2025 IEEE VIII Congreso Internacional en Inteligencia Ambiental, Ingenieria de Software y Salud Electronica y Movil (AmITIC) | 979-8-3315-7846-6/25/$31.00 ©2025 IEEE | DOI: 10.1109/AMITIC68284.2025.11214596

CBTC CAPACITYANALYSIS FROM THE CONVENTIONAL TO THE AUTONOMOUS GOA4 MODEL FOR THE CBTC ON PANAMA METRO LINE 2

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***Abstract*— This article presents the results of a formal and conceptual analysis for the CBTC Capacity analysis from the conventional to the autonomous GOA4 model for the CBTC of Panama Metro line 2 in view of the requirements of the IEC 62278 standard entitled: Railway applications - Specification and demonstration of reliability, availability, maintainability and safety (RAMS). For the Panama Metro to function, (GoA2) semi-automated train operation (STO) is the current degree of automation 2. To reach not just the GoA3 grade of automation, which is an intermediate level between the existing GoA2 and the intended GoA4, but also the GoA2 grade of automation, PML2 would need to be upgraded to GoA2 through both technological and human investment.**

Keywords—railway engineering, signaling and train control, subway, Panama metro

I. INTRODUCTION

The train signaling and control system for Panama Metro line 2 (PML2) was built with the following subsystems:

- The system known as Radio Communications-Based Train Control (CBTC).
- Automatic Train Supervision (ATS).
- Maintenance Support System (MSS).
- Semi-Automatic Train Operation (STO).

Regarding the concept of grade of automation, the Panama Metro has adopted the following definition: "*level of automation for train operation resulting from the sharing of responsibility for basic train operation functions between operating personnel and the technical system*." [1]

The operating premises of the signaling and train control system for the Panama Metro Line 2 are:

PML2 operates under a GOA2 system. This means that trains are operated, in nominal mode, by the ATC system with full protection from the ATP and the ATO. Door opening is enabled and authorized by the ATP but requested, for each door, by passengers (however, the driver will also have the authority to open all train doors once authorized by the ATP). The closing of these doors and the departure of the train is controlled by the train´s driver. In addition, drivers interact with the system, monitoring the proper functioning of train doors once they are at the railway station, reacting to incidents on the railway platform, announcing information to passengers, making track changes at the ends of the terminal stations, and selecting the appropriate train operating mode.

The operation uses a Wi-Fi system or something similar (which may be based on LTE technology), which has been extensively tested in the railway industry, and more especially in the metro lines. The data flow is redundant and protected from transmission failures, interference, and outside threats. The tools required to keep outside agents from accessing the data transmission system must be present and maintained by this transmission system.

The basic idea behind railway operations is that a train advances if the interlocking system gives it a movement limit (moving authority, also called movement authorization in railway parlance) and an exclusive route that is fixed, blocked, and based on a speed profile in compliance with the regulation order received from the ATS.

Beacons placed along the entire route serve as a train positioning system, initially determining the location and relocation of trains. In addition, on-board odometry employing wheel revolution counters (SIL-4) determines the exact position of trains.

As a backup method for train location without rail closures, PML2 incorporates a secondary train presence detection system. This enables the creation of cantons with varying lengths (shorter in switch areas, platforms, and any other singular track section, and longer in interstation sections). Additionally, this technology improves operation in degraded conditions by enabling the location of auxiliary trains or any other metal-wheeled equipment or materials that may be operating on the tracks.

• The trains on PML2 are equipped with an Automatic Train Protection (ATP) system that enables it to be halted if it breaches a track restriction or if its detected speed above the maximum speed established for that particular segment of the railroad.

• When entering the yard from the main line to the parking zone, the maneuvers are ostensibly in autonomous mode, but the yard and workshop areas are restricted to a maximum speed of 25 km/h.

• The procedures for leaving and entering the parking zone are regulated by the standards outlined in "*Starting/Shutting Down Trains Under CBTC*".

