# THE VALUE OF PROTOTYPING IN TRAIN CAB DESIGN

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This paper discusses the important role of prototyping in the design process. Drawing upon the recent experience of developing train interiors for the UK rail network, the paper discusses how the fidelity of these models should be adjusted to ensure it is appropriate for the stage in the design process and the level of uncertainly. In the earliest stage of the design, when the concept is more fluid, low-fidelity mock-ups support rapid development and iteration. By incrementally increasing the fidelity of the prototypes, the detail of the design can be verified throughout the process. The paper discusses the benefits of prototyping on the design process, stakeholder engagement and regulatory and contractual compliance.

## Introduction

This paper draws upon the recent experience of developing trains for the UK rail network, namely the Hitachi Class 800/801 Intercity Express Train. This train is to be put into service on the East coast and Great Western main lines from 2017. An existing Hitachi cab formed the starting point for the design; this was substantially modified by a multidisciplinary design team at DCA (involving designers, engineers, human factors professionals and modelmakers) working in close collaboration with the engineering team at Hitachi.

A wide range of prototyping techniques were employed throughout the project in order to ensure the usability, feasibility and compliance of the design. These ranged from Computer Aided Design (CAD) models, to low-fidelity paper-based physical prototypes, right through to full-sized visually representative mock-ups. This paper will focus on these different approaches and discuss the individual merits of each. To communicate the approach, the development project will be divided into seven stages:

- Stage 1: Review of all relevant standards and guidelines relating to human requirements and performance to extract key requirements (e.g. PRM TSI, LOC & PAS TSI, Group standards, contractual documents)
- Stage 2: Development of additional requirements based on the requirements of the train user population and the driving task
- Stage 3: Desk-based assessment of initial train design using 2D drawings and 3D CAD models
- Stage 4: Design, build and evaluation of low fidelity mock ups (spatial arrangements based on card and paper)
- Stage 5: Evaluation of full-scale ergonomic mock ups (dimensionally accurate low-fidelity finish)
- Stage 6. Evaluation of high-fidelity full-sized model (representative fit and finish).
- Stage 7. Documentation of compliance

## Approach

*Review of product requirements*
Contractual and regulatory requirements formed the basis of the human factors requirements. The relevant requirements were summarised and presented in tabular form in order to capture the description and their origin, along with a column allowing compliance to be recorded at each stage of the development process. Wherever possible, these requirements were also summarised as a graphical representations to support their communication to the wider team.

*Development of product requirements*
While some requirements are clearly measurable and testable, such as the minimum dimensions of the driver's external door, others require further development before they can be tested. For example, the LOC & PAS TSI states that the driver's seat shall be designed in such a way that it allows him to undertake all normal driving functions in a seated position. Accordingly aanthropometric datasets of the user population (e.g. Adultdata, 1998) were also used to provide additional information such as reach envelopes for the full driver population. The requirements list remained a living document throughout the project and was updated as new requirements were identified or existing ones refined.

*Desk based evaluation of concept*
The initial layout of the cab was constructed and evaluated using Computer Aided Design (CAD) models. In the initial stages, 2D projections provide an efficient way of considering the design. Reach envelopes and mannequins based on the population extremes (as described in anthropometric data) can be used to optimise the layout for reach and visibility of controls. Likewise, in terms of external visibility, standards exist (GM/RT2161, 1995) that describe largely

unambiguous test criteria for assessing forward visibility using sightlines. 3D CAD models are also used to optimise the cab layout as the design matures.

The initial cab control layout was also informed by the guidance provided in GM/RT2161. This standard classifies each of the commonly used controls within the cab as either primary or secondary in terms of reach and visibility. By arranging the controls based on this guidance and the familiar layout of legacy trains (such as the Class 395 train), a basic design was derived. The initial control layout for the cab was also heavily influenced by the requirement to operate the combined power brake controller (the 'T' shaped handle to the left of the driver; see Figure 2). As the actuation of this control requires the use of the driver's left hand, the majority of controls and screens with touch screen functionality were moved to the right side of the cab, while indicator lamps and displays without controls (CCTV screens) that do not require actuation, were located on the left side of the cab. Functional grouping was also employed to cluster similar controls to aid the task of identification (e.g. grouping all controls to do with the control of diesel engines in one place). Likewise consideration was made of the consistency with current rolling stock and the need for future upgrades.

