An ergonomic design for a HMI of locomotives in a CBTC system

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Summary: A key component in a CBTC (Communications Based Train Control) system is the interface with the human operator, where the operator interacts to the system, interpreting information, exchanging data and issuing commands. The HMI (Human Machine Interface), that is installed onboard of locomotives, must be designed to accommodate many objectives, from safety and usability issues to production improvements. To achieve such objectives, ergonomics and usability studies must be properly conducted; otherwise the final result will likely produce a wrongly designed solution when trying to handle conflicting needs and very distinctive information.

This paper presents the studies and the evolution of a design for a HMI of locomotives in a CBTC project at MRS Logistica S/A, a major heavy-haul railroad in Brazil. Many aspects were considered and the HMI design evolved from an initial layout created by the software team with no ergonomic design to a final configuration where ergonomics and usability requirements were applied, modifying completely the layout of the screens. The HMI of the MRS´s project had to accommodate three different sources of information: vital signaling information that provides the movement authorizations for trains; non-vital information that provides the operational conditions in the vicinity of trains; and events from the locomotives coming from event recorders.

Index Terms: Ergonomic Design, CBTC, Train Control, Heavy Haul operation.

1. INTRODUCTION

MRS Logística is a concessionary that controls, operates and monitors the Brazilian Southeastern Federal Railroad Network, formerly owned by the government, as a branch of the National Railroad Network. The company has been in operation in cargo railway transportation since 1996. It interconnects the states of Rio de Janeiro, Minas Gerais and São Paulo.

The company has 1,674 km of railways that make the transportation process easier in a region that concentrates approximately 65% of Brazil's gross domestic product and is home to the largest industries in the country. Through MRS' railways you can also reach the ports of Sepetiba and Santos (the most important in Latin America).

Figure 1 below shows the location of the MRS Logística network.

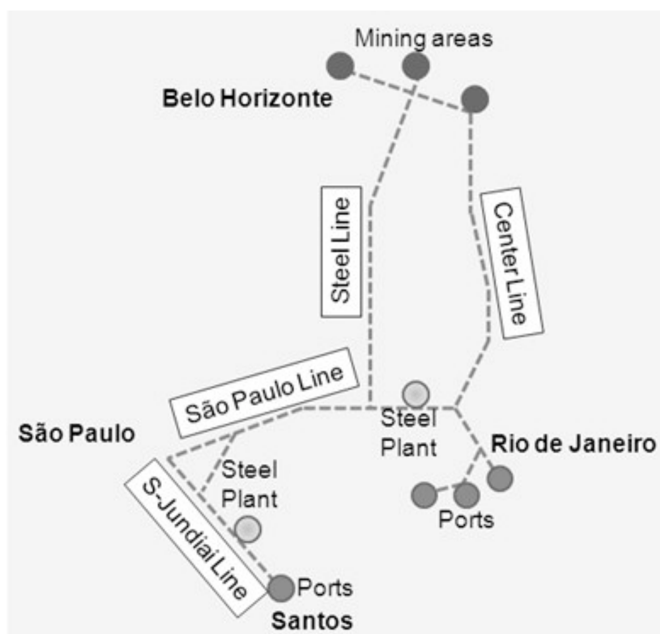

Figure 1: Simplified Map of the MRS railroad lines

1.1 The MRS´s CBTC system

The MRS's CBTC system, known as SIACO (Integrated Operations Control and Automation System) is equivalent to ETCS (European Train Control System) Level 2, even though it's not fully compliant to ETCS.

Figure 2 below depicts the system and its components.