• Except on the test track, all maneuvers in the yard, whether in nominal or degraded operating modes, must be performed at a maximum speed of 25 km/h.

The UNE-EN 13816 standard entitled: Transport - Logistics and services - Public passenger transport - Definition of service quality, objectives and measurements, "*specifies the requirements for defining, setting objectives and performing measurements of service quality in public passenger transport (PPT), and provides guidelines for the selection of the corresponding measurement methods*" [2]. There are several authors in the literature who have made scientific publications on management and service quality in railway transport [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

The table 1 presents the safety criteria or standards used to the electronic interlocking and train control system for the PML2 [16]:

TABLE 1. Safety Standards[16]

Code	Code´s title
EN-50126	Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)
EN-50128	Railway applications - Communication, signaling and processing systems - Software for railway control and protection systems
EN-50129	Railway applications - Communication, signaling and processing systems - Safety related electronic systems for signaling
EN-50159	Railway applications - Communication, signaling and processing systems - Safety-related communication in transmission systems
FIPS 140-2	Federal Information Processing Standard Publication 140-2
FIPS 140-2.2	Federal Information Processing Standard Publication 140-2.2
IEC 15408	Information technology security
IEC 61508	Functional safety of electrical/electronic/programmable electronic safety-related systems
IEC 62290-1	Railway applications – urban guided transport management and command/control systems
IEEE 1473-L	Bus de transmisión de datos a bordo
IEEE 1474-1	IEEE Standard for communications-based train control (CBTC) - Performance and functional requirements
IEEE 1472-2	Standard for user interface requirements in communications-based train control (CBTC) systems
IEEE 1472-3	IEEE Recommended practice for communications-based train control (CBTC) System design and functional allocations
IEEE 802.11	WIFI - Red inalámbrica ISO
ISO	ISO Reference Model

II. An Overview of the Panama Metro Line 2

On April 25, 2019, Panama Metro Line 2 went into service [17]. The first phase of Panama Metro line 2 has 21 kilometers [18][19] of elevated track with 16 stations at high-traffic areas like *San Miguelito* (where it connects to Line 1), *Paraíso*, the intersection with *Via Cincuentenario*, the *Villa Lucre* and *Brisas del Golf* neighborhoods, *Los Pueblos* and Metromall shopping centers; *San Antonio* Urbanization; *El Parador* in the *Pedregal* district; *Don Bosco* Urbanization; *Universidad Tecnológica de Panamá* (ISTE-UTP); *Las Mañanitas*; *Hospital del Este*, *Altos de Tocumen*; *La Doña* shopping center in the *24 de Diciembre* sector; and *Nuevo Tocumen* neighborhoods. Every station are elevated [18][20]. All stations include taxi and bus stops [21]. The maximum slope is 35 mm [18].

The geometric conceptual design, operational parameters, passenger demand, electrification, train control and signaling systems, and rolling stock technical specifications of the Panama Metro line 2 have been covered extensively by Berbey-Alvarez and Sanz Bobi[22]. Except for the yard and workshop zones, where it is situated on ballast, PML2 is a slab track system all the way. Additionally, the subway is electrified. PML2 is a double-track line with a 1,435 mm international gauge [18]. (See figure 1).

This subway system is designed with right-hand traffic[19], switches that provide partial operation in degraded mode, signaling that ensures a train interval based on user demand, and elevated double track without level crossings [18].

On the main track, yards and workshops, the rails are of type UIC54 E1 (54 kg/m), which has a tensile strength of at least 880 N/mm² [19], and a hardness value between 260 and 300 HB [18][20]. The main tracks' ballast-free superstructure is made up of 54E1 rails and elastic fasteners that are fastened to the viaduct beams[19].

Fig 1. Panama Metro Network (Lines 1 and 2). Source: Berbey-Alvarez (2023)

The CBTC signaling and train control system is based on an automatic train control (ATC) system that includes automatic train protection (ATP), automatic train operation (ATO), and automatic train supervision (ATS). All of these systems will contribute to the implementation of an integrated line operation system in STO (semi-automatic train operation) mode[16].

