



HAL
open science

PRODEC-Based Task Analysis for the Design of Semi-Automated Trains

Yang Sun, Guy André Boy, Marc Sango, Anne Barros

► **To cite this version:**

Yang Sun, Guy André Boy, Marc Sango, Anne Barros. PRODEC-Based Task Analysis for the Design of Semi-Automated Trains. *Complex System Design and Management*, Oct 2023, Beijing (Pékin), China. pp.220-230, 10.1007/978-981-99-6511-3_20 . hal-04313336

HAL Id: hal-04313336

<https://hal.science/hal-04313336>

Submitted on 29 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PRODEC-based task analysis for the design of semi-automated trains

Yang Sun^{1,2}[0009-0006-0696-5884], Guy André Boy^{1,3}[0000-0002-0497-7949], Marc Sango²[0009-0001-9671-5136], and Anne Barros¹[0000-0002-3386-453X]

¹ CentraleSupélec, Université Paris-Saclay, France
(yang.sun, guy-andre.boy, anne.barros)@centralesupelec.fr

² SNCF SA, Paris, France
marc.sango@sncf.fr

³ ESTIA Institute of Technology, Bidart, France

Abstract. The deployment of high-speed automated trains is a worldwide objective for railway stakeholders. The French railway operator SNCF has conducted several safety-oriented analyses and studies to better understand Automated Train Operation (ATO) impacts. But none of them is supported by human-the-loop simulation (HITLS). In PRODEC, AS-IS scenarios based on existing declarative configurations can help to project TO-BE scenarios based on new declarative configurations of the system to be designed. This paper is dedicated to the task analysis of the scenarios selected and constructed by safety analysis. The comparison between the train driver's tasks in AS-IS scenarios at Grade of Automation 1 (GoA1) for manual driving and the train driver's tasks in TO-BE scenarios at Grade of Automation 2 (GoA2) for teaming with ATO and ETCS enables to discover design gap and tasks evolutions to project potential functions and infrastructures.

Keywords: Railway, Safety analysis, Human System Integration, PRODEC, Human-in-the-loop simulation, BPMN.

1 Introduction

Automated trains take part in global increasingly autonomous mobility. This solution is expected to be more ecological, as well as to provide increased capacity and greater flexibility to the railway system. The International Association of Public Transport (UITP) and the International Electrotechnical Commission (IEC) defined four levels of automation for railway automation [1] [2]. From Grade of Automation 1 (GoA1) up to GoA4. Current trains operating within SNCF railway infrastructures are at GoA1 under manual driving. From SNCF automated train vision, the following decade is a key period for automated train design and deployment. The introduction of the European Rail Traffic Management System / European Train Control System (ERTMS/ETCS) and Automatic Train Operation (ATO) enables the transition from

GoA1 to GoA2. At GoA2, ATO is available when its operation conditions are met. ATO can take charge of acceleration, braking following the signals and recommendations of the ERTMS/ETCS. Train driver and ATO share the driving task once ATO is activated. This paper addresses the application of PRODEC [3] in the railway to analyze human tasks in the early design stage of the automated train operating system on GoA2.

Human performance cannot be separated from the organization and available technology. A good understanding of the aiming technologies on automatic driving is critical for both designers and train drivers. This is the basis for the analysis of the evolution of human roles and tasks. Based on ATO and ERTMS specifications, we model the process map for selected scenarios using Business Process Model and Notation (BPMN) [4]. BPMN standardizes the visualization of the process map and clarifies related tasks. More specifically, BPMN-formalized scenarios facilitate exchanges between various engineers and operators and support the clarification of tasks and responsibilities of the train driver when teaming with ATO. In our case, BPMN is used to support the specifications of technical systems and visualize the interaction between operators and systems. Humans differ from machines in that they do not do exactly what they are supposed to do. In other words, their activity is not necessarily the same as the task they are supposed to perform. Activity results from the performance of task executed by cognitive and/or physical functions [5]. Environment and allocatable resources can also affect the results of task execution.

PRODEC is a scenario-based design method [6], [7], based on two fundamental concepts: the declarative configurations of the system and the procedural scenarios [3], [8]. Since human activity is complex and hard to predict, human-in-the-loop simulation (HITLS) allows us to observe the natural human reaction in a simulated environment close enough to reality. By observing the differences between tasks from designed scenarios and activities from simulation results, emergent functions can be elicited and contribute to improve our initial design. More generally, these comparisons enable the discovery of emergent properties, projecting new functions and potential infrastructure(s) that will define the projection of the next TO-BE configurations of the sociotechnical systems being designed and developed. This human-centered approach is based on safety, efficiency, and comfort principles that need to be defined.

