AMSTERDAM METRO CAB: ERGONOMICS IN THE DESIGN, VERIFICATION AND VALIDATION PROCESS

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The Amsterdam Metro System replaces their 30 years old rolling stock for new metros. To our knowledge this is the first rolling stock purchasing project (in The Netherlands) that explicitly uses EN 50126 for RAMS requirements. This has implications for ergonomics in design, verification, and validation. The process of ergonomic design of the driver's cabin is described, and the results of the major layout are shown. It is discussed how theory and practice of this approach related. It is suggested that there is added value in combining ergonomic co-design parallel to building up evidence of compliance.

Introduction

The Amsterdam metro series M2/M3 are after more then 30 years at the end of their technical/economical lifespan. The Amsterdam municipal bureau AMSYS (Amsterdam Metro System) with support of the city's public transport operator GVB has ordered 23 metros from Alstom to replace the M2/M3 series. The new series are called M5/M6 (Figure 1).

As part of the Functional-Technical Specification Demands AMSYS/GVB has required the supplier to deliver an independent ergonomic analysis of the driver's cabin. This shall prove that the cabin complies with the Dutch occupational health act (ARBO) and with ergonomic guidelines:

- *The Supplier shall let an independent ergonomic evaluation report be drawn up of the suggested design of the driver's cabin and the passenger area. This shall prove that the design complies to the ARBO and ergonomic requirements. The independent ergonomic evaluation report shall be completed at the latest in phase 6 of EN 50126.*

- *At the latest in phase 6 of EN 50126, after the Client has agreed to the ergonomic evaluation report, the Supplier shall build a first version mock-up of the driver’s cabin on a scale of 1:1 as soon as possible. This mock-up is equipped with a driver’s seat and a dashboard with the main control instruments and will be placed on a location in Amsterdam to be determined. The Client has 1 month time to judge the first version of the driver’s cabin mock-up.*
- *The Supplier shall, in phase 6 of EN 50126, after the review of the Client, build a final integrated mock-up of the driver’s cabin and a part of the passenger area placed on a location to be determined in Amsterdam. The passenger area contains an entire carriage body including half of the first articulation and is closed off by a foto-wall of the following interior. This mock-up is suitable for reviewing functionality and design and to implement changes. The Client has 2 months time to judge the definitive version of the integrated mock-up.*
- *he driver's cabin shall comply with the most up-to-date directives related to ergonomics and with the legal requirements prescribed in the scope of ARBO (Dutch safety, health and welfare) requirements.*
- *The cabin interior shall be a suitable work space for drivers with a body height of at least 1600 to 2000 mm.*

Alstom has commissioned Intergo to perform the independent ergonomic assessment. However, due to time constraints the assessment has been transformed into co-engineering with Alstom. This article describes the ergonomic development of the driver’s cabin of the new Amsterdam metro, including the verification and validation process.

Figure 1: The old M2/3 metro (left) and the new M5/6 (right)

Applicable law and guidelines

EN 50126-1 (1999) describes the specification and demonstration of RAMS of railway applications. It contains the following definitions of verification and validation:

- *Verification: Confirmation by examination and provision of objective evidence that the specified requirements have been fulfilled.*
- *Validation: Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use have been fulfilled.*

In EN 50126-1 subclause 5.2.9 this is further clarified by stating: “The objective of verification is to demonstrate that, for the specific inputs, the deliverables of each phase meet in all respects the requirements of that phase. The objective of validation is to demonstrate that the system under consideration, at any step of its development and after its installation, meets its requirements in all respects.” As the ergonomic assessment is part of the requirements for phase 6 ‘Design and Implementation’ by definition nearly all our activities were aimed at verification. However, the verification activities cannot be seen apart from the broader perspective of validation.

Also, EN 50126-1 specifically asks for an analysis of human factors (subclause 4.4.2.3). Subclause 4.4.2.4. states: “Human factors can be defined as the impact of human characteristics, expectations, and behaviour upon a system. These factors include the anatomical, physiological and psychological aspects of humans. The concepts of within human factors are used to enable people to carry out work efficiently and effectively, with due regard for human needs on issues such as health, safety and job satisfaction”. Although it is recognised that in a metro system several human groups are involved, the scope of the ergonomic assessment is limited to the driver and the instructor.