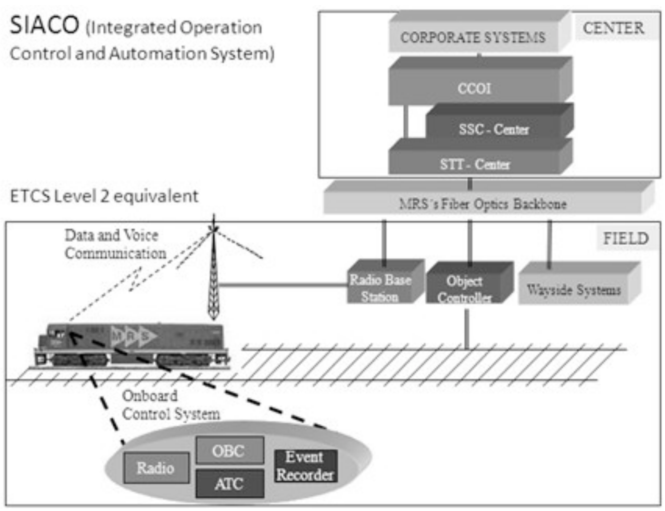

Figure 2: Architectural diagram of the SIACO System

- Integrated Operational Control Center (CCOI, in Portuguese). Provides the features for the management of the railroad (train dispatching and monitoring) and also integrates information coming from all systems involved with the railroad operation and other corporate systems;
- Signaling and Control System (SSC, in Portuguese). Responsible for the signaling system of the railroad. It is composed of a Safety Logic Subsystem (SLS) component in the Center side, and Object Controllers (OC) in the field. In the final system configuration, all the signal aspects of the existing CTC system installed along the line will be removed as the new signaling system interacts with the onboard component of the locomotives;
- Onboard Control System (SCB, in Portuguese). Responsible to provide a human machine interface (HMI) - essentially a conventional computer device (OBC – Onboard Computer) that allows Train Conductors to interact with the system. The SCB shall also guarantee the safe movement of trains through a vital component - the ATC (Automatic Train Control) - that enforces train movements according to the SSC authorizations. The SCB also provides non-vital features that implement operational procedures and monitors train operations, increasing the efficiency, safety and predictability of the railroad operation. Another component of the SCB - the Event Recorder - is responsible to acquire locomotive data in real time for telemetry purpose. A final component – the Electronic Jumper – provides means for the Train Conductor to control other locomotives in the Consist that are physically connected to the Lead Locomotive. The Event Recorder and Electronic Jumper are bundled together in a single component – the REJE (Portuguese initials for Event Recorder and Electronic Jumper);
- Wireless Data and Voice Communication System (STT, in Portuguese). Responsible to provide wireless data services along the entire railroad.

The SIACO system is being provided by three main providers: Alstom Brazil – providing the CCOI, SSC and SCB (OBC and ATC); EADS (European Aerospace Defence System) – providing the STT and Radios; Accenture-Atan – providing the REJE.

2. CONCEPTS AND REQUIREMENTS FOR THE DEVELOPMENT OF THE HMI

2.1 Operational Requirements

The SCB, as designed in the SIACO Project, had to address two major requirements that are essential for the train operation:

- Vital Implementation requirements: these are the requirements associated with the Vital components of the system - the SSC and the ATC. The SCB has to provide means for the visualization of the instructions that are mandatory for the train circulation, like Movement Authorization and Speed Limits, both controlled by the ATC. The SCB must also provide access to commands like ATC Mode recognition, Warning Recognition and other that will affect the vital control of the train movements;
- Non-Vital Implementation requirements: these are the requirements associated with the Non-Vital components of the system - the OBC and the CCOI. The SCB has to provide

access/visualization of many operational information that helps the operation of a train, like the visualization of extended train movement authorization, position and movement authorization of other trains in the vicinity, description of train activities in yards, train composition, maintenance activities in the line, track layout and topography. The SCB should also provide features that allow the interaction of the Train Conductor with Dispatchers at CCOI when executing special non-vital operations like coupling trains or entering/leaving a signaled area.

Besides these major requirements, the SCB was also required to provide means for the Train Conductor to interact with the REJE information, like temperature, oil pressure and alarms issued when thresholds are reached. It should also provide means for the Train Conductor to control the other locomotives of the train consist attached to the Lead locomotive, through the Electronic Jumper, like controlling the throttle or activate the horn of those locomotives.

