Towards Tramway Safety by Managing Advanced Driver Assistance Systems depending on Grades of Automation

Lydia Habib, Ouazna Oukacha, Simon Enjalbert

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Lydia HABIB * **Ouazna OUKACHA** * **Simon ENJALBERT** *

* *Univ. Polytechnique Hauts-de-France, CNRS, UMR 8201 - LAMIH, F-59313 Valenciennes, France, (e-mail: simon.enjalbert@uphf.fr)*

Abstract: This paper presents a preliminary study for the assessment of tram safety by managing Advanced Driver Assistance Systems depending on Grades of Automation. The Grades/Levels of Automation in automotive, aeronautics, maritime and railway systems are presented and compared with each other. Then, according to especially the implication level of a haptic system in each tram driving task, Grades of Automation for trams are proposed. In addition to the haptic system, a visual one that uses a Head-Up Display is defined. These systems are designed to help the tram driver cope with potential hazards by having a defensive driving. Therefore, the proposed Grades of Automation and the driver assistance systems are used in order to propose an experimental method to explore how this automation can affect the tram driver performance and the Human-Machine System safety.

Keywords: Grades of Automation, Levels of Automation, Tramway, Advanced Driving Assistance Systems, Haptic Control, Automatic Control, Human-Machine System.

1. INTRODUCTION

Tramway, tram or streetcar, also called trolley is a large and heavy electric vehicle that transports people, usually in cities, and runs on tracks in the road. The tram drivers have to manage a complex environment shared with pedestrians and other vehicles. Furthermore, they have to respect the traffic signals while boarding and serving passengers at different tram stations. Tram drivers also have to be punctual and ensure Human-Machine System security and, mainly the passengers safety.

Trams vehicles have a higher transport capacity, lesser traffic jam problem and lower emission of pollutants than other public transport vehicles. Therefore, trams have become an essential urban transport in many countries, especially in big cities. However, by their design and characteristics, trams are not always adapted to the complex and cramped environment they are used. From this observation, safety concerns arise and give place to many studies (Vandenbulcke et al. (2014), Richmond et al. (2014), Marti et al. (2016) and Currie and Reynolds (2010)). Naweed and Rose (2015) have identified factors related to tram collisions, in particular: lack of tram driver's situation awareness, time pressure and organizational behaviour. Naznin et al. (2017) have determined the need to investigate the road user factors affecting tram road safety and explored the key challenges in tram driving. To keep everyone safe as much as possible in and around the tram, and to run on-time are the priority challenges. The on-time running causes pressure and increases risk taking attitudes for a driver (going through red lights, for example), which endangers safety. Cacciabue et al. (2013) have studied the driver behaviour modelling and several types of driver-machine interaction in the different transport domains.

A concept involving the distribution of control between the human and machine system is called the Levels of Automation (LoAs) (Sheridan and Verplank (1978)). This paper deals with this concept and proposes Grades of Automation (GoAs) for trams, by defining the driving tasks allocation among the tram driver and assistance systems. Therefore, it establishes an experimental method to assess the impact of these GoAs on the Human-Machine System safety.

The section 2 of this paper presents a state of the art of LoAs by comparing different transport industries. Section 3 proposes driver assistance systems and GoAs for trams. The section 4 describes the general concept of the experimental tests. Finally, the section 5 provides the conclusion and perspectives.

2. STATE OF THE ART ON AUTOMATION IN TRANSPORT INDUSTRIES

Automation tends to reduce the scope of human activity by limiting the allocated tasks and makes the systems more and more autonomous. However, today many researchers consider the image of an increasing complexity of automated systems, and the role of human operator becomes increasingly important (Parasuraman and Wickens (2008)). Automation has many strengths, including lack of emotion and distraction, ability to implement actions precisely and to do many different tasks immediately, but also it has weaknesses, especially because it lacks the flexibility that humans have, which allows them to adapt to new or unpredictable events. Therefore, automation can be implemented with different degrees of reliability, and

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its introduction into a system requires careful preliminary testing and analysis to ensure the best fitting between Human and Machine while mitigating their respective weakness in order to get maximum Human-Machine performance. The LoAs are introduced and discussed in many other transport industries such as: automotive, aeronautics, maritime and railway sectors.

