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Possibilities of Introduction of Automated Operation on the Prague Metro

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Abstract

The issue of automated metro is a modern trend in rail transport. Its utilization is still mainly in the field of urban underground railways. This article shows the possibilities that the Prague Metro has in its expansion of the D line in the area of automatic operation. As a sub-part, the possibility of switching the current operation to automatic in the modification of the security equipment and new vehicles, was also solved. However, this option seems complex and inefficient.

This article focuses on automated metro operation systems, their basic requirements and functions. There is also a definition of various degrees of automation and a description of differences in functions of individual types. This article gives also a basic overview of functions, which are necessary for an automated metro operation system. In the second part, the article provides for an analysis of automated metro systems in the world. The last part deals with various types of interlocking systems for the automated metro operation system, including their basic functions.

KEY WORDS: *automated metro, operation systems, rail transport, vehicles, basic functions*

1. Introduction

As the preparations of the development of new metro line D are under way, ideas regarding the technical and technological aspects of the new line began springing up in the academic realm. It is the first time that an unmanned train set is about to be used. The concept of operation, as well as the exact route in the city centre are still to be finalised. This is why a diploma thesis [1] was drawn up at the Faculty of Transport Engineering at the University of Pardubice, aiming to simulate various concepts of operation on this new line including technical measures for the operation of unmanned train sets and the influence of ETCS L3 on the track capability. Unfortunately, due to a lack of input data, it was not possible to write this thesis in such a form. As an alternative, the thesis deals with the verification of functionality of SW Opentrack for metro operation, as well as a simulation of the ETCS L3 train control system on metro line C.

This article presents a summary of the first part of the research, defining and analysing various unmanned metro operations worldwide and covering the application of the chosen technology on the track of metro line B. The authors are now preparing another section of the article, which is about to cover the simulation of the current operation and the transition to ETCS L3 and its impact on the peak interval and transport capacity.

2. Automatic metro operation

Automatic operation refers to the operation of driverless or fully unattended self-propelled trains on a reserved guide track. Driverless train operation (DTO) is a type of operation with staff on board the train who are not responsible for driving the train or monitoring the track ahead of the train. In these cases, the operations staff are in charge of ensuring safe boarding and alighting of passengers, or, as the case may be, for a safe dispatching of the train from the station. Furthermore, there are unattended trains (UTO), in which there is no staff on board the train and all the functionalities are ensured by technical equipment [2].

2.1 Grades of Automation

Urban railway systems may be classified into a total of five grades of automation. Each particular grade exactly defines which basic functions need to be fulfilled (are the responsibility of) the operations staff and which are ensured by an urban guided transport management and control system. Table 1 provides an overview of basic functionalities for individual grades of automation. Functions ensured by operations staff are highlighted in red, functions ensured by EGTMS are highlighted in green.

Table 1:
Grades of automation

Basic train operation functions		Manual operation without automatic protection	Non-automated operation	Semi-automated train operation	Driverless train operation	Unattended train operation
		GoA0	GoA1	GoA2	GoA3	GoA4
Ensure safe movement of train	Ensuring safe route					
	Ensuring safe train separation					
	Ensuring safe speed					
Driving the train	Acceleration and braking		By operations staff only, or by UGTMS in part			
Supervising the guideway	Obstacle collision prevention					
	Prevent collision with persons on tracks					
Supervising passenger transfer	Opening passenger doors					
	Prevent injuries to persons between cars or in the boarding area					
	Ensure safe starting conditions					
Train operation	Putting the train in service /taking the train out of service					
	Supervising the status of the train					
Ensure detection and management of emergency situations	Fire/smoke detection and derailment detection, detection of the loss of train integrity, passenger emergency signalling					UGTMS or staff in OCC

Source: [2] edited by authors

In addition to these basic functions, the system may ensure other functions as well. However, these are not mandatory and do not affect its classification. The classification of particular optional functions is at the sole discretion of the railway manager and carrier [2]. At the same time, the IEC 62290 standard defines four basic grades of automation ranging from GoA1 to GoA4. These standards are included in Czech technical standards, such as ČSN EN 62267 (Railway applications – Automated urban guided transport (AUGT) – Safety requirements), ČSN EN 62290 – 1 (Railway applications – Urban guided transport management and command/control systems - Part 1: System principles and fundamental concepts) and ČSN EN 62290 – 2 (Railway applications – Urban guided transport management and command/control systems – Part 2: Functional requirements specification).