2.1 System Architecture and Conceptual Design of the SCB

The first issue in the design was to decide what types of user interfaces would be needed to address all the requirements. Initially, there was an approach to provide Vital and Non-Vital IHMs for the Train Conductor. This approach was due to a concept that a Vital implementation would require a Vital HMI, so a Train Conductor would never receive any wrong information that could be the case, if a Non-Vital HMI was used. However, this concept was questioned and the conclusion was that there was no need for a Vital HMI, since the ATC was able to keep operating in a vital condition even if the HMI fails. So, if, for instance, the HMI fails and displays a higher speed limit, the ATC would still not allow the train to trespass the correct limit.

Once concluded that all the user interface requirements could be satisfied by Non-Vital HMIs, the next step was the decision on how those should be arranged for the Train Conductor. The first approach had designed two HMI, one that would satisfy the REJE requirements and another that would satisfy the other requirements. However, once a more detailed analysis of the requirements was made, it was concluded that all the requirements could be satisfied by a single HMI.

Figure 3 illustrates the final architectural design of the SCB, with all its components.

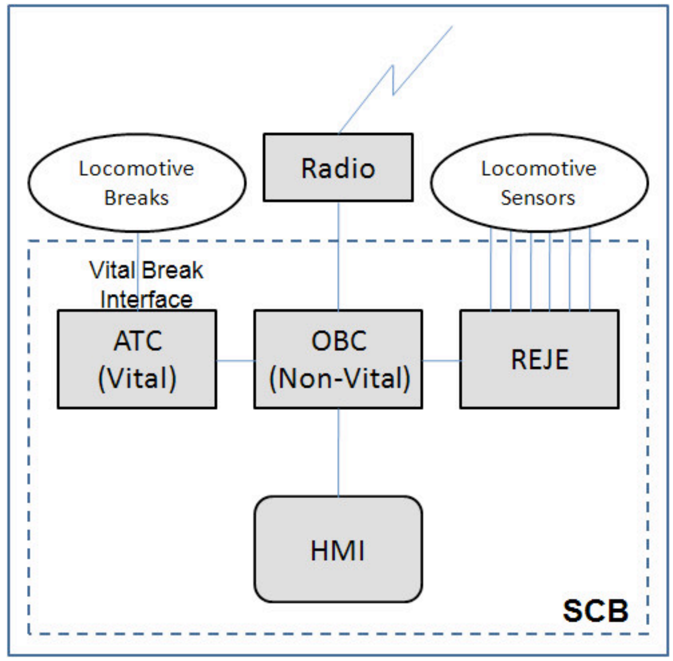

Figure 3: Architectural diagram of the SCB

3. INITIAL HMI DESIGN APPROACH

3.1 Distribution of Information and Access of Functionalities in the HMI

The development of the HMI was conducted by the MRS Project team and a Development team from Alstom Brazil. The first design step was the arrangement of the information from the three different components – ATC, OBC and REJE in a single HMI. After discussions and analysis with final users, the HMI was split into three areas.

Figure 4 bellow illustrates the distribution of the areas.

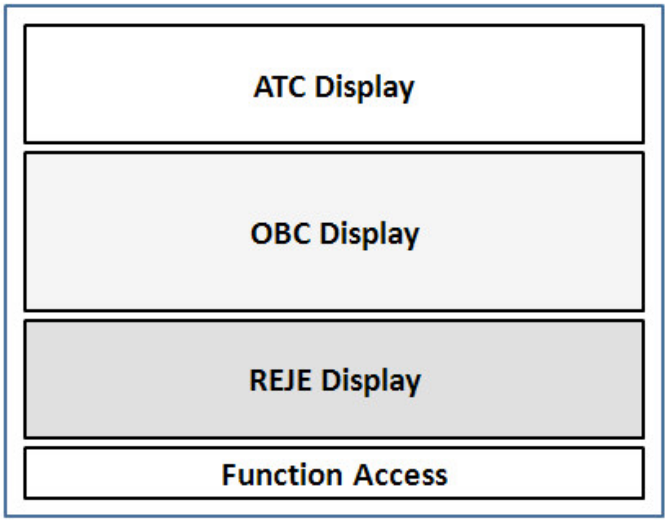

Figure 4: Distribution of information in the HMI of the SCB

Once the group display areas were established, those were filled with the information from each system which, in a summary, was the following:

- ATC: Current Speed, Speed Limit, Direction, ATC Mode, Time to Penalty, Acceleration and ATC Messages;
- OBC Display: Track Layout showing the condition in the vicinity (other trains and operational restrictions), Track Inclination and Curvature;
- REJE Display: Condition of the other locomotives in the Train consist, like locomotive id, throttle, current, status and alarms.