According to the Specifications the driver’s cab and driver desk must comply with the Dutch legislation on the occupational health, safety and welfare of employees; the so called “Arbowet”. The aim of the “Arbowet” is to prevent accidents (safety) and to avoid illnesses caused by work (health). The “Arbowet” has no specific requirements on the driver’s cabin and driver desk. The UIC 651 standard describes the specific requirements for the driver’s cabin and desk of rail vehicles. Although not specifically aimed at metro rolling stock, UIC 651 was used in this project taking into account:

- The larger Dutch body dimensions: it was required by the customer that a range of body statures of 1600 to 2000 mm (and preferably 2005 mm) was accommodated instead of 1600 to 1900 mm in UIC 651.
- Other relevant human factors / ergonomics standards and guidelines, like ISO 11226 on static working postures and ISO 9355 on actuating controls and displays.
- Extensive experiences with the ergonomic design of cabins/desks in other rail vehicles (Intergo: e.g. Dutch Railways, NSHispeed, GVB trams; Alstom: Barta et al, 2011; Miglianico, 2010).

The design, verification and validation process

The following activities were undertaken in the design, verification and validation process:

- Task analysis. A thorough understanding of current and future operational and task characteristics - including rolling stock, infrastructure, procedures - is needed to be able to identify risks of changes in driving strategies, controls, etc. One must realise that a period of mixed operation of old and new metros will occur.
- AmDriver mock-up (1). Based on a preliminary design Alstom built a low-level wooden mock-up (Figure 2 upper left). This basically consisted of a wooden console, pictures of controls and information, a driver's seat, walls and constructional constraints. This mock-up was evaluated using 6 experienced Amsterdam metro drivers of divergent body characteristics. Anthropometric data from DINED2004 regarding the Dutch working population were used. The required range of body statures (1600-2000 mm) was transformed to corresponding percentile values to be able to evaluate dimensions that depend on other anthropometric variables.
- AmDriver mock-up (2). Based on the first evaluation session design optimisations were implemented, like an improved shape of the console, relocated controls, and tilt of displays. Furthermore, the mock-up was extended with design features like a model windshield and roller blind (Figure 2 upper right). Using the same 6 drivers the optimisations were verified, and the new features were evaluated.
- 3D Manikin validation. During the entire AmDriver phase design changes were validated using the extension modules 'Human Builder', 'Human Measurement', 'Human Posture Analysis', and 'Human Activity analysis' of the 3D CAD design software Catia V5 R19 (Dassault Systemes). These modules were formerly known as Safework manikin, which is recognized as one of the most versatile 3D manikin models for ergonomic analysis (Seidl & Bubb, 2005). The default anthropometric database in Catia was adapted to the Dutch DINED2004 data to be able to evaluate design using the critical small female (body stature 1600 mm) and large male (body stature 2000 mm). The AmDriver phase was concluded with a report stating closed and open ergonomic issues (Frieling & van der Weide, 2010).
- AmStyle mock-up. This mock-up is a 1:1 model of the driver's cabin and 3 passenger compartments. It contains most functions, materials and colours of the real metro. Apart from driving, this mock-up gives the complete 'look and feel' (Figure 2 lower left). In this phase access and egress, windshield, roller blind, some actuator controls and lighting were first to be verified. The AmStyle phase was concluded with a report stating all closed ergonomic issues, a few unresolved issues, and suggestions for evaluation of ergonomic issues that cannot be validated

in a mock-up, like dynamic information presentation, driving behaviour, and climate control (Frieling & van der Weide, 2011).

- Test drive. Although not part of this project, the authors were given the opportunity to engage in a test drive in Amsterdam, which we used as an informal validation. The main train control display is missing in this vehicle, because of adaptations to the Amsterdam train protection system (Figure 2 lower right).

Figure 2: AmDriver mock-up (first session: upper left; second session: upper right), AmStyle mock-up (lower left) and test drive (lower right)

All (interim) reports about the ergonomic verification and validation were assessed by the customer purchase team. Also in this team ergonomic expertise was incorporated (the GVB ergonomist).

Results

For purposes of available space, in this paper only the results of design verification and validation of the major layout of the driver's cabin is presented. The driver's workplace is mainly determined by three principles whereby 1 + 2 = 3; i.e. the required body support follows from lines of sight and operating controls:

1. View on the track and on displays (lines of sight)

2. Operating the controls by hand and feet
3. Supporting the body in driving position / working posture

Lines of sight
According to the requirements, a driver must be able to see the track at a distance of 8.5 meter in front of the vehicle. This requirement is more strict than the requirement in UIC 651, because this is the closest distance that some metro trackside signals must be seen from. In combination with the proposed window dimensions and console height it was apparent from the AmDriver sessions that lines of sight for a small woman (1600 mm) would be critical. Evaluation with the 3D manikin showed that the requirement would not be met when in driving in a 'normal' driving upper body posture (10 deg. backward - UIC 651) (Figure 3). However, when in an 'active' upright posture the requirement is met. Because of the low frequency of the required line of sight - and short duration – this is judged to be acceptable. As expected, evaluation for medium and tall drivers showed no problems with required lines of sight.

