Function analysis for human-machine teaming for semi-automated trains

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Abstract. Increasing levels of automation is a solution for more efficient and better capacity for railway transportation. For the French railway company SNCF, the first step to enable this transition from manual driving to automate trains is to introduce automated train operation (ATO) to the existing train system. ATO provides a more precise train operation and speed control during the journey. By controlling the train at the operational speed calculated, ATO contributes to minimizing the energy consumption for train driving. In our work, we intend to integrate humans into system design at this early design phase to gain more flexibility and security of the system. This paper presents the ATO functional architecture from its specifications and functional analysis to clarify the task distributions between ATO and train drivers. This analysis identifies the safety-critical functions and tasks in the semi-automated train system. We emphasized these safety-critical functions and tasks while comparing human-in-the-loop simulation (HITLS) activities and the prescribed tasks. These comparisons enable the identification of the safety-related design gaps in the ATO system.

Introduction

The train drivers manually control the current train models circulating in the French railway network. From automation levels defined in the railway industry, these trains are on Grade of Automation 1(GoA1). The automated trains promise a better transport flux with more accurate train operations and less energy consumption. The next step for SNCF is transitioning from classical driving trains to semi-automated trains. We plan to introduce the automated train operation (ATO)(ERA 2022) system into the current locomotive to reduce the train driver's workload and increase the precision of train operation. This change increases the trains' automation level to Grade of Automation 2 (GoA2). At this grade of automation, the train driver and ATO share the driving mission in the cabin. Based on the European Union Agency for Railways (ERA) specifications, ATO can compute an optimal driving speed from the train and journey information. The journey information includes the departure and arrival time and the train hold information for each train station. ATO works under the supervision of the European Train Control System (ETCS). ETCS computes the maximal speed from the journey information. The train speed under ATO shall not reach the ETCS intervention limit to prevent an emergency brake initiated by Automatic Train Protection (ATP). During the driving, once the working conditions are met, the train driver can choose to activate the ATO and free himself from the train speed control mission. Nevertheless, the train driver is always responsible for the train driving. After ATO activation, the train driver needs to supervise the ATO functionalities and the driving environment outside the train. In case of emergency, the train driver should react accordingly to secure the train-driving.

The increasing automation for the system promises a better performance on precision and energy consumption. Nevertheless, introducing these new automated systems can also bring potential threats to the existing system design. The fundamentals of PRODEC (Boy et al., 2024.) method is the acquisition of procedural and declarative knowledge. Declarative knowledge concerns the field knowledge to be designed(Boy and Morel 2022). This is composed by the specifications of the emerging system and the domain knowledge from the field experience. Evolution is always referred to the existing system. To predict the potential threats to the TO-BE system, we should start from the analysis of our current system to obtain more declarative knowledge of the AS-IS state. We did the incident analysis from the SNCF open data to identify the safety-critical elements and situations for classical train driving(Sun et al. 2023). Combining the incident analysis and the experts' judgment, we select and build the scenarios to prepare the human-in-the-loop simulation. Procedural knowledge concerns the experience we can be elicited from the procedural scenarios. Human-in-the-loop simulation is adapted to obtain the procedural knowledge regarding the simulation can recreate different situations a train driver can meet during the train journey. Due to the complexity and uncertainty of human behaviors, instead of modeling humans and prediction, we can directly observe human reactions and behaviors when facing these situations.

Based on these safety-critical elements identified, we analyze in depth the safety-critical functions in the ATO and ERTMS specifications to allocate the functions and tasks for semi-automated train driving. We model the scenarios using the Business Process Model and Notation (BPMN)(Object Management Group 2013). By clarifying the different roles in the scenarios and the involved technical components, BPMN supports the visualization of the interactions between different parties in one scenario and the tasks of each role. These clarifications before simulation facilitate the exchange between the designers and the domain experts to pre-validate the simulation scenarios. We identify the safety-critical functions and tasks to better allocate the tasks in the driving cabin and obtain a more secure system design.

Human system integration and the railway systems automation

The increasing autonomy contributes to a promising interconnected and sustainable future railway system. Despite these automated changes, human is still the core of the system. Human roles evolve with the evolution of railway system. Human is the designer, the operators, and the travelers in railway system. From incidents analysis, more than 67% of the incidents registered in SNCF open data from 2015 to 2022 are related to human errors (Sun et al. 2023). But beyond this common opinion of human as threats in highly complex systems, humans are also a resource to anticipate the potential failures and to save the system from failure. Taking example in the driving cabin, compared to the setting of pilot and co-pilot in cockpit in aviation, the train driving mission is monotone. In normal situations, the repetitive mission and stable situation in driving cabin consist the main part of high-speed train driving. During the up to 8 hours train driving, the lack of concentration and cognitive workload of train drivers is a potential threat to the train driving(Sussman and Coplen 2000). Meanwhile, the incidents can happen at any time during the train journey. Once the situation degrades, the train driver needs to respond to the situation in a timely manner and decide to react accordingly to guarantee the safety of train driving and so to protect the travelers and the railway assets.