### *Physical evaluation and refinement of initial layouts using part prototypes*

Once a basic cab arrangement had been formulated, the initial cab layout concept was shared with stakeholders as a set of 2D panel drawings. This elicited a range of comments from stakeholders. In order to capture feedback and optimise the design, a workshop was arranged. The workshop included a range of stakeholders including representative train drivers from each of the train operators (three from each). To support this, a low-fidelity prototype was constructed (see Figure 1). This 1:1 scale mock up provided a low-cost representation of the cab panels along with controls printed on paper, allowing them to be easily repositioned. Each of the drivers performing the assessment was encouraged to rearrange the controls to best represent their ideal control layout. As expected, different drivers favoured different layouts, partly due to individual preferences and experiences and partly due to different working procedures between the two Train Operating Companies. However, through a process of rapid iteration, the group was quickly able to achieve a consensus of opinion that closely matched the original proposition.

The early engagement of stakeholders provided an extremely useful method for validating the design and accommodating changes before significant design work had been undertaken. It is, however, important to draw the distinction between stakeholder-informed design and user-led design. The low fidelity mock up allowed the physical space constraints of the cab to be communicated. In addition, a human factors specialist was involved throughout the process to communicate the importance of control grouping and spacing.

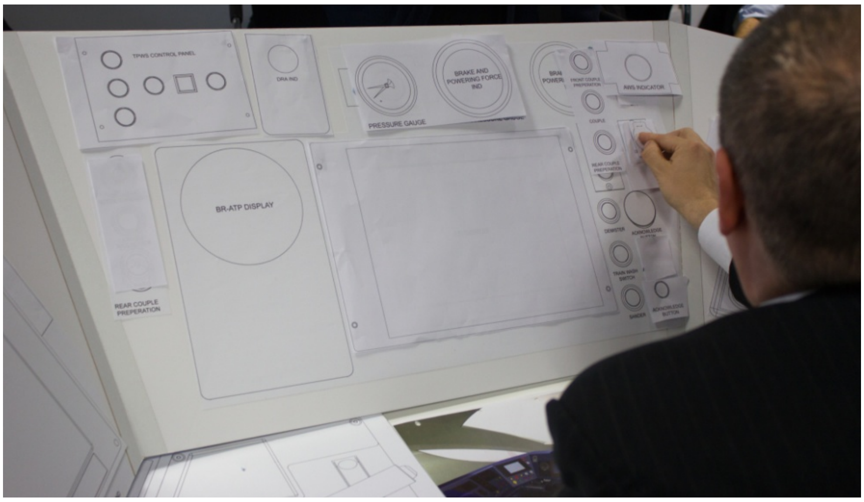


**Figure 1: Validation of early control layout**

*Evaluation and refinement of full-sized spatial mock ups*

Once an agreed design had been established, the design was revised in CAD and represented in a full-size spatial ergonomic mock up (see Figure 2). A second phase of assessment with train drivers was conducted to further refine the design. The addition of a fully functional production chair allowed a more accurate assessment to be made. As such, further refinements were made based on reach and visibility and the comfort of the posture required to actuate each of the controls.

