FEASIBILITY OF HEAD-UP DISPLAYS IN DRIVING CABS

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ABSTRACT
Head-up Displays (HUDs) were developed by the aviation industry to provide pilots of fighter aircraft with primary information without the need to refocus onto the instrument panel and so reduce observation of the external environment. The advantages are such that they are now in use on civilian aircraft. As with much of technology, advances are enabling the cost/performance ratio to decrease. Where there is opportunity for series manufacturing, the unit costs are decreased, and today the luxury automobile market is able to offer head-up display technology as part of the production specification. The railways are under pressure constantly to reduce costs, improve risk management and traffic performance. Technology must be continually reviewed, and those trends that offer synergy with the needs and processes of the railway should be assessed objectively. The objective encompasses understanding the technology, identifying the conditions that can lead to its beneficial use and assessing its justification within the context of the business.

HUDs were identified as one of the technologies where the trends indicated that application in locomotive cabs is becoming a possibility. Risk mitigation benefits can be identified. For example, one of the primary duties of a train driver is to survey the line ahead. Indeed, the observation of the adjacent lines is one of the mitigations of the risk of a train colliding with an obstruction on the track. One concern over the increased use of in-cab signalling is the implication that the driver will spend more time looking down at the controls and less time looking straight ahead.

INTRODUCTION
This paper presents a summary of the final report of the project referenced T513 managed by the Rail Safety and Standards Board (RSSB), located in the United Kingdom. The full report is available through the RSSB website¹.

A contract was let by the RSSB under the United Kingdom’s railway research programme to the Human Factors department of BAe Systems, Filton, UK. The work included a survey of the existing literature to review the lessons learnt in the aviation and automobile sectors. This was combined with a thorough investigation of the technical and human factors associated with driving a train with the aid of a head-up display. An innovative feature of this work was the use of a high fidelity driving simulator fully available to the project on the contractor’s premises. The value of HUDs to aviation has been proven. The project assessed the likelihood of similar benefits being realised by their adoption and adaptation to the rail domain.

¹ www.rssb.co.uk
METHODOLOGY

The project was structured in three phases. The first phase consisted of a study to review the lessons learnt from the use of HUDs in the aviation and automobile domains. The questions addressed included:

- How are HUDs used in these industries?
- What are their proven benefits?
- Can these benefits be applicable to the railways?

The second phase consisted of a thorough review of the technical and human factors implications associated with the installation and operation of HUDs in train cabs, using the results from first phase as a guide.

The third phase consisted of a simulator assessment as it is an effective way to readily assess the potential benefit of novel technology to the driving task. By fitting a HUD to a high-fidelity full-task train simulator (pictured) the project formally assessed its potential benefit with the direct involvement of train operators. Significant emphasis was placed on this phase of the study.

HUDS AND CONTROL

A head-up display is one which presents a virtual image in the forward line of sight of the vehicle operator (see Figure 1). The system is used to present information which would otherwise require users to divert attention from the forward view. Displays of this type are attributed with some positive qualities, such as a contribution to enhanced safety, task performance, and an increased envelope of operations. They are not, however, without their disadvantages which include restricted viewing zones and perceptual effects of 'instrument myopia' and 'attention capture'.

![Figure 1: Illustration of conventional (green) head-up display with head-down display in an aircraft](image)

The most established application for HUDs is as an avionic display in fast jet aircraft where a significant body of information on installation, use, and human factors research has accumulated. In this application in particular, the function of the HUD has evolved beyond early expectations [1].

The benefits of HUDs arise from two basic factors: firstly the time saving and benefits to situational awareness that arise from the presentation of information in the line of sight; secondly the HUD allows presentation of information not easily accomplished by any other means.
Reduction of time lost in diverting attention.

For a vehicle operator to look down at console instruments, a number of coordinated physical, cognitive and perceptual actions must be completed. Some of these occur in parallel and some serially. As vision is a sense which is directed to a particular point in space (as opposed for instance to the sense of hearing), visual attention cannot be directed to the forward view while simultaneously fixating console instruments. Critically, some of the time taken to shift attention from the view ahead to console instruments is effectively lost time - neither the view ahead nor instruments are being attended while attention is being redirected.