2.1 Automotive sector

The Society of Automotive Engineers (SAE) distinguishes 6 levels of driving automation from manual control (without automation) to full automation as defined in J3016 (SAE (2016)).

- Level 0 (manual control), the human driver performs all the driving tasks.
- Level 1 (assisted driving) consists of the assistance tools called Advanced Driver Assistance Systems (ADAS) implemented in the vehicle, assisting the driver from time to time in certain tasks such as cruise control.
- Level 2 (partial automation), the vehicle system is capable of performing certain tasks such as acceleration and guidance on its own. However, the driver must remain engaged in the driving task and monitor the environment at all times.
- At level 3 (conditional automation), the vehicle system may as well perform certain tasks on its own and ensure autonomous control of its environment. However, the driver must be able to regain control at the request of the vehicle (Borojeni et al. (2017)).
- At level 4 (high automation), the vehicle system can also perform certain tasks and ensure the control of its environment under certain conditions without the driver.
- At level 5 (full automation), the vehicle system can perform all driving tasks autonomously without the driver under all conditions.

2.2 Aeronautic sector

Unlike the automotive sector, a taxonomy of LoAs in aeronautics has not been properly defined in the literature. In general aviation, SAE presented a classification of LoAs based on that of the automotive domain (Anderson et al. (2018)). In reference to Crespo (2019), the authors also proposed another description of LoAs in aeronautics. However, LoAs could be identified from the technological evolution of the civil transport airplane (Airbus (2020)).

- The first generation of commercial jet flights began in 1950. It was designed with early flight instruments (dials and gauges in cockpit), which can represent the first LoA of the commercial airplane.
- The second generation appeared in 1964 with improved auto-flight and auto-throttle systems that may describe the airplane's second LoA (assisted flying).
- The airplane's LoA has been further increased with the coming of the third airplane generation in 1980. This generation is characterized by digital technologies with navigation displays and Flight Management Systems (FMS). Furthermore, it has embraced high automated features such as Terrain Awareness and Warning System (TAWS), and Airborne Collision Avoidance System (ACAS). The automated systems complete a wide variety of actions with pilot's permissions and decisions (the system identifies and proposes an action to face risks induced by the tasks, while human takes the decision to accept or not this action).
- The fourth and latest generation of civil transport airplane was established in 1988. It brought more sophisticated technologies like the Fly-By-Wire (FBW) control system and flight envelope protection. Using the FBW technology, the pilot tells the flight computer what to do, then the computer translates the pilot's intention into action and executes the maneuver. At this high LoA, the pilot is still in the loop emergency situations.

2.3 Maritime sector

All levels distinguished by SAE cannot directly be applied to maritime passenger transport due to complexity of the environment (visibility, weather conditions and etc.). Like in the aeronautic sector, the taxonomy of LoAs is not clearly defined for maritime domain and it is known as "Autonomy Level (AL)". The International Maritime Organization (IMO) defined 4 degrees of automation, where it was presented as provisional definitions of autonomous ships. Register (2016) proposed 7 ALs in maritime transport.

- AL0 (manual): this level is similar to other sectors, where human manually controls all actions.
- AL1 and AL2 are called "On-board Decision Support" and "On & Off-board Decision Support" respectively, the human operator directs and controls all actions. Data is provided by systems on board for AL1 and it is given either on board or off the ship for AL2.
- AL3 and AL4 are called "'Active' Human in the loop" and "Human in the loop: operator/supervisory" respectively. The decisions and actions are performed with Human supervision, the pilot can take control over the ship at any time for AL3 and he intervenes only if necessary for AL4.
- AL5 and AL6 are both called "full automation", all decisions are entirely made and actioned by the system, the Human intervenes very rarely for AL5 and never for AL6.