Train drivers' missions evolve with the increase of grade of automation (GoA). For the classical driving trains on grade of automation 1 (GoA1), the driving mission is completely taken by the train drivers. The train driver is taking in charge of the speed control, the observation of the environment and the communication with the signaler. On Grade of Automation 2(GoA2), ATO shares part of the train driving mission of speed control. On this grade of automation, train driver is always present in the driving cabin and responsible for the operation security. The driving cabin will be cancelled from Grade of Automation 3(GoA3). A driverless train operation system assures the start of the trip and driving and stopping. An agent from the railway company will present on board on GoA3 to supervise the train operation and to secure the train and the travelers in case of emergency. The fully automated train is projected on GoA4. At this grade, the train operates unattended with high autonomy.

From the classical manual driving to fully automated trains, human roles evolve with the increasing autonomy. On GoA1, train driver takes the crucial role in the driving cabin for the train operations from starting the train to arriving at destination. With the introduction of the automated system, human role changes from the operator to supervisor for train operation. On GoA4, the conventional train driver is not visible directly in the train operations, the responsibility will only be devoted to engineering designers and operational managers. Consequently, control will shift toward human technical management.

One main challenge for the traditional technology centric design method is the rigidity that human operators must adapt to. The related resources are engaged too early at the beginning stage of development cycle that the system doesn't have enough flexibility to adapt to the real working environment and human behaviors. The semi-automated trains design in SNCF is still in early design phase. To validate the design with safety requirements and human factors, we decide to apply PRODEC method.

PRODEC method is a scenario-based design method based on two kinds of scenarios: the procedural scenarios and the declarative scenarios. Human-in-the-loop simulation (HITLS) is a critical part in PRODEC method. Before human-in-the-loop simulation, we build declarative scenarios with the declarative knowledge for the TO-BE system and the procedural knowledge of the AS-IS system. These scenarios are composed by the tasks that we initially assign to agents or technical system. Task is what to be executed by the agents during the mission or the simulations. Activity is what the agents really do. The deviation from the task to activities are enables by human cognitive function. This function depends on the role of the agent, the context he is in and the allocatable resource for the agent.

By HITLS, we test the prototype (which can be either physical or virtual) and obtain the procedural scenarios of the TO-BE system. We observe the activities from these procedural scenarios. By comparing the activities in the procedural scenarios and the tasks in declarative scenarios, we deduce the emergent properties and infrastructures that we can integrate into the system being developed. The procedural scenarios provide us the first procedural knowledge for TO-BE system. By integrating these emergent functions into our initial TO-BE system design, the TO-BE system becomes AS-IS system for us with the procedural knowledge. The interactions of the PRODEC method can help the system designers and engineering to finally achieve a design with satisfaction.