2 Automated trains and safety-oriented PRODEC application

2.1 From manual driving to autonomous trains: the different grades of automation in railway

Automated trains can provide the modern railway system a better fluidity at a lower energy cost [9]. The International Electrotechnical Commission (IEC) defined the requirements and functions for four grades of automation in railway applications [2] from GoA1 to GoA4. GoA1 represents the fully manual-operated trains with Automatic Train Protection (ATP). Most of the long-distance trains today work under this

automation level. Telecommunication and information technology maturity increasing, ATO is now available to be integrated in the driving cabin on GoA2. At GoA2, ATP becomes a part of ERTMS by following the journey profile and signalizations. Nevertheless, at this level of automation, the driver is always present in the driving cabin. The driver oversees the doors open/close functions and assumes responsibility for managing the vehicle in the event of an ATO dysfunction. On GoA3, the whole train driving cabin does not exist anymore. A well-trained agent is supposed to be on board with the passengers to supervise train operation and take charge in case of emergency. And finally, autonomous trains on GoA4 are supposed to be unattended and fully automated. At this level, no agent is required to stay onboard. This level requires great capacity for situation awareness and decision making from the overall sociotechnical system.

Emphasizing the challenge today, from GoA1 to GoA2, the key evolution for train drivers is the introduction of ATO. When operating conditions are met, the ATO indicator illuminates to inform the train driver that the ATO is ready. Train driver can decide to either engage or disengage ATO during the journey. Once activated, the ATO can take over of the acceleration/braking according to the information provided by the ETCS. When the ATO is not engaged, manual driving is still possible, and the driving condition goes back to the same at GoA1. Regardless of these changes, at GoA1 and GoA2, the train driver always takes full responsibility for the safety and security of train operation under either situation.

From a system view, a system can represent either a natural or an artificial entity [10]. It means it can be either a human or a machine, hardware or software, concrete or abstract. A system can be cognitive, physical, or both [11]. Research results showing the introduction of automation in railway operation unloads the train driver from highly stressed work [12]. With the train driver's task reduction, we need to reassess the related human factors. This reassessment includes cognitive workload, attention level, and situation awareness, all factors that affect the performance of the train drivers' cognitive functions. The performance of these cognitive functions are hard to evaluate. A detailed analysis for tangible tasks performance enables the evaluation of related cognitive functions' performance by observing the differences between activities and tasks.

To identify the gap between AS-IS and TO-BE scenarios, we must first get an idea of the specifications and requirements of the future system to be designed. Back in the early 2000s, various railway signaling systems exist in European Union's member states. For example, the Thalys train which crosses the border of French, Germany, Belgium, and Netherlands is embedded with seven types of signaling systems. The European Rail Traffic Management System (ERTMS) is under deployment to increase interoperability in the EU. ERTMS includes the Global System for Mobile communications for Railways (GSM-R), which provides communication between the train and the Radio Block Center (RBC), and the European Train Control System (ETCS). ETCS provides Automatic Train Protection (ATP) and cabin signaling functionality. The cabin signaling calculates a target advice speed for each segment of the journey and displays this information to the train driver through the Driver Machine Interface (DMI) in the driving cabin. Under manual driving, the train driver decides

when to accelerate or brake according to this information and the journey profile he receives before the journey.