2.4 Railway sector

In railway sector, the degrees of automation are named GoAs rather than LoAs. GoAs are defined in IEC 62290 (International Electrotechnical Commission) for Automatic Train Operation (ATO). The motivation to increase the GoAs of the rolling stock in the railway domain is to expand the systems' capacity and performance without endangering safety. The railway automation is described through 5 Grades of Automation (cf. Cappaert-Blondelle (2012)). The automated tasks are mainly concerned with train acceleration and braking, departure and stopping at the stations, monitoring of driving environment (e.g. event detection, sign recognition, etc.), doors closure and opening, and management of emergencies (cf. Table 1).

Table 1. Grades of Automation in rail stock sector.

GoAs \ Tasks	Acceleration / Deceleration (Drive tram)	Departure/ Stopping at the stations/	Monitoring of driving environment(1)	Doors closure/ Opening	Detection and management of emergencies(2)
GoA0	Driver	Driver	Driver	Driver	Driver
GoA1	Driver / System	Driver	Driver	Driver	Driver
GoA2	System / Driver	Driver /System	Driver	Driver	Driver
GoA3	System	System	System	Train attendant	Train attendant
GoA4	System	System	System	System	System/Staff on OCC(3)

(1) Prevention of collisions with obstacles and persons on tracks
(2) Handling fire/smoke and passengers requests (call/evacuation. . .)
(3) Operation Control Center

Description

- GoA-0, the train driver must drive and ensure the safety of the train system, this level is called "on-sight operation" and is similar to the current grade of the tram system.
- GoA-1 represents the manual operation with the ATP system, the train driver controls acceleration and braking. The ATP system guarantees that the driver respects the speed limits, and it ensures the safety operation. The tram driver controls departure and stopping at the stations, doors closure and opening. Furthermore, he supervises the guideway and manages the emergencies.
- GoA-2 is characterized by the manual driving of the train with ATP and ATO systems (most common today), the driver operates the doors and starts the train. The system is responsible for controlling the speed and stopping the train at the stations. The train driver must be ready to take over control at any time and handle emergency situations.
- GoA-3 is the driverless control grade, the system is responsible for driving, departure and stopping the train. The train attendant operates the doors and takes over control in case of emergencies (driverless train).
- GoA-4 is the unattended train operation, all the tasks are performed by the system without any on-train staff.

2.5 Comparison between transport industries

A comparison between the LoAs in automotive, aeronautics, maritime and railway sectors is given in the table 2.

As mentioned above, the high LoAs are already implemented in the railway sector. However, they cannot be directly transposed to the control of trams, because trams operate in a less secure, more complex and dynamic road environment than that of metros and trains. The trams can therefore be the subject to various disturbances such as meteorological changes and risky obstacles on the track. Due to these limitations, today it remains impossible to automate everything and design an efficient tram system to cope with all complex demands of the dynamic road environment autonomously. Therefore, the autonomous tram is not our objective, so the human driver will always be present in the cabin control.

Table 2. Comparison of Levels of Automation in automotive, aeronautics, maritime and railway sectors

Automotive	Aeronautics	Maritime	Railway
No automation (LoA0)	Manual	Manual (Al0)	No automation (GoA0)
Driver assistance (LoA1)	Assisted	(Al1) and (Al2)	Manual driving with ATP (GoA1)
Partial automation (LoA2)	Highly assisted	(Al3) and (Al4)	Manual driving with ATP and ATO (GoA2)
Conditional automation (LoA3)	Highly automated	(Al5) and (Al6)	Driverless train (GoA3)
High automation (LoA4)			
Full automation (LoA5)	/	/	Unattended train (GoA4)

The following part presents the different GoAs of the tram and the way to apply them for Advanced Driving Assistance System in order to improve Human-Machine System safety.