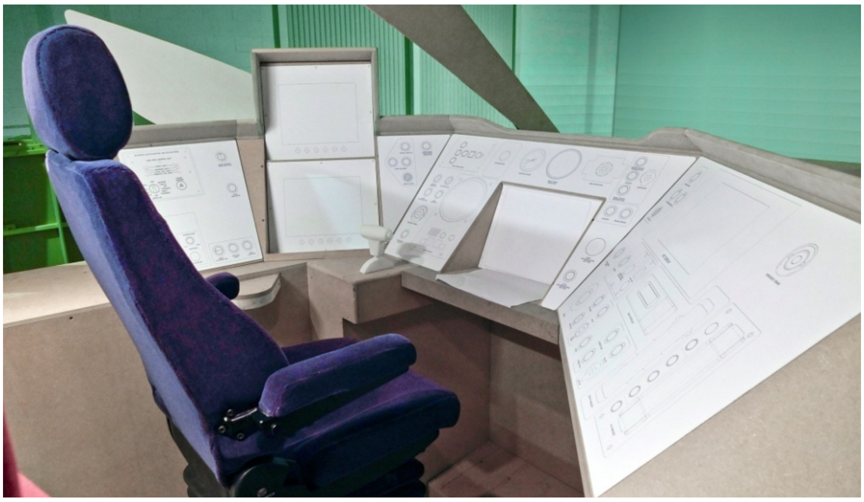

**Figure 2: Validation of control layout in ergonomic mock up**

*Evaluation and refinement of full-sized visually representative mock up*

Following the ergonomic mock up, a 1:1 scale visually representative mock up of the cab was constructed (see Figure 3 for internal view and Figure 4 for exterior view). This mock up adds an additional level of fidelity by using production versions of the driver's seat and controls, as well as providing representative colours and surface finishes.

Alongside fitting trials assessing comfort and reach, the full mock up was used to conduct a glare study (see Jenkins et al, 2015). Unlike assessment of other factors, such as forward visibility, there are no standardised approaches for performing assessments of glare. While it is unrealistic to evaluate every possible lighting condition that may potentially occur in the vehicle cab in service, a pragmatic and practical approach was taken to provide a good level of indicative information about the cab design's likely glare performance against internal and external light sources. The assessment of internal light sources involved blacking out the cab windows and assessing the impact of glare from internal lights and illuminated controls. The impact of external lights was assessed by simulating external light sources (e.g. the sun, other trains' headlights) by illuminating the cab mock up windscreen, side and door windows with a single light source manually located in a sequence of discrete positions and orientations and assessing the resulting glare impacts (see Figure 4). As a result of the glare study, modifications were made to the cowling along the top of the cab control console, internal lights were recessed, control panel angles were adjusted, and a patterned film was added to the side windows. The glare study was repeated following these modifications to the cab and found to confirm their effectiveness in terms of reduced instances of direct and indirect glare.