Contributions to the ‘time budget’ involved in an instrument scan are outlined in Table 1. In aircraft, the pilot is trained to carry out a formal and structured instrument scan, which may take several seconds. Even a glance down to the dashboard in a car (where the instrument cluster tends to be located as close to the windscreen as possible) takes over a second, and where significant light adaptation is involved (for instance when driving into the sun), it may take considerably longer to read head-down instruments and redirect attention to the road.

<table>
<thead>
<tr>
<th>Redirection of Visual Attention Component</th>
<th>Guide time taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saccadic Eye Movements</td>
<td>0.3 s per fixation</td>
</tr>
<tr>
<td>Convergence</td>
<td>0.25 s</td>
</tr>
<tr>
<td>Accommodation</td>
<td>0.25 s (90 ms per dioptre)</td>
</tr>
<tr>
<td>Adaptation</td>
<td>0.5 – 10 s</td>
</tr>
<tr>
<td>Mental Attention</td>
<td>&lt; 1 s</td>
</tr>
<tr>
<td>TOTAL</td>
<td>&gt; 2 s</td>
</tr>
</tbody>
</table>

Table 1: Guide to time taken to redirect visual attention from forward view to console instruments.

Studies measuring the gaze direction of pilots without a HUD have shown that, on average (covering all phases of flight), less than 20% of their time is spent looking outside the flight deck [2] [3].

In aircraft, the case for HUDs has been proven, and where adopted, HUDs have found an increasing range of applications which were not originally anticipated. This is likely to be the case in other transport domains. The additional capability of the aircraft HUD occurred partly because the HUD was the first multifunction display to be introduced in aircraft, and using a HUD the pilot could view information such as navigation, radar and warning systems, via a single screen. Further advantages arise from the fact that the display area can be relatively large without taking up any console space and, in addition, certain types of information can be aligned with the outside world features to which they relate.

In rail applications, it is likely that a HUD could find applications which cannot be imagined at this time.
Informational Content.

The information content of multifunction display HUDs may take two fundamental forms (see also Table 2):

- **Symbology.**
  The first class of displayed information is symbology. Here, instrument information is presented using alphanumeric characters, and other symbols, typically emulating the information presented by traditional instruments. Symbology may be subdivided into fixed symbology, where for instance speed information is presented at a predefined location on the display, and ‘conformal’ symbology, which is located to overlay some related feature in the view ahead (see figure 2). This conformal symbology has proved of immense benefit in HUD implementations and will be described in subsequent sections. Figure 3 shows a HUD image depicting current train speed and line speed limit only. More complex symbology is possible, but its effectiveness at providing information must be assessed.

- **Imagery.**
  The second class of displayed information is pictorial or image information. The image source can be synthetic, or from a sensor (camera or thermal imager) and is usually conformal.

<table>
<thead>
<tr>
<th>Class of Information</th>
<th>Subclass</th>
<th>Content</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbology</td>
<td>Fixed</td>
<td>Alphanumeric characters, symbols, line segments. Fixed position on display</td>
<td>Speed information, engine status, navigation/time data, warnings.</td>
</tr>
<tr>
<td></td>
<td>Conformal</td>
<td>Alphanumeric characters, symbols, line segments. Aligned with real world features</td>
<td>Artificial horizon, obstacle cue, wire frame synthetic terrain view.</td>
</tr>
<tr>
<td>Imagery</td>
<td>(Conformal)</td>
<td>Scene image, possibly synthetic image “enhanced and synthetic vision”</td>
<td>Low-light TV, thermal image, synthetic terrain view.</td>
</tr>
</tbody>
</table>

Table 2: Classes of information that can be displayed on a HUD.

Figure 2: Illustration of civil aircraft HUD showing fixed and conformal (in this case artificial horizon) symbology.
HUD COMPONENTS

Head-up displays comprise a display, a combiner, and possibly a light source. Figure 4 shows a schematic of their arrangement.
Display Technology.

In addition to cathode ray tubes (CRTs), a number of technologies are available to be used as the display element of a HUD. These include:

- Liquid crystal displays (LCD).
- Digital micro mirror device (DMD) reflective displays.
- Organic light–emitting diode (OLED) displays.
- Electroluminescent (EL) displays.
- Vacuum fluorescent emissive displays (VFD).

CRTs are costly and will become increasingly hard to obtain as the industry continues its trend towards using modified commercial displays. A review of CRT replacement multifunction displays for HUD applications is given by [4].

Combiner Technology.