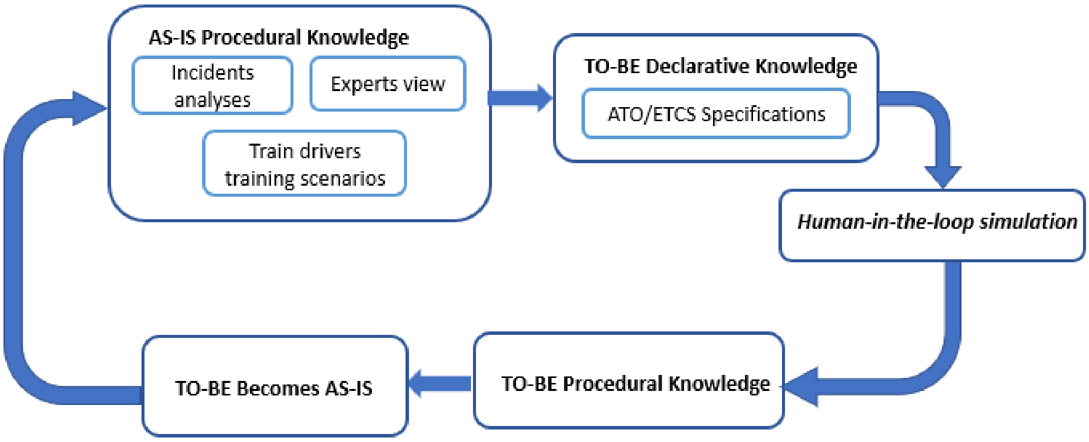

Figure 1. PRODEC Method Application for Semi-automated Trains Design

For the semi-automated train design, we start from the AS-IS procedural knowledge that we have. This AS-IS procedural knowledge is learned from the simulations and operations of the existing system design. In our research, we obtain this knowledge from three sources: i) the incidents analyses: The incidents records are available from SNCF open data. This database registers the incidents in SNCF network from 2015 including the incident type, date, location, severity and a short description about the incident. We analyzed this database to identify the safety-critical components of the AS-IS system on GoA1. ii) Experts view: We then consulted the experts' view on the analysis results of the safety-critical components to validate this result concluded from data. The train drivers validate our result, but they also provided us the information about the situations that are critical for train driving from their point of view. From the situations the experts describe, we retrieve the elements which are not presented in the database. iii) Train drivers training scenarios: For train drivers' training purpose, SNCF has several models of simulators and more than 1000 available scenarios with different training objectives. These scenarios represent the situations the train drivers can meet during his journey and the procedures to solve these situations from SNCF.

The TO-BE declarative knowledge in our use case is the specifications of the ATO and ETCS. Based on the available specification from ERA, we need to do a function and task analysis for the emerging ATO system on GOA2. This analysis can help us to clarify the capabilities of ATO and better allocate the driving operational functions between ATO and the rain driver. Combining this declarative TO-BE knowledge and the AS-IS procedural knowledge that we have, we define the tasks for human and machine to build declarative scenarios and prepare for the HITLS. From the HITLS, we can observe and measure human activities in different kinds of situations. There are three kinds of situations: Typical & Normal; Critical & Abnormal and Emergency & Near Accident. The procedural scenarios we observe from HITLS can provide us TO-BE procedural knowledge to validate the TO-BE system in all kinds of situations. We compare the observed activities with the prescribed tasks to find the emergent functions and properties. An emergent property is what we cannot deduce from the current knowledge of the system components. These emergent properties can lead to unexpected system behaviors that may be dangerous. By integrating these emergent properties into our initial design, we can validate the current TO-BE system in development. Once we have enough procedural and declarative knowledge about the TO-BE system, the TO-BE system becomes AS-IS system, and we can so iterate the design cycle until a satisfaction design.

Function analysis for semi-automated trains

To identify the potential system failures and risk, we need to have a thorough understanding of the TO-BE system functions. The key change on GoA2 is the ATO. To analyze the reliability of this emerging technical system, we need to clarify the functions and subfunctions of ATO and to identify the related elements of each function. This function analysis contributes our upcoming reliability ana lysis for this human machine teaming on GoA2. Before the simulations and the analysis of human reliability, we need to perform this risk and reliability analysis for technical system first.

13 ATO functions are defined by the European Union Agency for Railways (ERA) in Subset 125 for ERTMS/ATO system requirements specification (ERA 2022). From system reliability theory, these functions can be categorized into essential functions, auxiliary functions, protective functions, information functions, interface functions and superfluous functions(Rausand, Barros, and Hoyland 2020).

One function can meet several categories. For example, the train position determination functions which can determine the train position within a segment profile is an essential function for driving function and an informative function for the signaler. We first do a short summary of each function as described in Table 1. Then we also decide the function type of these functions according to these categories to have a general view on these functions.

Table 1: ATO Function Categorization

Function	Definition	Function Type
Driving Function	ATO generates the output commands to drive the train based on the speeds given by speed and stopping management.	Essential
Timing Point Management	ATO manages the stopping points and operates the open/close of the train doors accordingly.	Essential
Add/skip Stopping Point	ATO may add/skip additional Stopping Points on request of train driver in real time by updating the Journey Profile.	Auxiliary
Train Hold at a Stopping Point	ATO shall be able to request Train Hold at a Stopping Point by a Journey Profile Update and inform the train driver about the situation	Auxiliary
Low Adhesion Management	ATO shall be able to inform the other concerned trains once low adhesion is selected by the driver	Information, Auxiliary
Time Management	ATO shall use the UTC time with an accuracy of ±1 second and able to convert UTC Time to Local time for driver information	Auxiliary
Reporting Management	ATO-On Board (OB) should send reports to ATO-Track Side (TS) when there is a change of the train situation	Auxiliary, Information
Data Consistency Management	ATO shall detect date inconsistency about the routing error or a segment and journey profile consistency error	Protective, Information
ATO System Version Management	ATO-OB and ATO-TS version number should be managed to ensure the backward compatibility.	Protective, Information
ATO-OB Train Position Determination	ATO-OB shall determine the train position within a Segment Profile	Auxiliary, Information