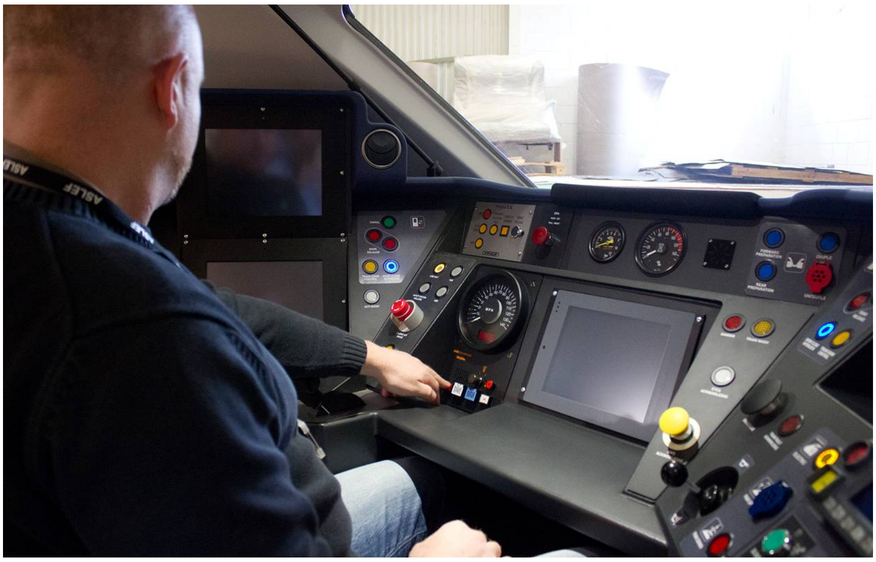

**Figure 3: Final mock up**

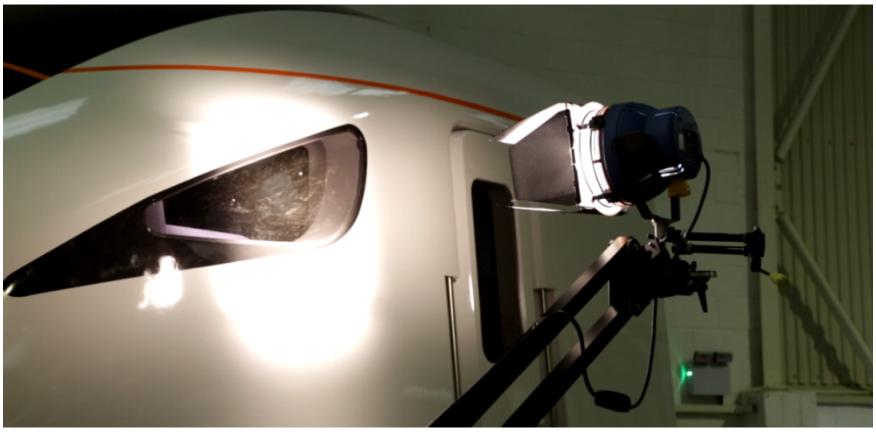

**Figure 4: Arrilite light source on a Hague CamCrane K16DV aligned to one of the positions on the train side window**

Formal assessments of the train operating tasks were also conducted in the full mock up. A structured approach for assessing a train cab against task requirements was developed. The assessment is divided into two stages; (1) the first assessed the location of each of the cab controls in turn against their frequency of use, functional grouping, and risk of inadvertent operation. (2) The second assessed the cab against routine tasks based on a Hierarchical Task Analysis (HTA) model. For the initial static assessment, a list of all the controls within the cab was compiled in tabular form (87 controls). Columns were added to the table to capture the control type, location, frequency of use, and whether the control was used while driving or stationary (e.g. door controls). Three train drivers (recruited to represent both Train Operating Companies, both genders and a range of statures) were asked to actuate and assess each of the controls in the cab in turn, observed by a human factors expert. For each control, the driver was asked to report any concerns or issues with visibility, reach, risk of inadvertent operation and suitability of posture while actuating. The driver's comments were recorded in the table along with any additional observations from the human factors expert.

In order to assess a cab against common tasks, or sequences of operation, some form of task description is required. Ostensibly, task analysis involves breaking down a task into smaller sub-tasks or operations. Arguably, the most commonly used and well-known task analysis technique is Hierarchical Task Analysis (HTA; Annett et al 1971). HTA involves breaking down the task under analysis into a nested hierarchy of goals, operations and plans. The end result is an exhaustive description of task activity, which, importantly for the train driving task, can be distilled down to modelling the actuation of individual controls. Despite HTA being one of the most commonly used human factors approaches, as reported by Rose & Bearman (2012) there are few examples of HTAs that cover train driving in the public domain. As such, the option of adopting an existing HTA model for the purpose of this analysis was not available. Rose & Bearman (2012) present a task analysis model of train driving for the purposes of identifying human factors issues in new rail technology. However, the model they discuss is based on goal-directed task analysis, a variant of HTA that places a focus on situation awareness. As a result of this focus on situation awareness, the model is primarily concerned with the cognitive aspects of the task, and does not contain the detail of the physical control manipulations required for this analysis. Accordingly, the first stage of the process was to create a task model that included individual manipulations of controls. Initially, an HTA model was built based upon a Class 395 operating manual and cross-referenced against the model created by Rose & Bearman (2012) and a report by Haworth et al. (2005; Based on the Australian railway) to ensure its completeness. The overall goal of the train driving specified at the top of the hierarchy is broken down into sub-goals (for example, start-up, drive train, manage communications). In turn, these goals were decomposed further until an appropriate operation was reached (e.g. place foot on DSD pedal, depress plunger, check for alarm, and check CCTV). The first draft of the HTA model was validated with two train driver experts on two occasions to ensure its suitability and completeness. The validation process involved stepping through the model task-by-task (in a tree view format), adding additional detail and validating the plans. Once an agreed task model was finalised, the task steps (nodes) were coded to indicate which of the tasks would be explicitly assessed in the cab. Omitted tasks included elements that were not supported by the mock up (for example, data entry on the train management system, or using the key to unlock the door). In addition, sub-routines that had been previously assessed a number of times were also omitted. The resultant model contains a total of 513 nodes (360 base level operations) of which 187 tasks were explicitly tested.