3. GRADES OF AUTOMATION FOR TRAMS USING ADVANCED DRIVER ASSISTANCE SYSTEMS

The trams operate in a temporal demanded mixed traffic environment that requires a high level of situation awareness, with consistently high perceptual demands for collision avoidance. Because of the nature of the tram-driving task and its relation with the road environment, our study is limited to GoA-0, GoA-1 and GoA-2 of the railway sector. GoA-0 is currently being used to drive the trams. GoA-1 is studied by La Delfa et al. (2016) and Enjalbert and Boukal (2019), it is called the eco-driving system that automatically generates speed profiles for the tram (ATP system). In this work, we defined other GoAs based on the GoA-2 which allows speed regulation.

3.1 Grades of Automation for trams

The GoAs for trams are defined from the allocation of two tasks (acceleration/deceleration and stopping at the station) between the driver and the automated system. Given the importance of the safety aspect of the driver-tram system, which is the focus of this work, we considered the dead man's switch device to study whether the safety of the Human-Machine System is maintained when the dead man's switch is disabled at a high GoA (GoA-2.3). The dead man's switch or driver's safety device is commonly used in the railway domain to permanently monitor the tram driver consciousness. The defined taxonomy of GoAs for trams is presented in Table 3.

The defined GoAs determine the force between the driver and an automated system applied to the manipulator when performing the acceleration/deceleration task. We note

Table 3. Description of the GoAs for trams

GoAs	Acceleration /Deceleration	Stopping at the station	Dead man's switch
GoA-0	Driver	Driver	Activated
GoA-1	Driver/System	Driver	Activated
GoA-2.1	System/Driver	Driver	Activated
GoA-2.2	System/Driver	System	Activated
GoA-2.3	System/Driver	System	Desactivated

that at each GoA, the driver controls the tram departure. The GoA-0 is equivalent to the GoA-0 of the rail stock taxonomy, where the driver is the only responsible for driving the tram. The GoA-1 is equivalent to the GoA-1 of the rail stock taxonomy, where the driver controls the acceleration/deceleration task with an automated system that grantees the respect of the speed limits. The GoA-2.1, GoA-2.2 and GoA-2.3 are equivalent to the GoA-2 of the rail-stock taxonomy. However, At GoA-0, GoA-1 and GoA-2.1, the driver is responsible for stopping the tram at stations except for the GoA-2.2 and GoA-2.3. Furthermore, at each GoA the dead man's switch is activated except for GoA-2.3.

In order to perform all the above mentioned driving tasks of the tram, two transmission systems are defined: visual and haptic. The visual system enables the driver to observe and analyse the environment and the haptic system to control and drive the tram.

3.2 Head-up visual system

The head-up visual system is based on a Head-Up Display (HUD). The HUD is a screen that is used to display an image into the driver's line of sight on a transparent display. It helps to improve the driver's situation awareness by getting information without looking away. HUDs are widely used in both military and commercial aviation with gradual adaptation in general aviation and passenger cars but much less common in rolling stock. The developed HUD is represented in Fig. 1, with the various indicators labelled in orange on the interface.

The distance to the next speed limit is represented by an arc (cf. label 5 in Fig.1) from the current speed limit until the next lower one (cf. label 3 and 4 in Fig.1 respectively). The arc is displayed when the tram reaches a given distance from the next lower limit speed. In fact, we argue that braking is safe. The tram driver must not exceed the speed limit and has to anticipate deceleration. Therefore, it is important to inform him in advance of only the decrease in the speed limit. On the contrary, the increase in speed limit can be unanticipated without endangering safety. The size of the arc decreases in proportion to the distance remaining from the next lower speed limit.

The target speed (cf. label 6 in Fig.1) is calculated by an eco-driving controller developed in previous work La Delfa et al. (2016). The controller solves online an optimal control problem in order to select the best speed profile that minimizes the tram-driver energy consumption and enhances the safety. It takes into consideration criteria such as the timetable, the tram and the track models.