The combiner can be flat, or it can be curved so that it forms part of the lens system, actively focussing the virtual image as part of the image forming system. Where the windscreen is used as a combiner, the possibility of secondary reflections must be taken into account. A double image can be particularly visible from a relatively thick windscreen where there is more displacement between the primary and secondary image, so in practice a coating or film is applied to the front surface to ensure that the secondary reflections are eliminated. This is the option chosen for most automotive installations.

To display HUD information in colour requires that the combiner reflects either all visible wavelengths, or at least those which carry the colour information from the display. In this case the forward view seen through the combiner will be darkened. The spectrally selective and neutral combiner effects on ambient and display illumination are shown in Figure 5.

![Figure 5:](image)

Figure 5: (Left) a spectrally selective combiner reflects the displayed information efficiently, removing those wavelengths from the incoming light; (right) a neutral combiner presents coloured display information, at the expense of attenuating transmitted light.
HUDs IN THE RAILWAY ENVIRONMENT

No in-service HUDs for the rail industry have yet been identified. HUDs exhibit considerable diversity in technical specifications and usage. Applications range from the relatively simple presentation of head-up information of speed to a car driver, to the technical challenges of providing fully conformal night vision systems to assist pilots in completing a landing during the hours of darkness. The range of applications is large and it is likely that a HUD suitable for the railway environment is feasible.

Predicted HUD Effectiveness in Rail.

Assessment of the accident reports revealed that the potential contribution of a HUD could be placed into a relatively small number of categories. These categories are described in Table 3.
<table>
<thead>
<tr>
<th>HUD Functionality</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head-up instruments</td>
<td>A common theme to the incidents and accidents is a general loss of situational awareness during the train driving task, especially of current vehicle speed. It is considered that the head-up presentation of instruments and information that is currently only available heads-down may help improve situational awareness and workload, thereby contributing positively to safety.</td>
</tr>
<tr>
<td>Previous aspect information</td>
<td>The AWS ‘sunflower’ display is usually intended as a reminder that signals have been passed showing a caution aspect; however, as it is not directly in the line of sight, it may be inadvertently overlooked. Placing an AWS ‘repeater’ closer to the direct line of sight, may have benefits and a number of incidents report drivers who have ‘forgotten’ that they are driving against adverse signals. As technology evolves (and especially initiatives connected with ERTMS and ETCS) additional technical capability will become available well beyond the current AWS system, and this capability may best be exploited using a HUD.</td>
</tr>
<tr>
<td>Night vision capability</td>
<td>Poor visibility at night may be a contributing factor in a number of incidents. The ability of HUDs to provide night vision may have the potential to assist in these circumstances.</td>
</tr>
<tr>
<td>Line speed indication</td>
<td>Inappropriate train speed may result from a number of factors, including poor situational awareness, missing critical visual cues and poor judgement in braking.</td>
</tr>
<tr>
<td>Conformal cue for signals</td>
<td>Many incidents, including a significant number of Category A SPADs, occur because drivers miss signals, often believing that a specific signal displaying a caution aspect does not apply to their train, or inadvertently ‘reading across’ to adjacent signals. A cue, presented on the HUD, indicating directly which signal applies to the current running line (perhaps by drawing a box around the signal head on the HUD as shown in Figure 6) may have the potential to significantly reduce the probability of such incidents.</td>
</tr>
<tr>
<td>DRA information</td>
<td>The DRA is a device in the driving cab that enables the driver to set a reminder that the signal ahead is at danger. When set, the DRA prevents the driver being able to take power. However, if the driver fails to set the DRA when required this may increase the probability of starting against a red signal. Information could be presented on the HUD to remind the driver to set the DRA.</td>
</tr>
<tr>
<td>System State</td>
<td>The status of the signalling system regarding train movement to determine whether or not the line could be occupied. Advanced warning on a HUD could warn the driver to adopt defensive driving techniques.</td>
</tr>
</tbody>
</table>

**Table 3:** Description of the HUD functionality indicated to assist in preventing the accidents

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2 In today's rolling stock the AWS may refer to events other than signals, for example, temporary or emergency speed restriction, automatic barrier crossing which is locally monitored. However, for the purpose of this study, the AWS refers only to signal aspect information.
Combining the results of the analyses 80 causing fatalities, reported by [5], and 200 incidents and accidents, reported by [5] and [6], gives the ranking of HUD behaviours shown in Table 4. This shows the combined data ranked in order of perceived benefit and normalised to a total of 100. The ranking was undertaken by two experienced assessors against a set of systematic criteria.