Driving Advisory System (DAS)	ATO shall compute a DAS trajectories defined by a "Target Advice Speed"	Information, Superfluous
Perform ATO-OB self-tests	ATO-OB system shall execute automatically self-tests procedures to determine the equipment state.	Auxiliary, Protective
ATO-OB Data acquisition	ATO-OB shall exchange signalization information with ETCS-OB	Essential, Interface, Information

The most critical function of ATO is the driving function and the timing point management. ATO-TS sends journey profiles to ATO-OB containing the train profile, infrastructure data and the departure/arriving time. From the signalization information received from ETCS-OB and the segment profile and journey profile of the mission, ATO-OB can calculate the optimized speed of the current trip. ATO then controls the train speed accordingly to this target advised speed. The time management function is less obvious than the essential functions as driving function or timing point management. But the failure of this auxiliary function is safety-critical to the train system. The data consistency management function and the ATO-OB self-test function are protective functions ensure the interoperability and compatibility of software.

We can then have a closer look at the most critical ATO function: driving function. We can use the SADT approach (Lambert, Riera, and Martel 1999) (Benard, Cauffriez, and Renaux 2008) to analyze the driving function on GoA1 and GoA2. In SADT, each function block is modeled by the elements of the function itself. On the left of the block is the input of the function which are necessary to perform the function. The controls are identified on the top of the block. These are the elements than govern or constrain the function. On the bottom of the block are the resource. The people, facilities or necessary equipment for the function. And finally on the right side of the block is the output of the function.

On GoA1, the driving function is performed by the train driver. A representation of this driving function is shown in Fig.1. The resources needed are the train driver and the traction/brake system. This driving function has several controls: before the journey, train driver receives the journey profile with the departure/arriving time of each stop. The signalizations provide the train driver information of movement authorization or stop. Along with the speed limit of the current journey segment, the train driver regulates the optimal train speed from his driving knowledge and experience. Trian driver is also in charge of the observation of the environment. In case there is an obstacle on the rail or abnormal rail situations such as dead leaves and bad weather, the train driver needs to decelerate or initiate an emergency brake.

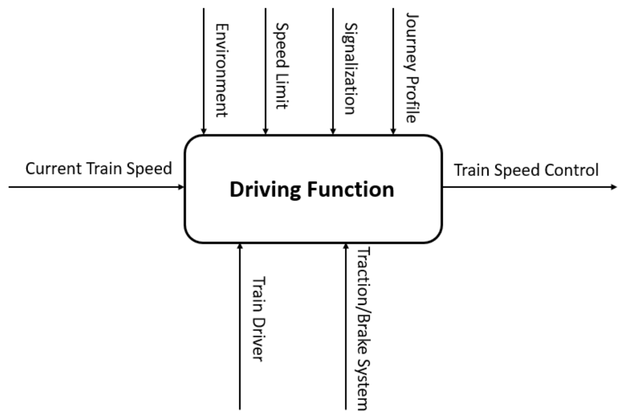

Figure 2. Representation of Driving Function on GoA1

On GoA2, the driving function is shared between the train driver and ATO. Here we do a function analysis for the situation of ATO engaged. Once engaged, ATO can calculate the optimal speed and generates the output command to the train accordingly. The function of ATO speed computation is composed by three sub-functions: Time Table speed management (TTSM), Supervised Speed Envelope Management (SSEM) and Automatic Train stopping management (ATSM).

TTSM computes an optimum speed profile based on the journey profile and the details about the rail to pass: the tunnels information, gradient and curve profile of the rail, etc. This optimum speed profile is the speed to achieve the stopping or passing points on time in the most energy efficient way.

SSEM establishes the maximum speed the train can run without interfering the speed limits of the signalization. With the protection of ATP, ATO generates the maximal speed curve considering of the rail profile and the safe brake distance to the stop. During the engagement, ATO shall keep the train speed lower than or equal to the ETCS release speed to prevent the emergency brake initiate from ATP.

ATSM calculates the speed profile to stop precisely at the stopping points. ATO generates this stopping speed profile considering the stopping window and the stopping tolerance in the segment profile.