III. METHODOLOGY

The generic security criteria were developed using a technique based on the life cycle phases outlined in IEC 62278. Figure 2 emphasizes the methodology's actions and displays the system life cycle in a V-shape.

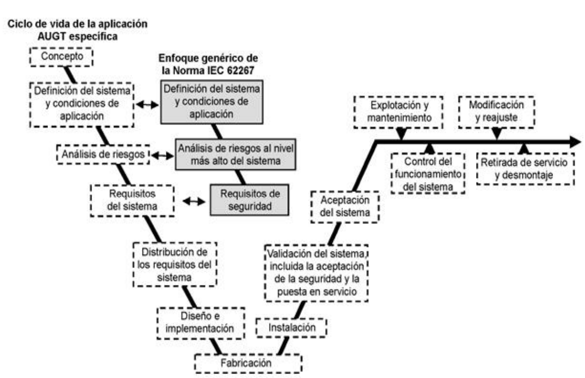

Fig 2. Life cycle phases covered by this standard (see figure 10 of IEC 62278 or figure 1 of UNE_EN 62267)

The Railway Applications Standard, UNE-EN 62267. Urban Transportation with Automatic Guidance (AUGT). Safety criteria includes *"the high-level safety requirements applicable to automatically guided urban transport systems, consisting of motor vehicles without machines or without crew, running on their own track"* [1]. The UNE-EN 62267 standard has been the subject of numerous authors' a publications in the literature [5], [23], [24], [25], [26].

The IEC 62290-1 standard defines the various degrees of automation (GoA) that are possible with modern CBTC systems. CBTC is frequently seen as a key technology for "*automated or driverless trains*," although it is not always the same thing.

From a fully automatic working mode to a manual operating mode with protection, there are many levels of automation available. These are the levels:

• GoA 0 (an emergency mode, usually found on railroad trains with a driver's cab, where the driver reads signals and makes all important decisions for full train management).

• GoA 1 (often utilized as a degraded mode or as a crucial component of providing passengers with a sense of security by having an agent on board). This is because the driver still has a big say in how the train accelerates, brakes, and opens doors. However, the system can respond by stopping the train without the driver having to brake if they disregard a red-light trackside stop signal or a command from a central control station. This is meant to increase safety and lower the number of train accidents that have happened because of fast trains, inattentive drivers, damaged trains, or misinterpreted signals.

• GoA 2 (Semi-automated Train Operation, STO): even when a driver is present, he takes on the responsibilities of opening and closing doors, initiating the formation's acceleration so that it reacts to the signals and radio frequency blocks of the onboard equipment, and serving as a catalyst and support in the event of an emergency.

• Driverless Train Operation (DTO), or GoA 3. The latter uses an attendant on board the train to manage deteriorated conditions and assist passengers in an emergency, but it does not have a driver in the cabin.

• Unattended Train Operation (UTO), or GoA 4. Without human participation within the formation—that is, without even a de facto driver or any kind of train crew capable of handling certain situations, this mode is entirely automated.

Similarly, CBTC can easily manage all these automatic control types, whether semi-manual or mixed, as well as other potential driving modes (as stated above, it is the foundation for a transition to a fully automatic system without human intervention within the formation). But it's important to keep in mind that increasing automation levels require better levels of usefulness, performance, and safety.

According to the UNE-EN 62267 standard, table 2 lists the various levels of automation along with how they relate to the fundamental operations of trains. railroad applications. Urban transportation that is automatically guided (AUGT). requirements for safety [1].