<table>
<thead>
<tr>
<th>HUD Functionality</th>
<th>Relative Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head-up instruments</td>
<td>30.0</td>
</tr>
<tr>
<td>Last signal aspect indication</td>
<td>24.3</td>
</tr>
<tr>
<td>Conformal cue for signals</td>
<td>20.2</td>
</tr>
<tr>
<td>Night vision</td>
<td>5.78</td>
</tr>
<tr>
<td>Adhesion information</td>
<td>4.8</td>
</tr>
<tr>
<td>Line speed information</td>
<td>4.2</td>
</tr>
<tr>
<td>DRA information</td>
<td>4.1</td>
</tr>
<tr>
<td>Track circuit information</td>
<td>3.9</td>
</tr>
<tr>
<td>Presentation of schedule</td>
<td>1.2</td>
</tr>
<tr>
<td>Braking airflow meter</td>
<td>0.8</td>
</tr>
<tr>
<td>Conformal braking cue</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4: Potential HUD functionality, ranked in order of potential value, data combined from the analyses (n=280)

These results are critical to understanding the potential contribution a HUD might make to safety in the rail industry. The findings were used to support the trials undertaken in the third phase. Those items scoring in excess of 20 in Table 4 clearly have potential for rail applications.

Overall, the analysis of fatal accidents in the rail domain revealed a potential for HUDs to contribute to safety, with a stronger potential value than seen for road applications, but weaker than seen for aviation.

**Engineering:**

Some applications have been proposed for head-up displays in the rail industry. Of these, two actually apply to using HUDs in driver cabs (as opposed to applications in maintenance and design). The European commission IST (Information Society Technologies) programme supports REOST [7], the Railway Electro Optical Systems for Safe Transportation. This is an Italian/Israeli collaboration whose objective is to improve rail safety by enhancing observation, warning and decision control. Low visibility and night vision aids such as thermal, hyperspectral and laser imaging are being trialled, and a high–level human computer interface for the driver is suggested. The natural form for this interface would be a HUD. The US Department of Transport Volpe National Transportation Systems Center [8] Operator Performance and Safety Analysis division also operates a high-speed train simulator, in which a head-up display is simulated.

Even though the experience obtained from the use of HUDs in aviation and automotive applications offers a sound basis for conclusions, each should be tested through a field trial to investigate, for example, which display technologies may be appropriate for rail HUD systems.

It is considered desirable to regulate symbology content for rail HUDs early, if their adoption by the industry looks likely, in order to limit variations.
THE HUMAN FACTORS OF HUDs IN RAIL

A two stage approach to human factors issues was adopted:

The first focused on those issues relating to usability and human factors. This categorisation is made on the basis of the best information available, together with considered expert judgement. No specific trials were undertaken to support the tentative conclusions obtained.

The second concerned the use of the simulator to assess the reactions of drivers to HUDs.

Installation Assessment.

There are many potential challenges associated with the fitting of a HUD to the cab of a rail vehicle. Successful installation requires the HUD to perform those tasks assigned to it dependably, to contribute to the driver's primary role of controlling the vehicle, and to offer minimal interference to secondary tasks. Although much is learnt by studying the use of HUDs in other transport sectors, the differences implicit in their use must also be understood. For instance, the workload in aviation is very uneven, mostly being concentrated on takeoff and landing. When making comparisons with the road sector, although the information content and lighting of the rail scene has more in common with road than with air transport, more consistency in visibility can be expected for the rail application.

Installation Issues:

The installation must meet criteria determined from the following environmental issues:

a. Daylight Viewing Conditions
b. Night-time Viewing Conditions
c. Rapid Transitions

The display must take into account questions of:

a. Range of focus
b. Vibration
c. Refresh rate
d. Sun shades
e. HUD eye box

Field of View & Viewing Zone:

A critical parameter which constrains both the field of view (the visual angle occupied by the display, and the area of the outside world which it overlays), and the viewing zone (the volume in the cab from which the display can be seen) is the size of the combiner.

In the ideal situation, the HUD would be capable of displaying information at any location on the outside world. This is not technically possible, therefore, in the current ideal, the field of view of the HUD should coincide with the area to which the driver most predominantly directs visual attention.