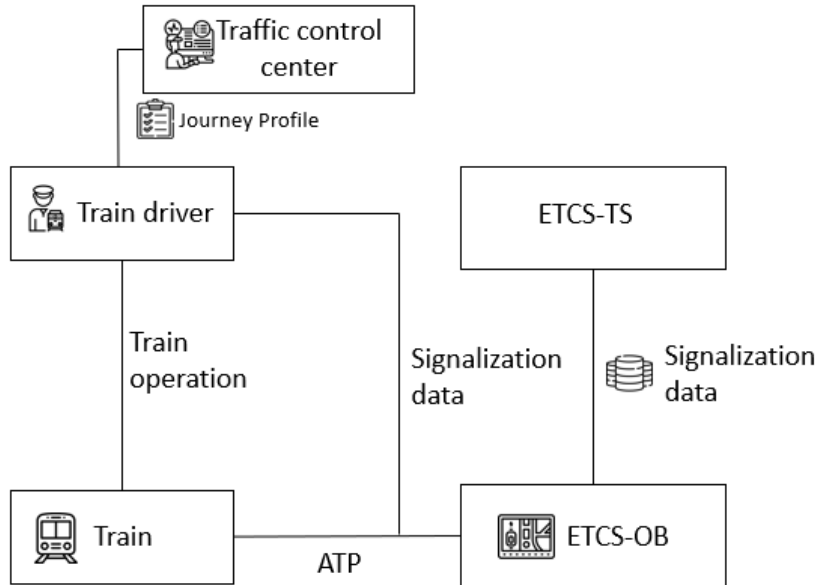


Fig. 1. ERTMS system architecture at GoA1 (adapted from [13]).

In the GoA2 configuration, trains must deploy the ATO. The ATO consists of two parts: ATO-Onboard (OB) and ATO-Trackside (TS). ATO-OB is onboard the trains and automatically drives the train while it is engaged. Before the journey starts, ATO-TS sends the Journey Profile (JP) to the ATO-OB. It contains information about the specific train (train length, brake percentage, brake position), the rail track profile (e.g., uphill, downhill, gradient, track profile), the scheduled timetable for arriving at a train station, and the ATO Operational Speed Profile. Using the JP, ATO can operate the trains based on the ETCS cabin signaling advice. Figure 2 shows the reference architecture of ERTMS/ATO. ATO frees train drivers from speed control of the trains between train stations. Nevertheless, the train driver is still in charge of door operations and communications between the other entities.

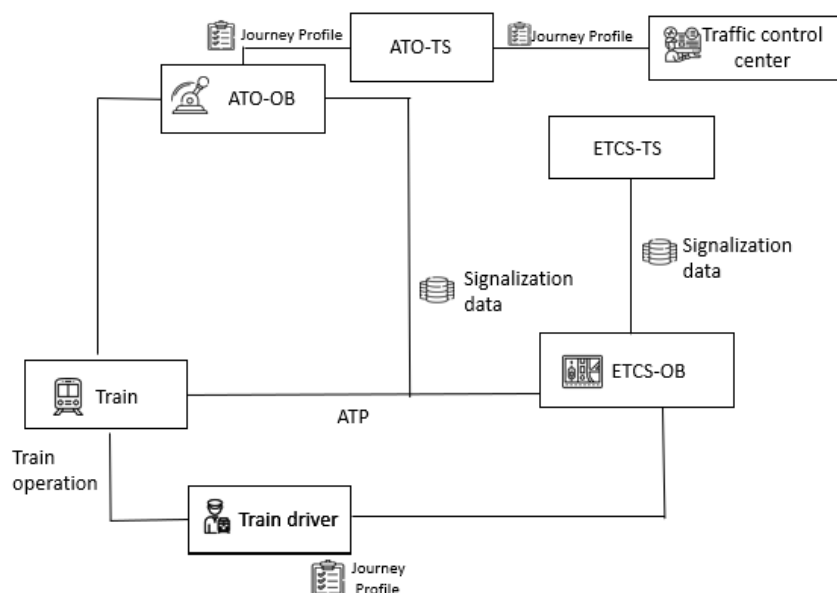


Fig. 2. ERTMS/ATO system architecture at GoA2 (adapted from [13]).

This teaming between the train driver and ATO is a concrete example of Human-Machine Teaming (HMT). HMT consolidates human-centered design and systems engineering to achieve Human System Integration (HSI) by combining human and machine properties and attributes in the same package. Indeed, a system can include machines and people, and people can include machines [3]. Appropriate physical and/or cognitive functions must then be allocated to the right human and machine systems within the overall system of systems. This is the purpose of the PRODEC method that starts by developing task analyses to better identify emerging functions to be further allocated.

2.2 Scenarios construction for safety-oriented PRODEC application

Following a good understanding of the specifications and needs for the future semi-automated trains at GoA2, we need to choose and construct the typical scenarios during train driving to build an effective presentation of train operations. Safety is always the highest priority in train operation. From our earlier research that included accident analysis and experts interviews, we identified several safety-critical conditions and events for railway operation: signaling, rail conditions, and one safety-critical area: the station [14]. For manual driving trains, several types and simulators are available for training purpose within the SNCF. From these existing training scenarios and the declarative knowledge that we learnt from practice; we selected five typical AS-IS scenarios. Based on the specifications and requirements of the future ATO application at GoA2, we foresee 5 corresponding TO-BE scenarios.