Figure 5 below shows the initial layout of the HMI.

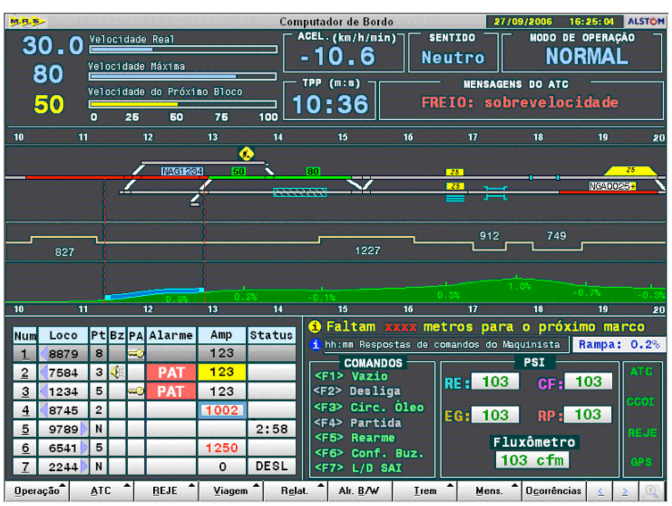

Figure 5: Initial screen layout (developed without ergonomic approach)

3.1 Initial User Validation Methodology

The final layout as shown at Figure 5 was achieved actually with no formal ergonomic approach from Alstom. The design was initially arranged by software developers after discussing the interface in brief sessions with the Project team and some final users. Once a prototype was released by the developers, it was submitted to final users in another brief "validation" session. During the validation session, the development team asked the final users about which colors they prefer and if the position of the information was good enough, taking notes of the comments made. The validation session used no actual hardware, but images projected in a conventional wall screen in a room. After a few sessions a "final" version was released.

The development team was also not considering any further steps to rearrange the screen. The validation sessions should be enough to guarantee a satisfactory operational condition of the screen.

4. THE ERGONOMIC DESIGN METHODOLOGY

To evaluate if the screen proposed by Alstom was designed with proper usability requirements and would be easily operated by Train Conductors, some Human Computer Interaction (HCI) methods and techniques were selected and applied in a two phase process.

The goal in the First Phase was the identification of all the issues that had usability problems and would demand improvements. For that, the heuristic evaluation method was applied. This method is an informal interface inspection, where experts evaluate each interface element that interacts with the user, driven by the ten heuristic usability principles defined by Nielsen [1]:

- Visibility of system status;
- Match between system and the real world;
- User control and freedom;
- Consistency and standards;
- Error prevention;
- Recognition rather than recall;
- Flexibility and efficiency of use;
- Aesthetic and minimalist design;
- Help users recognize, diagnose, and recover from errors;
- Help and documentation.

During the first phase, Focus Groups were also set and assigned to discuss the issues raised in the heuristic evaluation and validate a new screen proposal. The Focus Group is a technique where a group of users discuss their impressions about the issues raised and share their points of view.

With the results obtained from the First Phase, a new screen proposal was compiled, better addressing the user needs. However, this new screen should still be evaluated in an actual train operation in the field, which demanded the analysis to pass through a Second Phase, where other techniques were applied, like assistematic observation and video/photo records. As a conclusion of this Phase, some other adjustments in the screen were identified, regarding color, contrast and brightness, especially when used at night.

From the issues identified, new proposals were developed with different colors, contrast and brightness, to be evaluated in a train operation in different periods of the day. During the evaluation, satisfaction questionnaires were used, where visual comfort, readability and good appearance aspects were asked. After analyzing the results of the evaluation, two new screens have been defined – one for day light and another for night usage. It was also suggested a feature to allow the user to alternate between the two screen options.