Studies which have investigated eye movements of train drivers are directly relevant to this analysis. In a simulator based study [9], the point of gaze was categorised as:

- Sky
- Signs
- Cab
- Moving Objects
- Track Ahead
- Off Track
- Signals
The study demonstrated that drivers spent the majority of the time looking either within the cab, at signs, at the track ahead or at signals. A proportionally smaller amount of time is spent looking at the sky, at moving objects or off-track (landscape).

These findings are supported by [10] who deployed eye movement recording equipment on trains. An extract from the study is given in Figure 6. As can be seen, drivers predominately attend to a relatively small area of the visual scene (labelled as ‘ahead’). Maximum value will be realised by installation of a HUD which overlays this area. Additional benefit may be gained if the requirement to view within the cab can be removed by installation of a HUD, effectively combining the ahead (yellow) and in-cab (blue) categories.

![Figure 6: Analysis of point of gaze during train driving, analysed by driver age group (from [10]).](image)

The size (or field of view) of the displayed image of the HUD is critical to any potential user. The field of view is defined as the visual angle subtended by the HUD at the observer’s eye. The field of view is intrinsically limited by the angle subtended by the combiner at the observer’s eye.

The field of view required is affected by track curvature. HUD fields of view are typically of the order of 25° to 40°, with constant market pressure to extend the useful range. The project concluded that the fields of view available for HUDs today could be appropriate for rail applications. These fields of view would be capable of presenting useful conformal indications of approaching track features (in addition to basic information displays) if considered beneficial.

**Overall Risk Assessment of HUD Installation:**

The basic requirements for the use of HUDs in the train cab are likely to be easily met. It is certain that HUDs could be installed to provide useful information to the driver in a manner which is readable across most (and possibly all) viewing conditions. The project indicated the following range of risk associated with the issues identified:

- Issues related to night readability, display focus, refresh rate, sunshades, track curvature, combiner mechanism, integrity, and potential obscuration of external visual features are assessed to be low risk.

- Issues related to vibration, daylight readability (especially when driving into the sun), legibility during transitions associated with tunnels, and interactions between the outside view and the field of view of the HUD are assessed as medium risk.
• Issues related to readability of the display from the range of seating positions, and the long term reliability of HUD displays in the demanding environment of the rail cab are assessed to be high risk.

**Human Factors of System Use - Trials**

The potential benefits offered by HUDs are difficult to identify without directly soliciting the views of the train driving community. For this reason this feasibility study placed significant emphasis on a simulator-based usability trial.

**Trials Participants:**

Participants were a self-selecting sample of train drivers who responded to an email and poster campaign. A total of 16 drivers completed the trial, representing four train operating companies (Virgin Trains, GNER, EWS and Arriva Trains). They had between 3 and 29-years driving experience with a mean of 12-years. Some of the drivers also had experience as instructors or minders. Two were Driving Standards Managers (DSM) and one was an Operations Standards Officer.

**Rail Research Simulator:**

The simulator that was used during the trial is the Rail Research Simulator at BAE Systems, Filton. The simulator represents a generic modern cab and is closely based on a Virgin Trains/Alstom ‘Pendolino’ Class 390. The simulator replicates the layout of controls in a real cab and supports the following:

• Full driving controls (traction brake controller)
• Automatic warning system (AWS)
• Driver’s vigilance system
• Train management system
• Air suspended driver’s seat
• Train protection and warning systems (TPWS).

For the duration of the trial the simulator was fitted with a roof-mounted HUD as seen in Figure 7. This was a demonstration version of a fully operational civil aircraft HUD. In terms of functionality it differed from the production system only in the brightness of the output. In the relatively low luminance setting of a simulator, this was of no consequence.

![Figure 7: Simulator fitted with HUD.](image-url)
**Trial Protocol:**

Each participant was given both a written and a verbal briefing prior to participating in the trial. The verbal briefing gave an overview of the research programme and provided an introduction to HUDs as used in aviation. Following the briefing, all drivers were given a simulator familiarisation session. Participants drove the simulator for approximately 15 to 20 minutes, initially without the HUD deployed and subsequently with it. This gave the drivers the opportunity to become familiar with the simulator and the use of the instruments displayed on the HUD. Once each driver felt comfortable with the simulator and HUD, the assessment session commenced.

Participants drove sections of a 30 mile generic electrified route. To compensate for the driver’s lack of route knowledge, the simulator automatically provided a verbal announcement in advance of any changes in line speed.