The task model was taken into the cab in list form and the drivers were asked to perform each of the tasks in the order dictated by the HTA (read aloud by the human factors specialist). After each task step, the driver was asked to report any concerns or comments about the current layout. These were recorded in an additional column in the HTA table along with additional observations from the human factors specialist. Detailed assessments included an assessment of ingress and egress, an assessment of emergency evacuation of the driver's seat and the second person's seat, assessments of standard driving tasks, and an assessment of emergency procedures. The adopted approach proved to be an effective mechanism for validating the cab control layout. Specifically, the system design and the associated number and location of controls were challenged and in some cases simplified as a result of the process. The static assessment ensured that each control was considered and evaluated in turn. In addition, the sequenced assessment identified a number of issues that are unlikely to have been detected from a static assessment alone. Moreover, the clear structure of both assessments has allowed them to be readily communicated to the wide range of stakeholders involved in the project, thus supporting prompt and well considered decision making.

## Findings

Prototyping undoubtedly played a critical role in the design of the Class 800/801 train. As discussed, the fidelity of the prototypes, or mock ups, was gradually increased throughout the project. Creating physical representations of the train very early in the design process allowed initial concerns to be addressed and challenged. One notable example of this relates to the initial cab layout. Some drivers raised concerns with the layout when reviewed as 2D panel diagrams; however, once they experienced them in a 1:1 mock up the drivers perceptions were changed. Upon further examination, the 2D drawings were not immersive enough for the drivers to perform an accurate assessment of the complex trade offs between visibility, reach and the risk of inadvertent operation.

At each stage of the process the fidelity of the prototype must be traded off with the acceptance of risk and the time taken to generate the prototypes. At early stages, where the design is more fluid, it is generally acceptable to use low fidelity prototypes that can be rapidly generated and modified. Towards the end of the design phase, as the design matures, more detailed assessments such as the impact of the surface finish on glare and the perception of space need to be addressed. The two new methods (for assessing train driving tasks and glare) would not have been possible without a 1:1 mock up.

There are a number of exciting advancements in the field of computer aided design (CAD) and virtual reality (VR) that have the potential to replace the need for prototypes at a number of stages in the design process. The experience gained on this project, however, is that there is yet to be a suitable replacement for at least one physical mock up. While digital prototypes can provide high quality representations of the final design, and VR can give a perception of space, they are yet to provide the same space perception that can be gained by a physical mock up. Furthermore, a physical representation was found to be an excellent mechanism for co-creation and stakeholder discussions. The full sized mock up acted as a central talking point, encouraging stakeholders to collaboratively discuss design issues at the same location and time.

In the future, it is conceivable that high-fidelity mock ups may be replaced by a series of digital alternatives. These may include CAD models with ray-tracing to assess the impact of glare, and high quality visuals to assess appearance and perception of space. However, it is expected that these digital alternatives would need to be supported by a low-fidelity 1:1 physical mock ups along with smaller part prototypes of elements of the design.

Ultimately, the cost of generating high-quality mock ups (fiscal and time) must be weighed up against the cost of the digital alternatives and any increased or reduced project risk.

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