On GoA2, the train driver's mission changed to supervision from train operation. Train driver is always the responsible for train operation safety. As on GoA1, the train driver oversees environment observation for rail situation. With the introduction of ATO, once engaged, train driver also needs to supervise the operations of ATO. The driving function can be illustrated as in Fig.3.

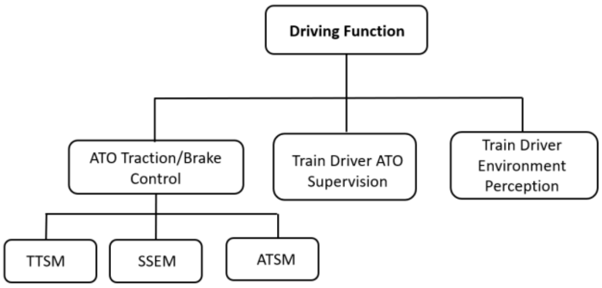

Figure 3. Function Tree of Driving Function on GoA2 (ATO engaged)

For this human machine teaming on GoA2, ATO is a driver assistance system for train driving. During the mission, the decision to either engage the ATO or not is still in train driver's hand. With a good understand of the ATO functions and the tasks allocation of human and machines on GoA2, we see the important role of train driver for GoA2 train driving with the help of ATO. To elicit train drivers' behaviors under different situations especially with ATO failure, we constructed the scenarios for HITLS. By comparing the activities in the simulations and the tasks prescribed, we can deduct the emergent properties and define the procedures inside SNCF to guide train drivers under different situations during train journey.

This function analysis is fundamental for our future work of risk analysis of the human machine teaming system on GoA2. By understanding the ATO functions and the underlaying connections among them, we can do a further analysis of reliability and failure modes of the future system. Based on this analysis, we can also build quantitative fault tree analysis and reliability block diagrams to obtain more TO-BE system declarative information before the human-in-the-loop simulation.

Related work

Human-in-the-loop simulation (HITLS) has been discussed in several studies to evaluate Human Machine Teaming (HMT) performance and reliability. Trust is one of the key elements to support this teaming. Boyce and his colleagues conducted a human-in-the-loop simulation to test the effects of displaying transparency information on operator trust (Boyce et al. 2015). The study showed that including transparency information in the display for a robotic agent can increase the trust. Enhancing the understanding of the automation process can also increase the trust in the automation (Lee, Hoffman, and Hayes 2004). Recent research propose a relational framework emphasis the goal is not to maximize trust or calibrate trust, but to support a process of trusting through automation responsivity (Chiou and Lee 2023).

HITLS is used to assess single pilot incapacitation (Castro et al. 2023). With low-fidelity simulations, HITLS can still elicit the interactions across organizations and domains. In the MOHICAN project, PRODEC method is been used and validated to support the integration of pilots and virtual assistance(Boy and Morel 2022). The HITLS supported the observation of activities in Human Machine Teaming. The research teal also explained the performance criteria of tasks. In our research, the automated trains on GoA2 is still in an early design phase in France. Some research has discussed about the human factors and workload with the introduction of driving assistance (Rees et al. 2017; Habib, Oukacha, and Enjalbert 2021; Onnasch et al. 2014) . But this discussion about human factors has not yet been validated by HITLS.

Conclusions and perspectives

The application of PRODEC method for the semi-automated trains is promising to integrate human and organizational factors in this early design phase. To prepare for the upcoming simulations, this paper describes a function analysis of the driving assistance system (ATO) to increase the declarative knowledge for our TO-BE system. Both system designers and train drivers can also benefit from this analysis to better understand the functions of ATO. A good knowledge about the assistant system can contribute to the trust between human and machine to achieve a more reliable human machine teaming.

Train driver is always the safety responsible and the most important role in train driving. A safe train driving on both GoA1 and GoA2 is dependent on the train driver. The goal of iterating the PRODEC process is to decrease the difference between activities and tasks. By HITLS of the constructed scenarios on different situations during the mission, we can conduct the optimal solution and procedure for train drivers facing degraded situations or emergencies.

In this Human-Machine teaming, AI can take an auxiliary role for ATO speed processing and journey profile generation. The supports other than display panel (voices, touch feedback, etc.) can also be developed to help the train driver's situation awareness. Based on this function analysis, we can do a further reliability and risk analysis of the railway system on GoA2 and analyze the impact of ATO on train drivers.

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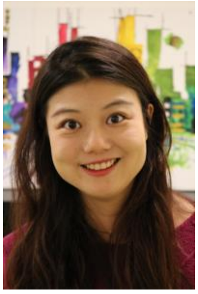
Biography



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