TABLE 2. Automation grade[1]

Note
X = Responsibility of operating personnel (can be carried out by the technical system)
S = Carried out by the technical system
0 = Train operation in sight-in-motion (TOS)
1 = Non-automatic train operation (NTO)
2 = Semi-automatic train operation (STO)
3 = Train operation without a driver
4 = Train operation without a crew (UT0)

Basic functions for train operation		0 GOA0	1 GOA1	2 GOA2	3 GOA3	4 GOA4
Ensuring the safe movement of trains	Ensure the safety of routes	X (command and control of changes by system)	S	S	S	S
	Ensure safe separation of trains	x	S	S	S	S
	Ensuring the safe speed of trains	x	(partially supervised by the system)	S	S	S
Driving	Controlling acceleration and braking	x	x	S	S	S
Monitor the track	Avoid collision with obstacles	x	x	x	S	S
	Avoid collision with people	x	x	x	S	S
Supervise the boarding and disembarking of passengers	Control the train doors	x	x	x	X o S	S
	Avoid injury to people between cars or between platforms and the train	x	x	x	X o S	S
	Ensure safe conditions for train start-up	x	x	x	X o S	S
Put a train into operation	Put the train into operation or take the train out of service	x	x	x	X	S
	Train status monitoring	x	x	x	X	S
Ensure the detection and management of emergency situations	Perform train diagnostics, detect fire/smoke and derailment detection, manage emergency situations (call/evacuation, supervision)	x	x	x	X	S and/or CRC staff members

IV. RESULTS AND DISCUSSION

The three stages of this standard served as the foundation for the development of IEC 62267's general approach:

• The system definition and application conditions.
• Risk analysis at the highest level of the system.
• Safety requirements. Analysis of the increase in the automation grade.

The system definition and application conditions. In Berbey-Alvarez and Sanz Bobi provides the Signaling and Train Control (S&CT) system's definition, characterization, and application conditions for the PML2. Additionally, it outlines the safety regulations that are applied to PML2's electronic interlocking and train control system.

The electrification system, a far more comprehensive train control and signaling system, passenger demand statistics, operational factors (supply, demand, historical records of operational quality), and the technical features of rolling stock and stations are all covered in Berbey-Alvarez and Sanz Bobi[22].

Risk analysis at the highest level of the system. This second phase corresponds to the examination of risk at the highest level of the system. For the automatic operation of the Panama Metro, the semiautomated train operation (STO) system has been adopted [46]. The grade of automation required for the operation of PML2 is GoA2, semiautomated train operation (STO) [46].

The semi-automated train operation (STO) system has been implemented for the Panama Metro's automated operation [27]. Two (GoA2) semi-automatic train operation (STO) is the level of automation needed to run the Panama Metro [27]. The grade of automation chosen for PML2 is displayed in the table 3.

TABLE 3. Grade of automation for PML2 [27].

Automation grade	Type of train operation	Configuration of the moving train	Train stoppage	Door closing	Operation in interruption events
GoA2	ATO and ATP with driver	Automatic	Automatic	Driver	Driver

The Panama Metro [46] states that the main components of the STO system for PML2 are:

• ATC systems for mass transit applications are a component of a general signaling system that includes communication functions, track clearance detection, automatic train supervision, and interlocking. The core of any semi-automated train guiding (STO) system is signaling equipment.

• Automatic train protection (ATP) is the system and the equipment that oversees basic safety; it applies the brakes automatically to avoid collisions, prevents overtaking a red signal and exceeding speed limits. The grade of automation 1 (GoA1) corresponds to a railway line with an ATP system installed.

• Driverless capability and partial or complete automatic train steering are offered by automatic train operation (ATO). All driver functions are handled by the ATO system, except for door closure. The train will automatically move on to the next station if the track is clear, and the driver only needs to close the train´s doors (GoA2).

The Panama Metro [27] states that this feature includes:

It is necessary to employ radio as the communication technology for train control (CBTC). Trains and trackside equipment can communicate at high bandwidth thanks to the radio.

Enough bandwidth was considered in the design for automatic train operation (ATO), automatic train control (ATC), and fully automatic train protection (ATP).

The capacity to establish a completely redundant communication link to trains is a significant benefit that radio provides over cable-based systems.

