HUMAN FACTORS ENGINEERING IN DESIGN OF SMART AUTONOMOUS TRAM SYSTEM

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ABSTRACT

To promote the user-centered design of autonomous transportation systems a holistic integrated approach is required. We introduce a human factors engineering (HFE) program that provides guidance to the accomplishment of HF activities throughout the design process. The program consists of nine activities that can be performed in an iterative fashion. Here we present how main HFE activities have to be executed in order to promote the user-centered design of smart autonomous trams. Lessons learned from the ongoing SmartRail project and from some of our earlier projects have been identified and discussed.

KEYWORDS

Human Factors Engineering, Smart Autonomous Tram, User Centered Design, Concept of Operations

1. INTRODUCTION

Our aim is to develop a holistic framework for the user-centred design of smart autonomous tram systems. We will apply good practices of ecological design and Human Factors Engineering (HFE) approaches. Research is conducted under 'The SmartRail ecosystem', in which the aim is to foster the transition from traditional transportation systems towards an advanced service and business ecosystem consisting of a smart autonomous tram and integrated digital services (https://smartrailecosystem.com/). The SmartRail research project supports industry projects and promotes collaboration between different stakeholders and facilitates the building of an ecosystem around the smart tram concept. The research project aims to integrate knowledge areas of transportation service chain and users, connectivity and automation, and low carbon and energy efficient solutions (https://smartrailecosystem.com/).

There is a trend towards increased automation of transport systems and promotion of services that are based on high levels of automation, and there are previous and ongoing attempts to develop autonomous tram systems (e.g., the autonomous Siemens tram). The autonomous Siemens tram was launched in Potsdam during the InnoTrans 2018 Exhibition, and it performed a couple of demonstration drives with hundreds of passengers (Palmer et al., 2020). Furthermore, there are several ongoing attempts to develop autonomous public transportation systems, for example in Dubai (https://www.rta.ae/links/sdt/en/index.html) and in the Czech Republic (https://www.fdu.zcu.cz/en/Partnership/ForCompanies/AutonomousTram.html).

An autonomous tram is driverless, that is, the tram is circulating along its route without a driver sitting in a driver's seat. A fleet of trams is operated from a remote control center, where operators monitor the fleet or individual trams, and intervene in the operation of a tram in challenging situations.

The design task, i.e., the development of automatic tram, is challenging because the tram needs to operate in an open infrastructure. The automatic tram will also introduce new job roles, because tram drivers are replaced by fleet operators. Furthermore, there are several other worker groups such as technicians and traffic controllers whose work will change. Autonomous trams will also change the game from the perspective of passengers and other road users. Hence, operating a fleet of autonomous trams will introduce new human factors challenges that have to be taken into careful consideration (Laarni & Väätänen, 2023).

We introduce a HFE program that has been developed under the SmartTram project in order to better understand the human factors issues in the design of the automatic tram system. There are several reasons for taking a closer look at human factor issues in the design of autonomous tram systems. It has been found that complex engineering projects do not always proceed as has been originally planned. One of the main reasons for missed deadlines and budget overruns is the lack of socio-technical systemic approach in the design work, that is, the social and organizational complexity of the environment in which the systems are used is not considered to a sufficient degree (Mumford, 2006). Similarly, experiences from several design projects have shown that the demand to deliver systems within budget and on schedule has resulted in insufficient attention to HFE considerations in system engineering (Madni, 2010). It is also typical for the organization to drift away from the systems engineering and human factors standards it still believes it is following (Mumford, 2006).

HFE is a scientific approach to the application of knowledge about human factors and ergonomics to the design of complex technical systems. It can be considered as one engineering framework among several others under the systems engineering discipline. It can be divided into tasks and activities in terms of which stages of the design process they are related to. Typically, HFE activities are classified into four groups: analysis, design, assessment, and implementation/operation. In the analysis phase, all critical analyses providing background information and context for the design work are performed, in the design phase human-system interfaces, procedures and training activities are developed; in the evaluation phase, the design systems and activities are verified and validated; and finally, in the operation phase, in-service monitoring of the new systems is performed.