5. REVIEWING THE HMI WITH AN ERGONOMIC APPROACH

5.1. Analyzing the results from the First Phase

The results of the evaluation developed during the First Phase pointed out many problems in the way the system was presenting information to Train Conductors: too much colors; legibility problems due to the text font selected and how it was presented; no differentiation of the background colors of distinct areas in the HMI; bad distribution and arrangement of information; no prioritization neither highlight of relevant information.

The excessive number of colors used, which was around twenty two different colors was one of the main problems identified. Colors in onboard display of control systems that provide critical information shall be used with caution, as the main function of colors in such systems is to highlight hazardous conditions (using red, yellow or orange colors), as well as identify normal states in the system (green color). Excessive colors in a display make it confusing and may become impossible to distinguish colors, especially the ones that mean a hazardous condition. According to Andre et al [2], when projecting an onboard display, it should be considered initially a monochromatic screen and add colors only to identify a relevant information. NASA apud Andre et al [2] suggests that such onboard display should have no more than 9 distinct colors, including black and white colors.

The legibility of the information is also a relevant aspect. A good legibility is achieved by the combination of the visualization distance, contrast between letters/symbols and background and the relationship among colors, characters size, font type and spacing of letters. In many aspects, the initial screen developed by Alstom had legitibility problems, like the information in the OBC display and the titles of the Function Access menu. The text font used was also not appropriate for this type of display. Green et al [3] recommends the sans-serif font Helvetica for onboard displays, alternating from upper to lower case. For its similarity with the Helvetica for also being sans-serif, the Arial font is an alternative, as it is a popular font, usually available in most of the fonts data base.

Another aspect raised was related to the background colors. The initial proposal used one single color (dark green) in the entire screen, making it impossible to differentiate the three operational groups – ATC, OBC and REJE – and the Function Access. The differentiation is relevant because the Train Conductor needs to know from which system the information comes, especially the ones from the ATC, which are critical for the train operation.

Despite of having some organization on how the information were spread in the screen, some group of information or single information were not properly arranged or were occupying areas in the screen that should display more relevant information. This bad organization was located in the lower right side were the brake pressure and communication diagnostics among other information were put together, giving the impression they were randomly placed. As said before, it’s very important to distinguish different areas in the screen, so the Train Conductor can easily recognize its origin.

In the ATC display area, the lack of priority and proper emphasis of information was the main problem. Actual Train Speed, Speed Limits and Time to Penalty are essential information for the Train Conductor and these information were not properly emphasized to allow for an easy reading during the operation of the train, at the same time as non critical information had unnecessary emphasis in the screen.

A new screen proposal was, then, designed to provide a more suitable option, taking into consideration the problems identified in the initial screen, interviews with key users and the technical viability of the Alstom software.

To validate the new screen proposal, a Focus Group composed of ten Train Conductors, a Moderator, an assistant and technical support (technical team from Alstom) was organized. The discussions started with the description of the behavior of the system, from the point of view of the new operational concepts and then new HMI proposal was presented in details, depicting the screen areas and graphical elements. Each detail was exhaustively analyzed, with the goal to collect the opinion of all the Train Conductors of the group. All the discussions were video recorded for later analysis and validation of conclusions.

As a result, some modifications were requested by the Train Conductors. Those requests were based on the own knowledge of the Train Conductors about their tasks when operating a train. This is an essential input for the design of a HMI, as the user is the best judge of what is relevant to perform his tasks.

Taking into account those requests and the legibility requirements, as the size of the characters at a maximum distance of 700 mm (suggested distance for good onboard display visualization), a new proposal of a screen for the HMI was developed. The sizes of the characters were defined from the guidelines defined by Andre et al [2] and Stevens et al [4]. (see Figura 6 below).