One scenario can be represented by both on-board and environmental components. Suitable environments are as the train itself in ensuring the full functionality of the rail system. For environmental factors, an obstacle on the rail can simply turn a nominal situation to an emergency on both GoA1 and GoA2. The train driver remains responsible for monitoring the environment, regardless of the degree of automation. Regarding on-board components, the safety analysis shows that signaling is another essential element for safe train operation. The most frequent type of incident in the last 8 years on SNCF network is: inadvertent crossing of a closed signal. 91% of this type of error is related to driver error according to the Rail Safety and Standards Board (RSSB) report [15]. We also interviewed a group of train drivers for their opinions on the safety analysis. From their point of view, one critical area during the journey is entering train station. The environment perception, signalization reading, and speed control are the difficulties for entering a station and stopping the train precisely on the platform. The weather is an important factor for this operation. Rain, wind and dead leaves fell on the rail can highly impact train drivers' judgement to stop the train. Therefore, we add the weather factor into our scenarios for the enter in destination station driving phase.

We classify the driving situations in three types: Typical & normal situation, Critical & Abnormal situation, and Emergency & Near accident situation. Human errors can be committed at all three kinds of situations. Minor infractions of procedures are often related to insufficient cognitive resources for physical and/or cognitive functions. Technical failures of life-critical systems can lead to different kind of driving situations depending on the driving phase of the train. Taking example of a high-speed train, dysfunction of signalization screen display before entering high-speed zone lead a typical & normal situation to a critical & abnormal situation. Because in this phase, the train driver can refer to the track side signalization to continue the train operation. However, in high-speed zone, the same technical failure leads a typical & normal situation directly to an emergency & near accident situation.

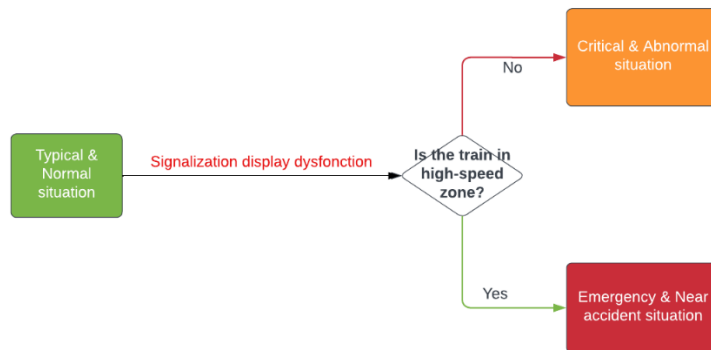


Fig. 3. Situation transitions in different phases.

Human-in-the-loop simulation (HITLS) allows to elicit train drivers' behaviors in these different driving situations. Before practicing the simulation, several preparatory works are necessary. We first divide the train journey into several driving phases: leaving the departure station, entering the high-speed zone, driving in the high-speed zone, leaving the high-speed zone, entering the destination station. A task analysis is performed for each driving phase for AS-IS scenarios (GoA1) and TO-BE scenarios (GoA2). Then we perform physical and cognitive analysis with AUTOS pyramid [5]. Human and machines can share the operation mission by performing series of functions. To ensure the train safety, some human tasks and machine tasks can be the same. For instance, from the specifications for GoA2 operation, the manual driving is always at train driver's disposal. This is a safety barrier for train operation. One possible situation is: ATO disengages without train driver's order. Under this emergency & near accident situation, the train driver needs to quickly get awareness of the situation and retake the task of acceleration/ brake according to the signalization.

3 Task analysis supports declarative modeling.

BPMN enables the visualization of scenarios and clarification of exchanges between various entities within the operating system. Each entity has his own lane in BPMN. The entity can be either human or machine. One technical system can be divided into several subsystems to precise his function. In practice, operators are not always familiar with modeling technologies and stakeholders' expectations. This visualized process model is easier to understand by all entities in system engineering. Human operators of different roles can identify themselves in BPMN to clarify his/her tasks and interactions with other entities before practice. By involving different entities and roles, we can align the stakeholders' expectations and the domain experts' fields experience in one common agreed model.

As a step of PRODEC application, we modeled manual driving (AS-IS) scenario and semi-automated driving (TO-BE) scenario in normal situations. We did a task analysis for the two automation grades to analyze the impact of the introduction of ATO on train operation. Task analyses clearly supported the elicitation of emergent properties that contributed to the definition of appropriate (declarative) functions.