It is well known that the way the design work is carried out and how the human and organizational issues of the design are analysed during the design process has implications in how humans interact with the designed system in the future (e.g., Electric Power Research Institute, 2015). HFE activities are concurrent, iterative processes conducted to reduce project risks at different stages of the design work. HFE activities should both aid design work and progressively promote risk reduction during the lifecycle. HFE does not only enable to avoid accidents and to increase efficiency of technical systems, but it also enables to reduce project costs and to produce improvements in performance and productivity (Booher, 2003).

The following activities are typically included in the HFE approach for complex technical systems such as smart tram systems: management and planning including screening and grading of HFE activities, operating experience review, function allocation and analysis, task analysis, treatment of important human actions, manning, operator selection and qualifications, system design and development, design of maintenance activities, procedure design, training design, verification and validation, and commissioning and in-time monitoring. In the next section, the main HFE activities in design of smart autonomous tram systems are described in a more detailed fashion (see Figure 1).

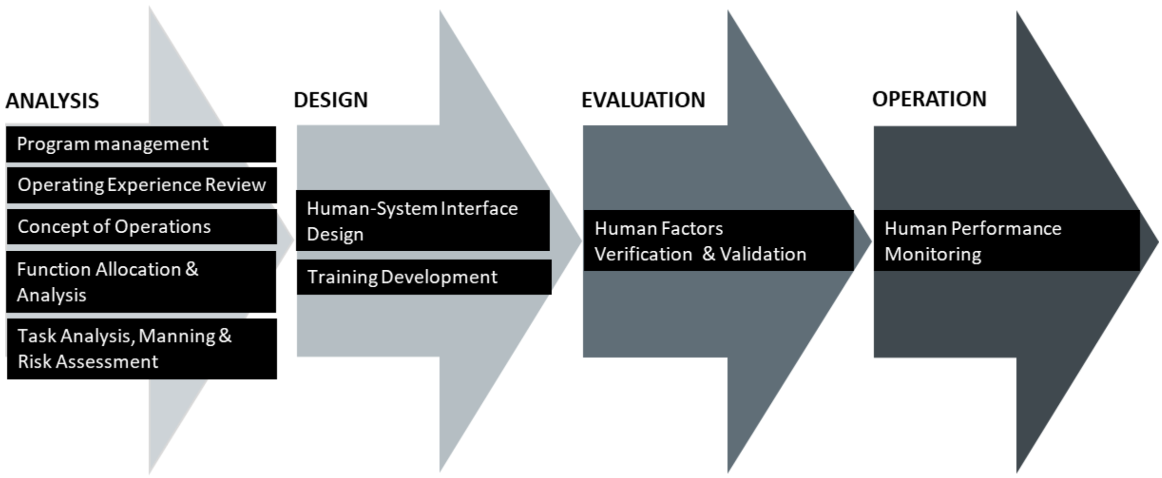

Figure 1. The main elements of the HFE process model for the design of autonomous tram systems

2. MAIN HFE ACTIVITIES IN DESIGN OF SMART TRAM SYSTEMS

2.1 Project Management

Project management is required at all the stages of the design process to efficiently integrate HFE activities into the design of an autonomous tram system (Bruseberg, 2008). In this first stage of the project, a detailed plan is needed for HFE, which is applied in parallel with the system development plan. The HFE program plan provides guidance to the accomplishment of individual HFE activities throughout the project.

Screening/grading, in which the impacts of the new design are determined in terms of complexity and safety impact in order to tailor HFE activities for design targets, is typically performed early in the project. An early-stage screening process is important in determining the emphasis and amount of effort allocated to HFE activities. In general, most of the efforts should be paid on the treatment of high-risk activities (Electric Power Research Institute, 2015).