The simulator is instrumented to monitor and record all events associated with its operation in a similar manner to a on-train monitoring recorder (OTMR). For the purposes of this trial, the train speed against the target line speed was the only recorded measure.

**Trial Content:**

These trials were designed with reference to the output from the analysis of accidents and incidents. This analysis revealed that the major positive contributions of HUDs should focus on providing instruments in the line of sight (especially speed information), providing an indication of the last signal aspect (e.g. AWS information), and providing a conformal cue to indicate signal locations. The trials were designed to focus on these three themes in particular, and to examine in less detail other broader applications of HUDs in rail cabs. During the simulator trials, assessments were made of each of the following:

1) Potential of the HUD for presentation of speed information: five different formats assessed,
2) Potential of the HUD for presentation of last signal aspect information: three different formats assessed,
3) Potential of the HUD for presentation of brake information: five different formats assessed,
4) Potential of the HUD for presentation of conformal symbology (indicating signal locations): five different formats assessed,
5) Implications of a HUD for speed keeping and workload: comparison of driving with and without the HUD,
6) Structured discussion.

The participants were presented sequentially with each format to be assessed in trial sections 1 to 4, and asked to drive for 5 to 10 minutes until each format was adequately demonstrated and the participant was able to provide an assessment.

During trial section 5, participants were asked to drive the same route twice, both with and without the HUD. The order in which this was completed was balanced over the whole trial, eight participants driving with the HUD first, and eight driving without it. During this speed-keeping task, drivers were also required to provide an indication of mental workload every 30 seconds.

Trial section 6 comprised a structured discussion with each of the participants. This gave the opportunity to discuss other potential uses for the HUD, and to remark on any further issues that may have arisen. A number of drivers made further comments well after their session.

**Trial Symbology:**

Examples of the projected images are given in Figures 8 and 9. The designs were produced based on the dial format already used in the cab and on formats used in the aviation industry. These were all for investigative purposes for this study and further work would be required to
ensure that they conform to HF standards should they be used on a HUD on an operational rail vehicle.

Figure 8: Examples of the symbology used in the simulator study:
(1) speed and brake information presented as conventional dials on the HUD;
(2) speed and brake information presented as pure digital readouts;
(3) Speed and brake information presented as scrolling digits;
(4) speed and brake information presented as tape indicators (two variants were used, both visually similar);
(5) same as no. 1 but with repeater of AWS sunflower;
(6) Same as no. 5, but with addition of conformal box to indicate signal location (left centre).
Figure 9: Enlargement of a single example from Figure 8 to illustrate the symbology in more detail. This shows:
(a) speed dial (indicating 50 mph);
(b) power brake setting (indicating power setting of 3);
(c) conformal cue indicating position of next signal;
(d) repeater of the AWS sunflower;
(e) a head-up repeater of the twin brake pressure gauges. (Note that photographs of images through HUDs are technically difficult, therefore, this is a simulated version of the symbology used in these trials.)

Last Aspect Information and Conformal Symbology:
For the purpose of this study, conformal symbology was demonstrated by highlighting signals applying to the current running line. The accident reports indicated a loss of situational awareness in a number of Category A SPADs. Because it is more difficult to overlook information when it is prominently displayed in the direct eye line, it was judged that there might be some advantage in presenting a reminder of AWS information on the HUD. Last aspect information was presented on the HUD as the British AWS sunflower.

Human Factors Tools and Techniques:
Human factors data were obtained using questionnaires, an instantaneous measure of workload. Although the sections of the trials were completed in a fixed order, the order of presentation of different formats within each section was counterbalanced to reduce order effects. Numerical ratings of perceived benefit (or otherwise) of presenting information on the HUD were gathered throughout the trials.
**Questionnaire:**

The trials session was broken into five distinct subjective sections (together with testing of speed keeping and workload), and the questionnaire was structured to cover each in turn. These sections were:

a) Speed display.
b) Previous aspect display.
c) Brake pressure display.
d) Conformal symbology display.
e) Discussion.

**Workload Instantaneous Self Assessment (ISA):**

The aim of the workload data collection using ISA was to identify and compare operator workload with and without a HUD. The ISA technique of workload assessment was used [11]. The version of ISA used is a self-contained programme that was run on one of the simulator workstations. So as to minimise interference with the driver’s primary task, the driver gave a verbal response of workload every 30s (when prompted by the experimenter).

Each participant gave an assessment of workload based on five levels.