3.1 AS-IS model and function analysis for typical & normal situation

A typical situation model on GoA1 enables a task analysis of the daily tasks and functions performed by different entities in railway operation. Before tasks execution, each role in the operational system should be aware of his tasks and functions to perform. Figure 4 presents a AS-IS typical & normal scenario at GoA1. Three roles present in three lanes: train driver, signaler, and other agents. One journey cannot be completed successfully without a harmony cooperation between these roles.

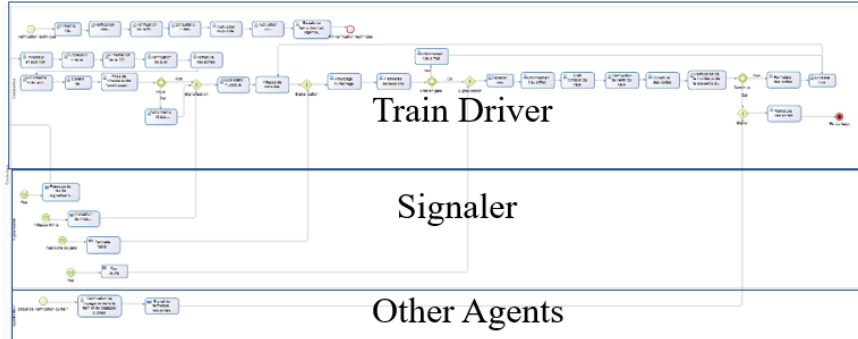


Fig. 4. AS-IS model under BPMN for typical & normal situation.

From this BPMN model, we summarize and define the following functions for these three roles (Table1). A preliminary work of definition of the various functions enables the association of each task with the right function [8]. Following Endsley and Rasmussen models [16], we categorized these functions in three types: Situation Awareness (SA), Decision-Making(DM), and Action Taking(AT).

Table 1. Function analysis for AS-IS scenario in typical & normal situation .

Role	Function	Definition	Type
Train driver	Technical check	Check the technical systems before starting the train	SA
Train driver	Observe signalization	Observe the signals, speed limit, and journey profile	SA
Train driver	Environment perception	Observe the operational environment	SA
Train driver	Drive	Accelerate/ Brake following the signalizations	AT
Train driver	Press the automatic vigilance system pedal	Press the automatic vigilance system pedal every 30 seconds to confirm the driver's level of alertness	AT
Signaler	Signal control	Control signals according to the railway traffic and journey profile	AT
Other agents	Safety control	Ensure the onboarding/ offboarding of the passengers and no luggage is left behind	SA
Other agents	Send authorization	Send authorization for train departure to the train driver	AT

In a typical & normal situation, the involved operational roles are supposed to be capable of performing the train operation by following the procedures. So, in this situation, most functions are action taking and situational awareness. Anomalies can be observed by inspections and verifications. The normal situation then can change into critical or near accident situations.

3.2 TO-BE model and function analysis for typical & normal situation

Based on the AS-IS model and ATO over ETCS specifications, we can project to the semi-automated trains (TO-BE) operation scenarios at GoA2. Fig.5. is BPMN model for a typical & normal scenario. At this automation grade, train driver and other agents are always presented in the model. There are two important changes on the roles in operating system: i) ATO is embedded for train operation. ii) The signaller's role is replaced by ERTMS. Therefore, we find four lanes in this BPMN model.

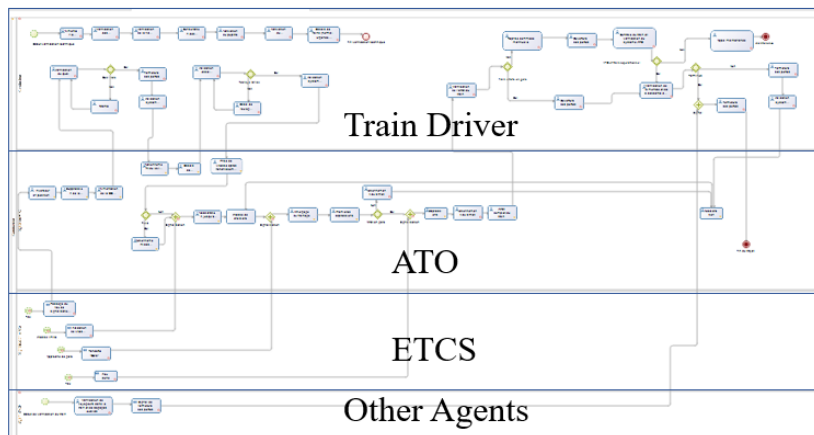


Fig. 5. TO-BE model under BPMN for typical & normal situation.