2.2 Operating Experience Review

The aim of the operating experience review activity is to better understand current work of tram drivers, identify possible operational problems that can be addressed in smart autonomous trams and collect potential experiences with autonomous driving in other domains. Data is collected by interviewing tram drivers, trainers and traffic controllers. Tram drivers are experts in identification of potential hidden dependencies between activities that may at worst trigger an accident. It has also been valuable to discuss with experts working on research and development of autonomous road vehicles. For example, lessons learned accumulated over years in the development of autonomous cars are highly relevant in the design of autonomous tram systems.

2.3 Development of a Concept of Operations from the Perspective of Main Stakeholders

One of the first tasks in the analysis stage is to develop a Concept of Operations (ConOps) for the new system. The ConOps method was introduced by Fairley and Thayer (1997) as a bridge from operational requirements to technical specifications. ConOps can be considered as a transitional design artefact promoting the requirements specification activity during the early stages of the design (Laarni & Väätänen, 2023).

An overall Concept of Operations (ConOps) has to be defined for the smart autonomous tram system in the beginning stage of the design project. The objective is to specify the main aims of a smart rail system, potential challenges and open questions, identify key use cases and develop a Concept of Operations from the perspective of various stakeholders and user groups (Laarni & Väätänen, 2023; Figure 2). Recently, Laarni and Väätänen (2023) developed a ConOps for an autonomous smart tram system to demonstrate how smart trams can be applied in public transportation in the future. The ConOps for an autonomous tram system consists of, e.g., concept for human-autonomy teaming, identification of main operational states and of characteristics of user interfaces for supervising the tram fleet and occasionally controlling individual trams (Laarni & Väätänen, 2023).

2.4 Function Analysis and Allocation

Functions are activities that have to be performed in order to achieve a particular goal. Examples of main functions in the operation of an autonomous tram system are, e.g., approaching and passing a tram stop, approaching a pedestrian crossing, and crossing a street junction (Laarni & Väätänen, 2023). They can be presented in a hierarchical manner, from high-level functions to more detailed functions at the lower levels of the hierarchy. The primary aim in function analysis/allocation is to specify main functions and allocate functions of fleet operation in such a way that operator capabilities and capabilities of the autonomous tram system are used in an optimal manner. Furthermore, the aim is to identify the design consequences of allocation decisions.

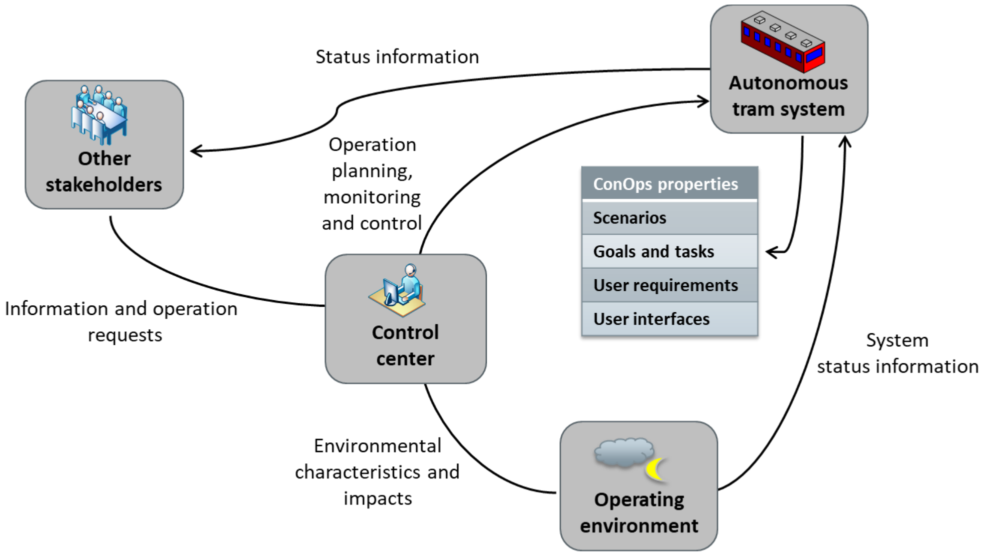

Figure 2. ConOps diagram for a smart autonomous tram system (modified from Laarni & Väätänen, 2023)