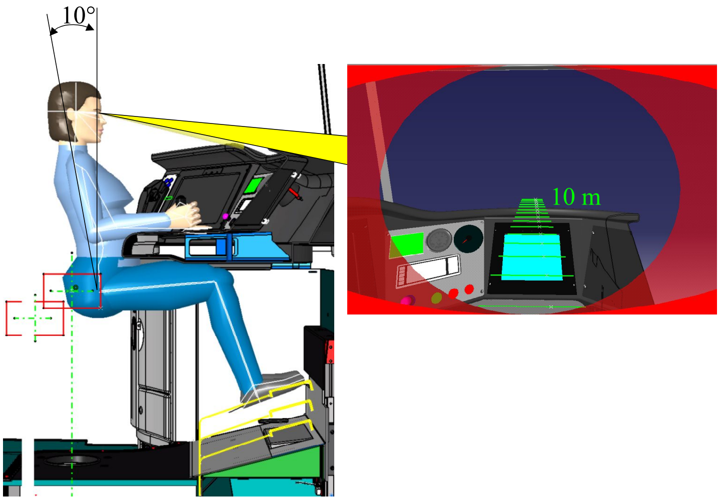

Figure 3: View for a small woman (1600 mm body stature) on the track. It is shown that for normal driving posture (upper body tilted 10 deg. backward) the track at 10 m distance can be seen.

The angle of the displays was determined to be 37 deg. backwards to the vertical. This angle is in the range of UIC 651 and a compromise between the view on displays and the view outside on the track (the more upright the displays the higher the console, thus obstructing view outside). The view is perpendicular on the screen for the average driver.

Actuating controls
In the AmDriver stage also the position of displays and actuator controls was determined. Ergonomic principles like frequency of use, importance, sequence,

but also existing conventions in Amsterdam metros were leading. For displays, viewing angle and distance were relevant, and for controls reaching distance was critical. The master controller (traction and brake) and door opening/closing buttons are of major importance and most frequently operated, and should be within primary reaching zones. The position of the master controller was determined to be in line with the right arm support of the seat. As the seat was required to be the 'standard' GVB seat (supplied by SAVAS), the lateral location of this (fixed) armrest is known. The AmDriver sessions learned in which area the master controller was preferred to be located by the drivers. Analysis with the 3D manikin determined the optimal location: the master controller is placed 110 mm from the edge of the desk (at centre) and in line with the armrests (270 mm from centre). The height of the master controller handle is 130 mm (measured from the desk). Again, the small woman is critical in this analysis. Figure 4 shows the results: the upper arm flexion is 3 deg., upper arm abduction 20 deg. and lower arm almost horizontal, which is within accepted comfort ranges in e.g. ISO 11226. The favourite shape of the handle according to the drivers is a smooth cylinder without texture (diameter 35 mm); ergonomically this is also acceptable. The main problem that arose in earlier stages of this analysis was the thickness of the master controller box. The complete unit would protrude several centimetres below the desk, thus impairing drivers to choose an optimal body posture. The 3D analysis visualised this problem, and convinced Alstom to redesign the master controller box: the new design now fits into the desk (75 mm thick).
The same kind of analyses was performed for other controls, although reaching distance and posture criteria are different because of lower frequency of use.