Same work of preliminary function definition is done for this scenario. At GoA2, the ATO and ETCS functions are analyzed for the first time. ETCS takes charge of the optimal speed calculation following the signalizations and speed limit. ETCS then sends this information to ATO for acceleration/brake control. ATO has two principal functions: status indication and drive when engaged. When ATO operational conditions are met, the ATO informs the train driver that it's ready to be engaged.

The engagement/disengagement of ATO is decided by train driver. When ATO is ready, the train driver can decide to engage ATO for automated driving. ATO disengages when its operation conditions are no longer met. However, during the journey where ATO operation conditions are met, train driver can still decide to disengage ATO if he finds manual driving is more suitable for the current journey segment. This decision of when the train driver engage/disengage ATO is a question of trust and collaboration between human operators and automated machines [17].

Depending on the situation awareness and train driver's field experience, he/ she can have different trust levels to ATO under different situations. And these different trust levels can lead to different decisions.

Table 2. Function analysis for TO-BE scenario in typical & normal situation.

Role	Function	Definition	Type
Train driver	Technical check	Check the technical systems before starting the train	SA
Train driver	Observe ETCS status	Observe ETCS status	SA
Train driver	Observe ATO status	Observe ATO status	SA
Train driver	Engage / Disengage ATO	Decide to engage /disengage ATO when the ATO status is 'ready to engage'	DM
Train driver	Environment perception	Observe the operational environment	SA
Train driver	Press the automatic vigilance system pedal	Press the automatic vigilance system pedal every 30 seconds to confirm the driver's level of alertness	AT
ETCS	Journey profile computation	Calculate the optimal speed for current segment and send this information to ATO	AT
ETCS	Signal control	Control signals according to the railway traffic and journey profile	AT
ATO	Drive	Accelerate/ Brake following ETCS	AT
ATO	Status indication	Inform train driver the current ATO status	AT
Other agents	Safety control	Ensure the onboarding/ offboarding of the passengers and no luggage is left behind	SA
Other agents	Send authorization	Send authorization for train departure to the train driver	AT

Once ATO is engaged, the train driver's workload is significantly reduced. Compared to AS-IS scenario, the train drivers' principal tasks are supervision and perception. Along with this advantage, another question of how to keep train drivers' attention is raised. In current driving cabins, the automatic vigilance system requires the train driver to press a pedal every 30 seconds to confirm train driver's presence and vigilance. From research in aviation, a shared responsibility of human machine teaming can keep pilots involved and improve pilots performance and situational awareness [18]. This next step of human machine teaming in next generation of semi-automation trains can potentially be an optimal solution for train driver's vigilance.

3.3 Analysis between AS-IS and TO-BE

One new function for train driver at GoA2 is the decision making to engage/disengage ATO. Such decision is impacted by operational context and the allocatable resources for train driving. During different driving phase, the train driver can make different decision to engage/ disengage ATO. To evaluate the trust and collaboration between

train driver and ATO, we propose to observe the following vigilant points during the Human-in-the-loop simulation: i) time interval from ATO ready to train driver's engagement of ATO. ii) duration of ATO engaged iii) when the train driver disengages ATO. After ATO indicates its 'ready' status, the time interval until train driver engages ATO is an indicator for trust between train driver and ATO.

Trust can be seen at different levels. To start with, the train driver needs to know what ATO is capable of. From ATO over ETCS specifications, ATO can strictly follow ETCS to achieve best performance for train journey. Then on next level, train driver evaluates the quality of feedback information provided by ATO. The train driver evaluates ATO performances by supervising the signals and the speed limits.

Based on the task analysis, the eye tracking and ECG (electrocardiogram) equipment are to be applied during human-in-the-loop simulation. By analyzing human behaviors by appropriate algorithms, we can evaluate human cognitive loads for each task and functions associated. This analysis also enables us to evaluate train drivers' technical and non-technical knowledge for train driving. Once a weak point identified, we can either reinforcement the training for concerning knowledge or provide more information to facilitate train drivers' operation.