Function analysis determining what is required to perform a particular function provides input to function allocation (e.g., Electric Power Research Institute, 2015). Function analysis should be conducted to 1) determine the objectives, requirements, and limitations of the interface between the operator and the autonomous control unit; 2) specify the functions that must be accomplished to meet the objectives and required performance; 3) define the relationships between functions and the autonomous control unit responsible for performing the function; and 4) provide a framework for understanding the role of controllers (whether personnel or system) for controlling the tram (e.g., Electric Power Research Institute, 2015).

Function allocation describes the allocation of responsibility of the supervision and operation of a fleet either to an autonomous agent, a fleet operator or some combination of the two. Function allocation is optimized by selecting an optimal level of autonomy for each level of a function. Potential failures and malfunctions are also considered, including how they will be detected and what actions will be required to deal with the situation (e.g., Electric Power Research Institute, 2015). For each function, we have to determine whether an autonomous agent or human action is required and feasible and allocate the function either to an autonomous agent, to a human or share the allocation between both entities (e.g., Electric Power Research Institute, 2015).

2.5 Identification of Main Stakeholder Roles, Task Analyses and Risk Assessment

In the next activity, the aim is to first identify main worker groups and networks of groups (i.e., who participate in the fleet management); second, to identify and specify the main tasks included in the fleet management and analyze them (i.e., what kind of tasks are included in the use of tram systems, and what kind of subtasks can these tasks be divided into); and third, it is analyzed the dynamics of the activity and identified and specified the main risks and hazards associated with the activities.

Task analysis focuses on the analysis of functions that have been allocated to a fleet operator so that requirements can be specified for user interfaces that the operator needs in order to accomplish the human actions. Its main aim is thus to ensure that necessary fleet operator tasks can be successfully performed. Each task is described in sufficient detail so that requirements for task support can be specified. Typically, the task requirements include all the information, controls, alerts and other operator aids that are required for successful task performance (Electric Power Research Institute, 2015).

Based on our interviews we conducted with experts on public transportation, manning, operator selection and qualifications are important issues throughout the life-cycle of an autonomous tram system. The main goal of manning and qualification analysis is to show that the requirements for the number and qualifications of operators has been systematically analyzed and specified, and task requirements of manning and qualifications are well understood.

The objective of the assessment of risks and hazards is to identify and analyze critical operator activities and the potential of errors associated with the activities. The Functional Resonance Analysis Method (FRAM) was used in hazard analysis (Hollnagel, 2012). Several challenging activities were identified in tram operation related, e.g., to carelessness of pedestrians and car drivers, consequences of emergency braking and passengers' boarding on or off the tram. The FRAM method is used to establish a model of a certain activity representing the main features of how the activity is performed. The model specifies the potential variability of the system in terms of main functions (Hollnagel, 2012). FRAM is based on a couple of principles, for example, successes and failures are equally valued, fleet operators are considered as proficient in adjusting their behavior to the contingencies of an actual situation, and unanticipated events may be caused by unexpected interactions of multiple functions, e.g., in demanding weather conditions. FRAM has shown to be a valuable tool in understanding the reasons behind the gap between work-as-designed and work-as-done (Hollnagel, 2012).

2.6 User-Centered Design of Smart Tram Systems

Design of a control center for the management of autonomous tram systems is based on design dialogues between various stakeholders. Also, the design of training activities (that is, determination of what kind of training and education is needed) engages various stakeholder groups.

During the design process, function and task requirements are translated and developed into human-system interface characteristics and functions. The HFE activity aims to assess the process by which design requirements are identified, developed and refined. Typically, design guides are prepared in accordance with relevant human factors engineering principles.