Figure 6 – Revised screen layout (after Firs Phase evaluation)

5.2. Results from the Evaluation of the Second Phase

Initially, the new screen proposal was designed with colors, contrast and brightness according to ergonomic requirements for computerized interfaces as well as the requirements for the tasks to be performed onboard. The colors were mostly light for the efficiency in environments where there's sunshine daylight. It allows for a better visibility of the screen during the day, minimizing the effects of solar light reflection in the screen. On the other hand, this type of implementation in dark environments would not work well (too much bright), so it was proposed to reduce the brightness of the monitor (hardware adjustment), to avoid the Train Conductor to be dazzled, allowing a good external visualization. However, the OBC hardware has a limited capacity of brightness adjustment, and even at the lowest brightness of the monitor, the screen was still too bright to be operated at night, making it hard for a Train Conductor to have a good external visualization.

The selection of ideal colors, considering its luminance level, for the locomotive onboard computer, depends on the amount of light and sunshine that get inside the locomotive through the windows. When there's too much light, like in daylight conditions, the ideal is to use clear colors in most of the screen, being the background light, with letters, numbers and graphs in dark colors (positive polarity screen), to guarantee a good contrast of the information displayed. On the other hand, when the environment is mostly dark, the ideal is to have a dark background in contrast with letters, numbers and graphs in light colors (negative polarity screen). This combination reduces the quantity of light emission of the screen and avoids the dazzling the Train Conductor during the night. So, the ergonomic design of a computer screen that is operated 24 hours a day, suggests the usage of at least two screen options for the user to select – a positive screen for daytime operation and a negative screen for night-time operation [2], [3], [4].

However, as the development of a feature to alternate from the two screen options shown to be a complex task for the Alstom development team and also because of the limitations on the brightness adjustment of the monitor, just one single screen would have to be selected. Four new screen options were, then, designed and submitted to users in evaluation tests in diverse conditions. The four screen options had darker colors than the ones from the First Phase, as the main problem identified was the dazzling condition when operating at night.

All the five screen options (the one from the First Phase and the four options from the Second Phase) were tested with Train Conductors inside a locomotive with static screens displayed in the OBC. After analyzing the results of questionnaires filled by the Train Conductors, a darker screen (negative polarity screen) was selected, to be used either when it's daytime or night-time (see Figure 7).

Figure 7: Final screen layout (after the Second Phase evaluation)

Besides being a negative polarity screen, one of the main characteristics of this screen was the option of an amber color for the neutral information, which is similar to another locomotive system installed in the MRS's locomotive fleet – the Locotrol (GE Transportation distributed power control system). This similarity harmonizes the lighting ray emission inside the environment and contributes with the recognition of information in a user cognition process.

6. ANALYSIS OF THE FINAL HMI DESIGN

The problems related to usability of information systems and HMI, cause influence to the performance of users and ultimately accidents whose origin is a "human error". However, studies have shown that "human error" related accidents may be avoided if the design and development of systems and its HMIs take into account the characteristics of the users and their tasks while operating the system. This is a critical issue to develop a functional and efficient system.

According to Santos [5], it's not enough just apply legibility or diagramming requirements without taking into account the user characteristics, the requirements to performs his tasks and the environment where the task is executed. The ergonomic criteria, methods and tools to evaluate the development of user interfaces must be proper applied in conjunction to get actual improvements in the usability of an interface.

The user opinion is fundamental for the development of a user interface. In a HMI project, more than technology or the system itself, it must be properly addressed the communication among the elements that are interacting in a specific context. When inserting the human element into the whole context, the technology itself can't drive all the design process of an interface [5].

So, as experienced with the development of the onboard HMI of the SIACO project, it requires more than a superficial evaluation from software developers and analysts to successfully develop an easy to use, comfortable and safer HMI. There are various ergonomic criteria, methods, techniques and tools that must be applied when developing computerized interfaces that provide proper human-machine interaction.

The first HMI developed for the OBC had many problems because neither the ergonomic and usability criteria nor the analysis of the user tasks were considered, which culminated with the development of a very confusing and polluted screen, which might easily lead a Train Conductor to mistakes when operating the system. After applying an ergonomic approach, driven by ergonomic experts and taking into account the human element in the process, it was possible to achieve a much better solution for the onboard HMI.

7. REFERENCES

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