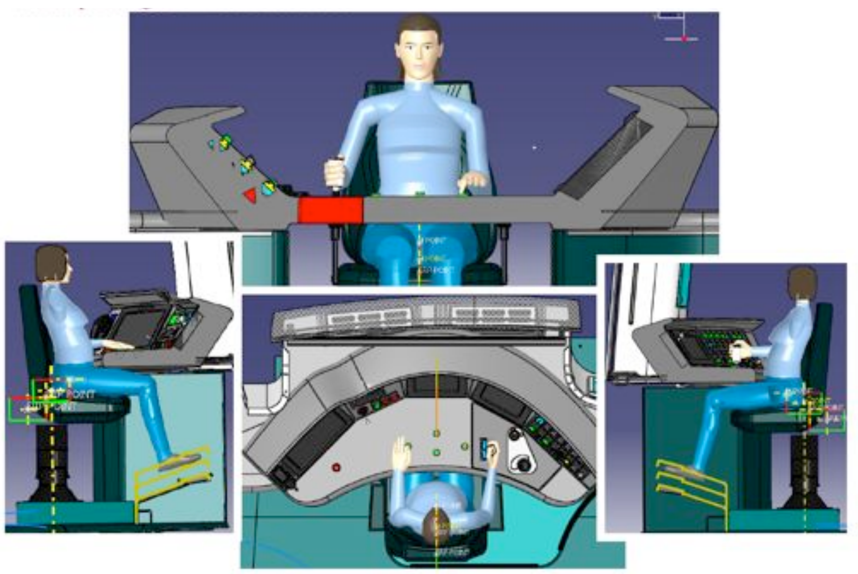

Figure 4: Body posture for a small woman (1600 mm body stature) in normal driving posture (upper body tilted 10 deg. backward) when operating the master controller and pushing ‘door open’ button

The main device to be operated by foot is the deadman’s pedal mounted on the adjustable footplate. The driver has to activate this safety device frequently to show that he/she is still physically capable to drive the metro vehicle. Ergonomic aspects of the deadman’s pedal are very important because of the almost permanent use of this safety device and the strong influence on the sitting position. Some ergonomic guidelines for the deadman’s pedal are:

- Principle: intermittent (no static physical load)
- Actuation: mainly by one foot / also possible by other foot (or by both feet or by hand)
- Operating position: front edge of pedal 5 mm above the footrest (natural foot position)
- Material: smooth metal plate (in contrast with embossed metal plate of foot rest)

The proposed design of the deadman’s pedal was not compliant with the latter 2 of these guidelines. Also, task analysis had revealed that the current position of the pedal in the ‘old’ M2/3 metros is designed for use by the left foot. The proposed design of the new pedal was aimed at operation by the right foot. To mitigate the risk of unintended non-operation of the pedal (which would cause the vehicle to emergency stop), this design was mirrored. The result is shown in Figure 5.

Figure 5: Adjustable footplate (embossed) with smooth deadman’s pedal just left off centre and actuating pedal top left

Body support

Body support for optimal (range of) body postures consists of a footplate and a seat.

The footrest can be adjusted easily in height with a separate pedal (top left). The embossed metal plate is slip resistant and creates a tactile contrast with smooth metal plate of deadman's pedal. The plate has small ridges at the side for cleaning purposes (Figure 5). The required range of adjustability follows from the analysis shown in Figure 3 and Figure 4; in these figures the Heel Point (HP) in its highest position can be seen. The same analyses with the tallest man determine the lower limit of the adjustable footplate. The same analyses also show the range of Seat Reference Points (SRP): these determine the adjustability range of the seat in fore-aft direction and in vertical direction. The standard SAVAS seat of GVB is compliant with these ranges, when equipped with the larger 120 mm gas spring.

Discussion

To our knowledge this is the first rolling stock purchasing project (in The Netherlands) that explicitly uses EN 50126. From an ergonomic / human factors perspective this is evident in:

- A clear division in roles and responsibilities between customer and supplier
- Clear ergonomic requirements in the Strategic and Functional-Technical Specifications
- Explicit verification and validation activities required

In this case this meant that the supplier was responsible to deliver an independent prove of ergonomic compliance of the driver's cabin. However, due to time constraints customer and supplier agreed that the independent assessment was built up during co-design activities of the assessor. Thus presuming that the result – an ergonomically compliant cabin – would be reached quicker.

The results and the process certainly indicate that the presumption has become true. Both customer and supplier are satisfied. Application of ergonomics in the role of co-designer has various advantages compared to the sole assessor role:

- Ergonomic expertise is used in a constructive way (focus on improvement) instead of an evaluating way (focus on what is wrong)
- Design and building up proof of compliance (verification and validation) are done in parallel instead of serial (possibly with several iterations), which is time efficient
- Optimal use of strength of all parties involved (ergonomics, design, mock-up builder)
- Early and continuous end-user (driver) involvement

The above points lead to a process and a product that is both better in quality and in time; acceptance by the customer and end-users is better guaranteed.

Potentially, there may be a conflict of interest between the independent assessor and co-designer role. However, the ergonomic validation report that is produced contains traceable and verifiable evidence. Ergonomic expertise on the customer side to audit both process and result should further guarantee that these different roles do not interfere.

A limiting factor of the approach chosen is that the independent ergonomic assessment is constrained to phase 6 (design) of EN 50126. Certainly, the major ergonomic adjustments to the design can be made in that stage. However, more dynamic issues related to actual driving, like MMI-behaviour, light/lighting, climate, vibrations, etcetera, are out of scope for this assignment.

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