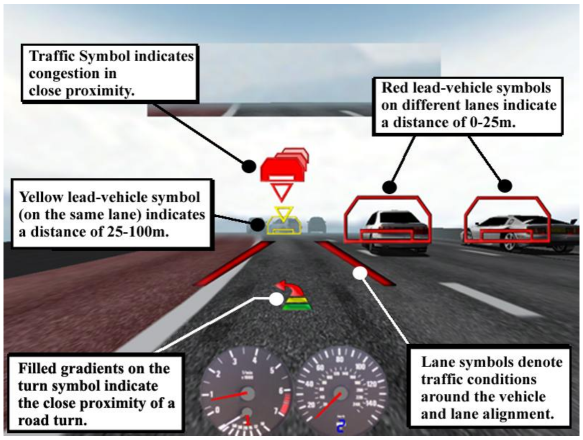


Figure 5. Symbols positioning on the HUD

Earlier work by Yoo et al. has studied the full-windshield HUD regions with respect to response times (RTs) by the driver on symbol appearance. The relevant regions are depicted in Figure 5. According to the results in [20] the sections that gave the best RTs were the ones forming the second row in Figure 5, as they were located in the horizon line in front of the driver's field of view. Only a few equally low RT measurements were recorded in the first and third row. By consulting the grid pattern in [20], the lead-vehicle symbols in our design were superimposed in B2, C2 and D2 areas which exhibit the fastest RT sections. The lane symbols were mostly projected in C3 and E3, which offer lower-than-average RTs. The turn symbol was presented within the square of D3, underneath the middle lead-vehicle. Notably, as it is acting as an early warning symbol, a position with slightly slower RT was deemed appropriate and non-distracting.

In the case of the traffic symbol, a number of different positions were tested during the preliminary trials. Initially it had been positioned in E1, attempting to avoid visual cluttering, which nonetheless made the symbol almost invisible to participants, verifying the grid experiments in [20]. Position A1 proved to be a better choice as it had approximately the same RT level with the turn symbols position. Note, that the traffic symbol also indicates the location of the traffic and follows a path on the HUD, starting in the first row and ending up at D1. Due to this motion, the symbol goes through three fast RT positions



(a) Screenshot of the driving simulator

(b) Driving simulator setup

Figure 6. The driving simulator system

further stressing the significance of the information. By the time it has settled in D1 (as the vehicle approaches the congestion point), it has also reached a slow RT position; but by then the symbol has already served its purpose.

5 Driving Simulator

In order to evaluate the effectiveness of the proposed HUD system, we performed trials using participants of varying driving experience and age on a number of traffic scenarios. The user tests were carried out in the eMotion lab at Glasgow Caledonian University in a room equipped with video cameras, an eye-tracking device and a pulse measuring system to record the subjects' reactions. The system setup involving a driver's chair, gear stick and steering wheelpedals is depicted in Figure 6(b). A preliminary test was conducted with 14 users in order to identify the possible flaws of the interface and the simulator. A screenshot of the simulator in action is shown in Figure 6(a). The simulator is further discussed in previous work [3]

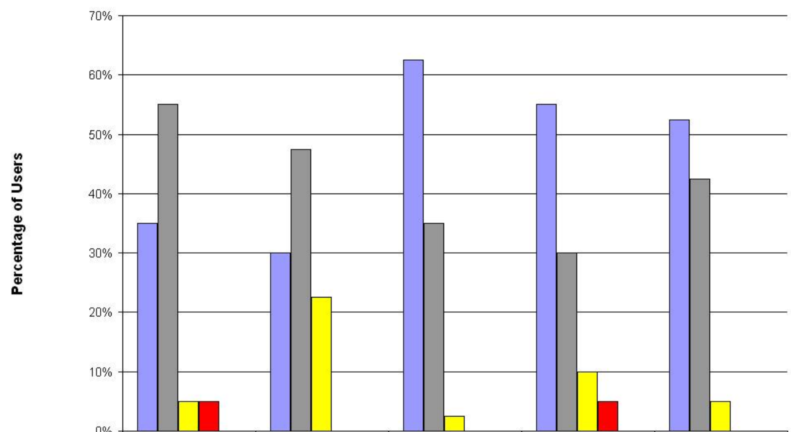
A total of forty users took part in the final trials. Overall, six scenarios were played out in each trial. The first two involved driving for approximately 35km under light traffic conditions so as to enable the users to familiarise themselves with the simulator and the controls. Then, the following two driving scenarios were designed to recreate possible accident prone situations under low visibility conditions. In this particular case, dense fog conditions were simulated restricting visibility to below 50m (zero visibility). These two *car-following* scenarios were played out with and without the HUD interface. Throughout the trials, users were instructed to drive as they normally would in these conditions, respecting the speed limits. In fact, the testing track was a 3D representation of the main motorway (M8) between the UK cities of Glasgow and Edinburgh. A detailed account of the scenarios used is included in [3].