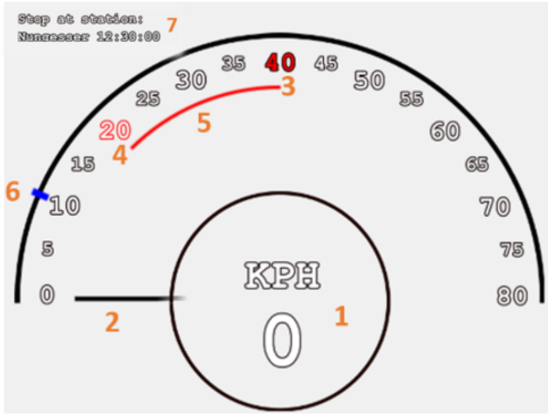

Fig. 1. The Head-Up Display.**(1)** the current speed and the unit it is measured in. **(2)** the needle moves around the gauge as a visual representation of speed. **(3)** the current maximum permitted speed. **(4)** the next speed limit. **(5)** a simplified representation of the distance to the next lower speed limit. **(6)** the current target speed. **(7)** the next station and the time this station is expected to be reached.

3.3 Haptic system

According to the GoA presented in the Table 3, a haptic manipulator is used to provide acceleration limits to the driver or to perform the acceleration/deceleration task autonomously without the intervention of the driver. The haptic manipulator structure is similar to the manual one with an added function of a haptic feedback that would allow to provide sensory stimuli to the driver for better situation awareness and efficient control. The single axis manipulator is the structure whose vertical axis can move up and down. This movement is indicated by the two arrows on the right side of the manipulator, with 5 color zones that are dedicated to the different types of operations (cf. Fig. 2) and as explained in detail by La Delfa et al. (2019):

- Green zone: is indicated by an arrow pointing upwards. This zone allows the driver to increase the tractive effort or to reduce/maintain the speed of the tram)
- White zone: is called the neutral zone and is located between the two green and yellow zones. It is a transition point between steering and braking. Thus, the tractive effort in this zone is equal to zero. We note that the manipulator returns to the neutral zone each time the tram stops.
- Yellow zone: is indicated by an arrow pointing downwards. This area allows the driver to reduce the tractive effort and to activate the electric braking to stop the tram smoothly.
- Orange zone: allows the driver to apply the reinforced electrical braking and to activate the mechanical one.
- Red zone: corresponds to emergency braking.

At GoA-0, the driver performs the acceleration/deceleration task without any assistance from the haptic manipulator. At GoA-1, the driver controls the acceleration and deceleration. However, the haptic system prevents and ensures the safety operations. Indeed, the driver controls the tram

(a) Tram cabin control (b) Haptic manipulator

Fig. 2. Haptic driver assistance system of a tram.

speed within a certain safety margin, beyond which the haptic system alerts the driver. Then, if the driver does not decelerate, the haptic system regains authority and progressively applies a stiffness in the manipulator until a mechanical stop is reached. At GoA-2.1, GoA-2.2 and GoA-2.3, the haptic system is responsible for driving the tram. However, the driver must stay fully alert and be ready to take control at any time. If the driver intervenes on the control (exerts a force on the manipulator), the acceleration/deceleration task is allocated to him and the authority is managed in the same way as at GoA-1. The HUD and the haptic manipulator will be implemented in the PSCHITT-Rail simulator for a future experiment which is presented in the following part.

4. FUTURE EXPERIMENT

This section proposes an experimental method for a future experiment. Its objective is to evaluate the impact of the defined GoAs (cf. Table 3) on the driver performance and the Human-Machine System safety.

4.1 Method

Materials. The PSCHITT-Rail (Collaborative, Hybrid, Intermodal Simulation Platform in Land Transport-Rail) designed by LAMIH was used as the tram simulator for this experiment (cf. Fig 3). The PSCHITT-Rail simulator is a cabin installed on a motion platform with six degrees of freedom. It is composed of real tram equipments interfaced with the software part. The simulator is equipped with a dashboard, a manipulator, a realistic sound rendering and a visual field projected on a screen giving a panoramic view of 225°.The simulator allows to implement personal dynamic tram model, to record the simulation data (speed, manipulator position...) and to create different scenarios, for instance, by modifying the density of cars and pedestrians. It is based on the OK-SimRail simulation software developed by AVSimulation company.