**Speed Keeping Assessment:**

Speed keeping is a significant component of any driver’s task. This section of the trials was included to test the hypothesis that drivers would keep more accurately to the line speed limit when using a HUD. Because the HUD presents speed information in an immediately accessible form, without the need to look down at cab instruments, the hypothesis was tested that the HUD would improve speed keeping. The capabilities of the simulator allowed an assessment of adherence to the line speed limit. The adherence to the speed limit was recorded and there were three reductions in speed over the total route:

For the purpose of this study, each participant drove the same route twice, once with the HUD and once without. On each occasion, the participants were instructed to drive the train as closely to the line speed as possible, taking into account the changes to line speed. The order in which this task was completed was balanced to reduce order effects (and a t-test [12] completed after the trials indicated that the order had no significant effect).

**Data Analysis & Results.**

**Speed Keeping Analysis:**

The speed traces from a single driver are illustrated in Figure 10. This represents the simulated train speed for two runs of around 10 minutes, one with a HUD and one without. In assessing RMS speed variation over the entire run, these data were analysed in their entirety. In the analysis of ‘steady-state’ speed keeping, the approximate sections highlighted in yellow (which otherwise dominate the RMS error) were discarded. The sections blocked in blue were analysed for steady-state driving with a HUD. The sections blocked in red were analysed for steady-state driving without a HUD. A similar analysis was applied to the data from all drivers.

Figures 11 and 12 show the results of the analysis with and without a HUD. Figure 11 shows the RMS speed error across 16 drivers for the entire journey. Figure 12 shows the same data, but only for periods of ‘steady-state’ driving.

It may be concluded that there is no evidence that the HUD improved adherence to the line speed limit. Both statistical tests described above suggested that there was no statistical evidence that the HUD influenced each driver’s ability to keep to the speed limit.
Figure 10: Example speed keeping data for a single trials participant (S5). The line speed limit is shown as a yellow trace, train speed when driving with a HUD as a blue trace and train speed when driving without a HUD has a red trace.

Figure 11: RMS divergence between train speed and line speed limit across 16 drivers for the entire run with and without a HUD.
Workload Analysis:

During the speed keeping task, drivers provided a score between 1 and 5 to indicate the current level of mental workload at intervals of 30 seconds. The overall percentage workload score recorded over the entire trial (n=16) both with and without a HUD is presented in Figure 13. An example of a workload score trace from one of the participants is presented in Figure 14. The total frequency score is presented in Figure 15.

Figure 16 shows the difference in mean workload for the 16 trials participants between the HUD and the non-HUD condition. A negative difference implies that workload was reduced by the presence of a HUD. As can be seen, in the majority of cases (a total of 13 of the 16 drivers) workload was lower with a HUD.

A Wilcoxon matched pairs test revealed that there was a significant reduction in driver workload when driving with the HUD when compared to driving without it (n=16, Z=2.84, p<0.005). This statistical test indicates that the difference seen is highly unlikely to be seen by chance and there is a 99.5% probability that the HUD genuinely improved workload. This reduction was substantial — with a mean workload approximating to 2 on the 1 to 5 scale, a reduction of 0.38 workload points was seen. Because workload scores are measured only in relative units, it is not valid to describe this as a percentage reduction in workload (although workload reported without a HUD was 20% to 40% higher than that reported with a HUD, depending on how this analysis is completed). The reduction in workload seen is a dramatic difference and is a highly significant finding.
Figure 13: Percentage workload score across all participants driving with and without a HUD (n=16).

Figure 14: An example of a workload score trace (S4) driving with and without a HUD (n=1).
Figure 15: Workload frequency score for driving with and without a HUD (n=16).

Figure 16: Difference in mean workload during driving task, mean workload with a HUD minus mean workload without a HUD. Results for individual drivers (n=16) ranked in order of difference recorded.
Feedback.

**Conformal Symbology:**

The concept of conformal symbology received a positive response from the majority of the participants in this study. Conformal symbology could be used to highlight any number of other objects in the outside world. For this reason, drivers were also asked to comment on other potential uses for conformal symbology. The responses included:

- Level crossings
- Temporary speed restrictions (TSR)
- Emergency speed restrictions (ESR)
- Permanent speed restrictions (PSR)
- Advance warning boards
- Stop boards
- Limit of shunt
- Worksite marker boards
- Car stop markers
- To draw attention to where signals and signs should be in case they have been vandalised or are obscured by overgrown foliage.