6 Evaluation Results

The metrics used in assessing the systems effectiveness were the response 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 lane. The response 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 collision (mild or otherwise), a driver's error event was recorded. Although evaluation of these is ongoing, early analysis 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).

Further, through questionnaires, we recorded the participants' preferences and feedback regarding the visual elements. The HUD interface was, specifically, evaluated and compared against contemporary dashboard dials with favourable results. Here, we present results on the user preference ranking of the designer's choices of symbol designs. Essentially, users were asked to evaluate the system's features on a scale of "Extremely helpful" to "Not helpful at all", as depicted in the chart in Figure 7.

The lane symbol revealed some interesting results for both its functions. The first function (the lane navigation) was ranked as "extremely helpful" by 35% of the participants while 55% thought it was "very helpful". It was particularly stressed that the lane symbol was effective in assisting the users to maintain the vehicle position within the lane boundaries. The second function of the lane symbol, which facilitates overtaking, was ranked as "extremely helpful" by 30% of the users and as "very helpful" by 47.5%. Further analysis of the collected data showed that 22.5% of users who had rated the function as "neutral",



	Lane Navigation	Lane Overtaking	Lead Vehicle	Traffic	Turn Icon
Extremely Helpful	35%	30%	62.50%	55%	52.50%
Very Helpful	55%	47.50%	35%	30%	42.50%
Neutral	5.00%	22.50%	2.50%	10%	5%
Not Very Helpful	5.00%	0%	0%	5.00%	0%
Not Helpful At All	0%	0%	0%	0%	0%

Figure 7. Subjective evaluation results

had not tried it out, as they had preferred to remain in the slow speed lane and avoid any lane changes. Some users even suggested that the second function of the lane symbol (overtaking), should be preferably activated by the indicators (if technically possible).

The most highly rated symbol was the lead-vehicle warning, as 62.5% of the drivers ranked it as "extremely helpful", 35% as "very helpful" and only 2.5% as "neutral". Drivers reported that the symbol was boosting their confidence by increasing their spatial awareness and significantly reducing distance misjudgement. The traffic symbol received equally good feedback despite the technical and design challenges encountered during its implementation. Specifically, 55% of the interviewees considered it as "extremely helpful", 30% as "very helpful", a 10% as "neutral", and a 5% condemning it as "not very helpful". A few users suggested emphasising further the traffic warning information by making the icon bigger or accompanying it with an audio cue. Finally, the turn symbol was rated as "extremely helpful" by 52.5%, "very helpful" by 42.5% and "neutral" by 5%, which marks it as a moderate success. We feel it succeeded in its role of augmenting the already existing road signs, by also providing the driver with crucial information on tricky road turns.

Most participants mentioned that driving with the help of the HUD interface in heavy fog conditions made the experience less stressful. However, and this was stressed as well, utilising this system in normal daylight could become annoying. Overall, as the preferences results demonstrated, the interface design received positive feedback. We feel that the analysis of the numeric data for the RTs and braking distance supported our design choices with minor reservations.

7 Conclusions

Full-windshield Head-Up Displays (HUD) have been proven to be very effective in raising the driver's spatial awareness and reducing average response times compared to traditional instrument panels. This paper has described the factors taken into consideration and the design decisions made in an effort to create a HUD to aid driving in low visibility conditions. The proposed system was built and eventually evaluated using a custom-made simulator in a moderately-sized group trial of forty users.

Preliminary results of the evaluation have indicated that the HUD design and implemented functionality aided users in successfully dealing with potentially dangerous situations on the road. Subsequent questionnaire responses were encouragingly positive and indicated that the system was pleasant to use and relatively unobtrusive.

We plan to refine the HUD interface and produce further scenarios for future trials. In particular, we aim to incorporate audio cues in the system to investigate their effectiveness in complementing the visual feedback. Further, the simulator is being developed to incorporate errors, or false feedback to the driver, so as to assess the system in a more realistic setting. Being very aware of other research in the area, we are actively seeking permission from other groups to incorporate their designs in our simulator and conduct comparative studies on the subject. Finally, we have began a serious effort to build a HUD prototype system in a real vehicle that will incorporate some of the features described in the proposed HUD design.

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