Procedure. A slide show of the simulator and driver assistance systems description will be given to the participants before the training session. Then, they will be asked to fill out a consent form and reply to a demographic questionnaire. Before starting the testing, the participants will be trained on the driving task using the tram simulator with the HUD and the suitable GoA. Each participant will be allowed to ask any questions related to the experimental platform or the task to perform. When the training session will be correctly performed by the participants, the testing session will be started. At the end of each experimental condition (GoA-0, GoA-1, and GoA-2.1 or GoA-2.2 or GoA-2.3), the participants will be asked to answer some questions about their experience during the experiment. In order to avoid the learning effect, the scenario in the training simulated environment and the experimental one will be changed. In addition, to avoid the order effect, the GoA order will be counter-balanced between the participants.

Fig. 3. PSCHITT-rail tram simulator.

The participants will have to safely and punctually drive/supervise the simulated tram along a 6 km-long simulated track. This track will resembled the drive from station A to station B with 12 stations to stop. The allowed speed limits will be ranged from $(30 - 70)$ km/h so that the participants will drive approximatively 4 min under each GoA. At the end of each experimental condition, the participants will be asked to fill out some other questionnaires including questions corresponding to their experience during the experiment.

Data collection. Objective and subjective data will be collected during the experiment. The objective data are:

- The different speeds (tram, limits, targets).
- The times at the stations (expected and arrival).
- The number of accidents.

The subjective data are the responses to post-experiment questionnaires related to the feelings of comfort, safety, quality of control and workload.

4.2 Hypothesis and Indicators

During an itinerary, the driver is subjected to several stressful traffic situations that lead to a change in his behaviour. In fact, the tram driver can be disturbed by, for example, traffic lights, speed limit signs, station stops, crosswalks, turns, intersections, and cars. The future experiment aims to investigate whether the automated driving (GoA-2.1, GoA-2.2 and GoA-2.3) improves performance and safety in comparison to the no and less automated one (GoA-0 and GoA-1). These driving modes will be examined during the experiment to test these following hypothesis:

- **H1**: The respect of speed limits increases with the GoA regarding the ”acceleration/deceleration” task.
- **H2**: The punctuality (schedule respect) increases with the GoA regarding the ”stopping at the station” task.
- **H3**: The number of accidents decreases when the GoA increases.

- **H4**: The feelings of comfort, safety, quality of control increase with the GoA while the workload decreases.

These hypothesis will be tested using the data presented in Section 4.1. These data will be manipulated to obtain Indicators that will respectively be used for each hypothesis:

- **I1**: The difference between the targeted speed and the tram speed.
- **I2**: The difference between the time a station is reached and the one it was expected to.
- **I3**: The number of times over speeding, and potentially the number of people and cars getting hit by the tram.
- **I4**: Post experiment questionnaires.

Thanks to these indicators, we expect to validate the hypothesis and to conclude about the impact of Advanced Driver Assistance Systems depending on GoA on the Human-Machine System safety.

5. CONCLUSIONS AND PERSPECTIVES

In this paper, we have presented the Levels/Grades of automation in the aviation, rail, road and maritime transports and then made a comparison among them. Afterwards, we defined two driver assistance systems dedicated to trams: a visual one that is presented by an HUD and a haptic one that is materialized by a manipulator with a haptic feedback. Then, we proposed a taxonomy of GoAs for trams that is especially related to the haptic system degrees of assistance. The objective of the haptic and visual driving assistance systems is to improve the driver-tram system safety by enhancing the quality of control and the driver situation awareness. These systems and the GoAs are being implemented on the PSCHITT-rail tram simulator that will soon be used to test the hypothesis in order to identify the best Human-Machine System cooperation, *i.e.* GoA.

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