4 Conclusions and perspectives.

This paper is a part of the preliminary work¹ for the application of the PRODEC method. Before practicing HITLS, we identified the tasks for each role in railway operation following the specifications of ATO/ETCS and field experience. We compared AS-IS and TO-BE scenarios to identify the task changes from GoA1 to GoA2. After this preliminary work, the next step will be the HITLS on GoA1 and GoA2 simulators to observe the difference between tasks and activities.

According to the current specifications, the ATO over ETCS is not yet sufficient to allow the deployment of fully autonomous trains on the GoA3 or GoA4. Our studies have shown that machines must support situational awareness and decision making for the application of autonomous trains in GoA3/4. Artificial intelligence (AI) is a promising solution to make optimal decisions for train operations.

References

1. D. Trentesaux *et al.*, "The Autonomous Train," in *2018 13th Annual Conference on System of Systems Engineering (SoSE)*, Jun. 2018, pp. 514–520. doi: 10.1109/SYSOSE.2018.8428771.

¹ Therefore, this contribution is a work in progress in a doctoral program that will continue to be published in another article to come. It was important to publish this account to describe the method and first task analysis results.

2. "Railway applications - Urban guided transport management and command/control systems - Part 1: System principles and fundamental concepts, International Standard, ." 2014. Accessed: May 03, 2023. [Online]. Available: https://infostore.saiglobal.com/preview/98701647820.pdf?sku=861023_SAIG_NSAI_NS_AI_2048445
3. G. A. Boy and C. Morel, "The machine as a partner: Human-machine teaming design using the PRODEC method," *WORK*, vol. 73, no. s1, p. S15, Oct. 2022, doi: 10.3233/WOR-220268.
4. Object Management Group, "Business Process Model and Notation (BPMN), Version 2.0," Dec. 2013.
5. G. A. Boy, *Cognitive Function Analysis*, Illustrated edition. Stamford, Conn: Praeger, 1998.
6. J. M. Carroll, "Scenario-Based Design," in *Handbook of Human-Computer Interaction*, Elsevier, 1997, pp. 383–406. doi: 10.1016/B978-044481862-1.50083-2.
7. G. A. Boy, *Design for Flexibility: A Human Systems Integration Approach*. Cham: Springer International Publishing AG, 2021.
8. G. A. Boy, D. Masson, É. Durnerin, and C. Morel, "PRODEC for Human Systems Integration of Increasingly Autonomous Systems".
9. Y. Wang, M. Zhang, J. Ma, and X. Zhou, "Survey on Driverless Train Operation for Urban Rail Transit Systems," *Urban Rail Transit*, vol. 2, no. 3–4, pp. 106–113, Dec. 2016, doi: 10.1007/s40864-016-0047-8.
10. G. A. Boy, *Tangible Interactive Systems: Grasping the Real World with Computers*, 1st ed. 2016. in Human-Computer Interaction Series. Cham: Springer International Publishing : Imprint: Springer, 2016. doi: 10.1007/978-3-319-30270-6.
11. G. A. Boy, "Human-centered design of complex systems: An experience-based approach," *Des. Sci.*, vol. 3, p. e8, 2017, doi: 10.1017/dsj.2017.8.
12. N. Brandenburger, A. Naumann, B. Friedrich, and J. Grippenkov, "Automation in Railway Operations: Effects on Signaller and Train Driver Workload," Apr. 2018.
13. ERA, "ERTMS/ATO. System Requirements Specification." 2022.
14. Y. Sun, M. Sango, A. Barros, and G. A. Boy, "Preliminary Safety-Critical Scenario Analysis of Semi-Automated Train Operation," 2023.
15. "How to use the SPAD toolbox." <http://www.rssb.co.uk/what-we-do/key-industry-topics/spad-good-practice-guide/how-to-use-the-spad-toolbox> (accessed Feb. 28, 2023).
16. J. Rasmussen, "Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-13, no. 3, pp. 257–266, May 1983, doi: 10.1109/TSMC.1983.6313160.
17. J. D. Lee and K. A. See, "Trust in automation: Designing for appropriate reliance," *Hum. Factors*, vol. 46, no. 1, pp. 50–80, 2004.
18. W. H. Rogers, "Automation Promises and Concerns for Three Levels of Automation: A Survey of Pilots of Advanced Automation Commercial Aircraft," SAE International, Warrendale, PA, SAE Technical Paper 951984, Sep. 1995. doi: 10.4271/951984.