The bandwidth requirements for ATC are relatively low given the technology currently in use and needed for this operation. This frees up a significant amount of bandwidth for other services like remote diagnostic equipment, communication from train to Operations Control Center (OCC), passenger operational information, and announcement dissemination.

Trains can locate themselves using intermittent communication provided by fixed trackside equipment (beacons) that conveys permanently recorded data.

The fundamental capability needed for ATO is provided by this communication, which enables fixed block operation with ongoing monitoring. A free-propagating radio system can provide continuous communication.

<u>Requirements for safety. Analysis of the increase in the automation grade</u>. To reach not just GoA3, which is an intermediate level between the existing GoA2 and the anticipated GoA4, but also GoA2, increasing the current degree of automation of PML2 to GoA2 will require a technological and human investment.

<u>Driverless train operating for grade of Automation 3 (GoA3):</u> Compared to GoA2, extra precautions are needed because there isn't a driver in the train cabin to monitor the guidance system and halt the train in case of an emergency. A train attendant—a member of the onboard operations staff—is necessary at this level of automation. The operations team may oversee ensuring the train leaves the station safely and that the doors are closed, or it may happen automatically (see table 3).

<u>For unattended train operating at grade of Automation 4 (GOA4).</u> Since there is no onboard operating staff at this degree of automation, extra precautions are needed in comparison to GOA3. Door closure and the train's safe exit from the station are accomplished automatically. More precisely, the system facilitates emergency circumstances like passenger evacuation as well as the identification and management of hazardous conditions. Specially qualified workers may be needed to intervene in some dangerous situations or emergencies, such as derailment or the discovery of smoke or fire (see table 4).

TABLE 4. Increase in the grade of automation

Note
X = Responsibility of operating personnel (can be carried out by the technical system)
S = Carried out by the technical system

Basic functions for train operation		Semi-automatic train operation (STO)	Train operation without a crew (UT0)
		GOA2	**GOA4**
Ensuring the safe movement of trains	Ensure the safety of routes	S	S
	Ensure safe separation of trains	S	S
	Ensuring the safe speed of trains	S	S
Driving	Controlling acceleration and braking	S	S
Monitor the track	Avoid collision with obstacles	x	S
	Avoid collision with people	x	S

Supervise the boarding and disembarking of passengers	Control the train doors	x	S
	Avoid injury to people between cars or between platforms and the train	x	S
	Ensure safe conditions for train start-up	x	S
Put a train into operation	Put the train into operation or take the train out of service	x	S
	Train status monitoring	x	S
Ensure the detection and management of emergency situations	Perform train diagnostics, detect fire/smoke and derailment detection, manage emergency situations (call/evacuation, supervision)	x	S and/or CRC staff members

The investment in personal resources and technology would affect the fundamental operations of trains. Instead of the train operator, the system would do these tasks. These include keeping an eye on the track, overseeing the boarding of passengers, placing a train in operational mode, and making sure that emergency situations are identified and handled. In other words, as the GoA4 picture illustrates, there is no driver because there are no staff on board to run the train. In contrast to GoA3, the train has an operator on board to deal with instances of compromised system performance (See table 5).

TABLE 5. Features of automation levels and illustrations [28], [29][30][31][28], [32].

GoA	Operation type	Starting the train	Train brake	Closing doors	Operation in disruption events	Examples
1	ATP with driver	Driver	Driver	Driver	Driver	ECTS 1
2	ATP+ATO with driver	Automatic	Automatic	Driver	Driver	ECTS 2 ECTS 3
3	Driveless	Automatic	Automatic	Train assistant on board	Train assistant on board	----------
4	UTO	Automatic	Automatic	Automatic	Automatic	CBTC with all the features

Using schemes from mathematical set theory and expressing union and insertion links in their respective contexts, Martínez and Martin [30] created an interesting classification and relationship of train protection and safety systems. According to the viewpoints of the railway system's functionalities by system type, Martínez and Martin [30] classified the systems (see figure 3).