Participants commented that although the benefit of conformal symbology for signals was clear, its use for attracting attention to other items (e.g. those listed above) should be limited in order to maintain its impact.

It is concluded that conformal cues for signal location (and possibly other trackside features) is a concept which could be favoured by the driving community and requires further investigation.

**Positive feedback:**

The general feedback received from the drivers who participated in these trials was positive. Understandably there were questions regarding implementation and some drivers expressed some reservation about the display formats presented during the trial. However, none of the drivers (from the sample of 16) stated a dislike for the concept of HUDs in trains. On the contrary, a number of extremely positive general comments were received. A range of these are listed below:

- “I've been driving trains for 27 years, but after only one hour with a HUD I missed it when it was gone.” (EWS Driver)
- “I'll be disappointed if I retire [in 2012] before these [HUDs] come in.” (EWS Driver)
- “When can we have it?” (EWS Driver)
- “I can see a HUD being a useful aid but I would be worried about deskilling the driver if too much information is presented.” (GNR Driver)
- “If information can be given to a driver that keeps them "heads out", then fantastic.”. (EWS Driver)
- “A HUD is a better invention than TPWS.” (EWS Driver)
- “I think in the future, with the development of new trains, the HUD would be an essential feature. A safety aid that could help reduce SPADs and assist drivers during adverse weather conditions can only be welcomed.” (Virgin Trains Driver)

There can be no doubt of the positive feedback from these drivers for HUDs.
CONCLUSIONS

Summary of Results.

1. An analysis of the use of HUDs in other transport sectors and their demonstrated benefits has indicated that they can provide safety benefits if applied in the railway sector. It is judged that a suitably equipped HUD might help prevent up to 10% of incidents and 3% of accidents with a total potential annual value of £2M.

2. The results indicate that HUDs adapted to the railway environment will reduce workload on the drivers. Based on the known performance benefits in other applications, an assessment of the potential value of HUDs in contributing to performance suggests that a saving of up to £5M per annum might be made. This is derived from the improvement in punctuality arising from a reduction in driver workload.

3. A net financial benefit to train operators was indicated.

4. The engineering of an installation in a train cab requires innovative solutions, but the issues do not invalidate their use.

5. Drivers responded positively to the experience of their use in the driving simulator. Drivers were positive about the potential for cueing the position of signals, a measure judged to be of assistance in reducing the probability of SPADs.

Further Work.

The project indicated that there is potential value in investigating certain questions. Amongst these are:

a. A significant drop in driver workload was revealed, however no noticeable effect on driver performance was evident. This is an apparent paradox and further investigation of this theme is suggested.

b. The range of potential applications remains to be defined. For instance:
   ▪ one of the primary duties of a train driver is to survey the line ahead. Indeed, the observation of the adjacent lines is one of the mitigations of the risk of a train colliding with an obstruction on the track.
   ▪ One concern over the use of in-cab signalling is the implication that the driver will spend more time looking down at the controls and less time looking straight ahead.

c. The costs and benefits conclusions are tentative and need to be supported by engineering experience.

For this reason, one of the recommendations of this study is that subsequent work should consider fitting a HUD to a real rail vehicle. This would provide the opportunity to assess multiple issues, and only through this experience can definitive conclusions be made concerning the many topics. Such a trial would expose a HUD to the full range of conditions that might be experienced in the rail environment and would significantly increase the confidence in the decisions to be made.

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ABBREVIATIONS

AWS  Automatic Warning System
CRT  Cathode Ray Tube
DMD  Digital micro Mirror Device reflective displays
EL  ElectroLuminescent displays
ERTMS  European Rail Traffic Management System
ESR  Emergency Speed Restriction
ETCS  European Train Control System
EWS  English Welsh and Scottish Railways
GNER  Great North Eastern Railway
HUD  Head-Up Display
ISA  workload Instantaneous Self Assessment
LCD  Liquid Crystal Displays
ms  milli-second
OLED  Organic Light– Emitting Diode
OTMR  On-Train Monitor Recorder
PSR  Permanent Speed Restriction
RMS  Root Mean Square
RSSB  Rail Safety and Standards Board
s  second
SPAD  Signal Passed At Danger
TPWS  Train Protection and Warning System
TSR  Temporary Speed Restriction
VFD  Vacuum Fluorescent emissive Displays