Based on expert interviews, also HF aspects of the maintenance of the autonomous smart system has to be dealt with, including all activities that are conducted to prevent tram system failures and repair failed tram systems. The ultimate goal is to facilitate future maintenance activities by anticipating possible future malfunctions and to strive to make the systems more error-resistant.

Training must be performed to acquire the skills for using and maintaining the HSIs of the control center, and to adapt to new job practices. The aim is to develop training programs that teach skills fleet operators need in order to perform their critical duties in an adequate manner. Training design is based on systematic analysis of job and task requirements. The output of the design work is a concrete training program. Typically, the systematic approach to training design is based on four activities, analysis of training needs, design of training, implementation of training, and evaluation of training effectiveness (e.g., Laarni et al., 2011).

2.7 Verification and Validation, and Human Performance Monitoring

Verification and validation (V&V) activities are performed to ensure that the human-system interfaces of the control center are well designed and easy to use, and they fulfil main performance requirements (Koskinen, Laarni et al., 2021). A special attention has to be paid on the implementation of operator-autonomous system interaction. V&V is then planned to the evaluation and testing the operator's interaction with the autonomous system. It consists of the determination of acceptance criteria, execution of the test activities and the analysis of test results.

The verification and validation process must be iterative by nature, and there must be a systematic procedure for aggregating and systematizing V&V data. We have applied the Systems Usability Case (SUC) approach which enables a requirement-based human factors evaluation of complex systems (Koskinen, Laarni et al., 2021). SUC is based on Safety Case thinking and on the application of the Systems Usability construct. According to Koskinen, Laarni et al. (2021), SUC can be seen as a conceptual procedure within which a reasoning process takes place enabling a shift from abstract understanding of human performance and usability of complex tools to a concrete proof of an autonomous tram system, and finally to understanding of what is learned about the overall acceptability and level of Systems Usability of these systems.

In the implementation phase it is evaluated that all HFE issues have been adequately resolved and closed out. It is also designed the practices for the documentation and deployment of operating experiences throughout the system's life-cycle (i.e., human performance monitoring).

3. DISCUSSION

Many authors and organizations have called for a more integrated and holistic approach to HFE. According to Madni (2010), two kinds of integration of HFE activities with systems engineering are needed: Since the HFE area is quite fragmented itself, the HFE activities have to be first integrated with each other; after that they can be integrated with system engineering domains.

One of the key requirements for a unified HFE process for the design of autonomous tram systems is to start human factors activities as early as possible in the design process and continue them throughout the life-cycle of the autonomous tram system (cf., Koskinen, Laarni et al., 2021). When HF issues are considered late in the process the required changes become costly, and they are not necessarily any longer optimal to the problem (e.g., Bruseberg, 2008). In addition, it is also possible that HF issues will be treated in an inconsistent and fragmented manner, if the HFE process is started in the later stages of the design work.

There are clear benefits of HFE in autonomous tram system design: It is a support function through which HF problems and challenges can be avoided and mitigated throughout the project lifecycle (e.g., Bruseberg, 2008). HFE activities provide input to the design of autonomous tram systems, and they also function as a quality control at various stages of the design process. HFE experts play a mediating role between operating personnel and designers of an autonomous tram system and in establishing contacts between different parties. HFE also has a critical role in mitigating operational risks due to the fact that potential problems and risks can be better identified at early stages of the project when applying HFE.

We have focused here on the establishment of a HFE program for the design of a control center for fleet management. The focus has thus been quite narrow. To develop a similar integrative program for the SmartRail ecosystem, a broader Human Systems Integration (HSI) perspective may be feasible. According to Booher (2003), HSI takes an overarching holistic approach and integrates knowledge of various areas of human and organizational factors to promote systems engineering activities.

ACKNOWLEDGEMENT

The research was funded by Business Finland under the SmartRail 2 project.

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