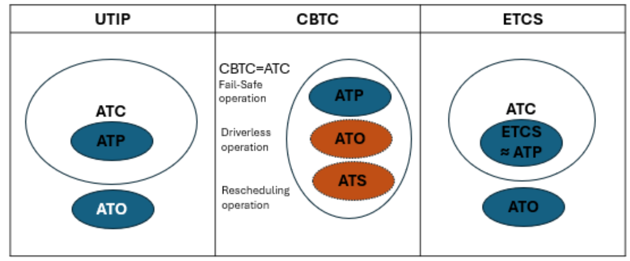

Fig 3. Perspectives on the functionalities of the railway system according to the system [30].

In the context of the CBTC system, the ATP has mandatory functions, whereas the ATO and ATS have optional ones. Due to the threat to their jobs, train drivers may also oppose the installation of GoA4 on PML2. As per [29], both automation levels 3 and 4 enable a decrease in the number of staff needed on trains, i.e., less personnel needed. Additionally, the Panama Metro network has prioritized expansion projects to additional sectors of the Panama City metropolitan region in accordance with its master plan [33], [34],[35], [36].
An infrastructural base that is suitable for the operation of new high-performance automated systems is necessary, according to regional experiences, such as the Buenos Aires Metro (Argentina) [29], [37]. Therefore, before adding new components, it is best to spend it on the core infrastructure.

CONCLUSIONS

Building smart cities requires the development and deployment of an automated operation system for urban rail transportation. The semi-automatic train operation (STO) system was chosen for the automated running of the Panama Metro [27]. For the Panama Metro to function, (GoA2) semi-automated train operation (STO) is the necessary degree of automation 2 [27]. In order to reach not just the GoA3 grade of automation, which is an intermediate level between the existing GoA2 and the intended GoA4, but also the GoA2 grade of automation, PML2 would need to be upgraded to GoA2 through both technological and human investment.
The investment in people and technology would affect the fundamental operations of trains. The system would handle these tasks rather than the train operator. These include keeping an eye on the track, overseeing the boarding of passengers, placing a train in operational mode, and making sure that emergency situations are identified and handled. In other words, as the GoA4 picture illustrates, there is no driver because there is no staff on board to run the train. The installation of GoA4 on PML2 may also encounter resistance from train drivers [29] who perceive their jobs as being in jeopardy, in contrast to GoA3, which has an operator on board to handle circumstances of deteriorated system management. It is advised to think about certifying the Panama Metro in accordance with EN ISO 22163 standards in order to enhance the management systems for the network's operations. Applications for railways, railway quality management

systems, ISO 9001:2015, and particular requirements for railway applications (ISO 22163:2023) [38]. The requirements for a quality management system are outlined in ISO 22163:2023 when an organization:

a) Must show that it can reliably deliver goods and services that satisfy client demands as well as relevant legal and regulatory requirements, and

b) Through the efficient use of the system, including procedures for system enhancement and guaranteeing compliance with client demands as well as relevant legal and regulatory requirements, aims to increase customer satisfaction.

The requirements for a railway quality management system (QMS) are outlined in ISO 22163:2023:

— relevant to all industrial goods and services supplied by railroads,

— supporting ongoing development, with a focus on minimizing and mitigating supply chain flaws, and

— enhancing and preserving the quality of the product, particularly its safety features.

After the framework is in place, it is recommended that funds be obtained to carry out experimental research on potential real-world scenarios pertaining to expanding PML2's CBTC capacity, particularly on the main section and the branch that offers transportation services to and from Tocumen International Airport.

Acknowledgment

The corresponding author expresses her gratitude to the Department of Mechanical Engineering of the School of Industrial Engineers of the *Universidad Politécnica de Madrid* (Spain) and especially to Dr. Juan de Dios Sanz Bobi for granting her a scholarship to pursue studies in the postgraduate program of own degree E.05.D420.01 – Railway control, command and signalling. Also the authors express our gratitude to the *Universidad Tecnológica de Panamá*.

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