For classification purposes of this paper, systems with a grade of automation ranging from GoA0 to GoA2 are considered to be conventional train operation systems and grades GoA3 to GoA4 are considered to be automatic operation systems. As far as track-side equipment is concerned, it is not necessary for all parts of the track to be equipped with applications of identical grade of automation. The extent of security shall always be at the highest possible level as far as the compatibility of track-side and vehicles is concerned. The individual grades of automation have to be fully mutually compatible [3].

Train operation without automatic train protection (GoA0) – while guiding/driving the train only by vision, without automatic protection, the train operator is fully responsible for the safe movement of the train. The train operator is not supervised by any technical equipment. The operations staff is responsible for the safety and efficiency of track-side operation and railway transport. Train, station and track-side signalling equipment may be set up for this grade of automation of operation, but this is only optional [3].

Non-automated train operation (GoA1) – during non-automated train operation, the train operator is at the front of the vehicle and supervises the track-side ahead of the train. Acceleration and braking of the train are carried out by the train operator, who drives the train based on the observable signals of wayside signalling or based on signals passed on to the position of the train operator. The train operator drives the train under the supervision of automatic train protection. This equipment may be of a point, line or semi-line type and carries out supervision as specified. This supervision entails vigilance supervision, train speed supervision and the supervision of compliance with signalling. In this case, the operations staff is fully responsible for the safe departure of the train from the station, including the closing of the train doors [3].

Semi-automated train operation (GoA2) – for semi-automated operation, the train operator only supervises the safe movement of the train. The train operator monitors the track ahead and may stop the train in case of imminent danger. Acceleration and breaking are carried out automatically, as well as the supervision of the speed limit of the train. The operations staff is responsible for the safe departure of the train from the station. The safe closing of the doors may be entrusted to the operations staff or done automatically [3].

Driverless train operation (GoA3) – for this grade of automation, there is no member of staff at the front of the train to visually monitor the track and stop the train in case of danger. Safe movement of the train fully relies on the correct functioning of the protection equipment supervising the free passing and safety of the track. However, there must be operations staff on board the train to supervise the train itself. Depending on the optional functions of this grade of automation, the staff may be responsible for safe departure of the train, for closing the door, for the monitoring of the state of the train and safety of passengers. In particular, this member of staff is responsible for handling emergency situations during irregularities and system breakdowns, as the case may be [3].

Unattended train operation (GoA4) – at this grade of automation, further measures are required as opposed to GoA3, because there is no operations staff on board the train. The entire system must be equipped with safe detection equipment to report hazardous conditions and emergency situations. Whenever a hazardous situation requiring the intervention of operations staff occurs, such staff must be automatically informed and take remedial measures subsequently [3].

2.2 The organization of metro operation

A basic hierarchy applies for urban guided transport operation, as well as for metros in general. This classification defines specific levels of operations organization, as shown in Fig. 1. Optional and mandatory system requirements are set for specific parts of the system, depending on the grade of automation. For all grades of automation, operations control is carried out from an Operations Control Centre (OCC)[1].

In case of automatic operation, it is necessary to clearly define the area covered by UGTMS control. The equipment needs to offer the possibility to check the train equipment at this area´s boundaries or within the area as such, in order to make information available about flawless functioning of the train-borne part of the equipment before putting the train into operation. This testing must be implemented in a way which does not require stopping the train when it is driving into or out of the area. In the UGTMS controlled area, all the functions depending on the given grade of automation, must be available. Train runs of trains not equipped with the train-borne part of the equipment are carried out alternatively and are governed by internal regulations of the railway manager [3].

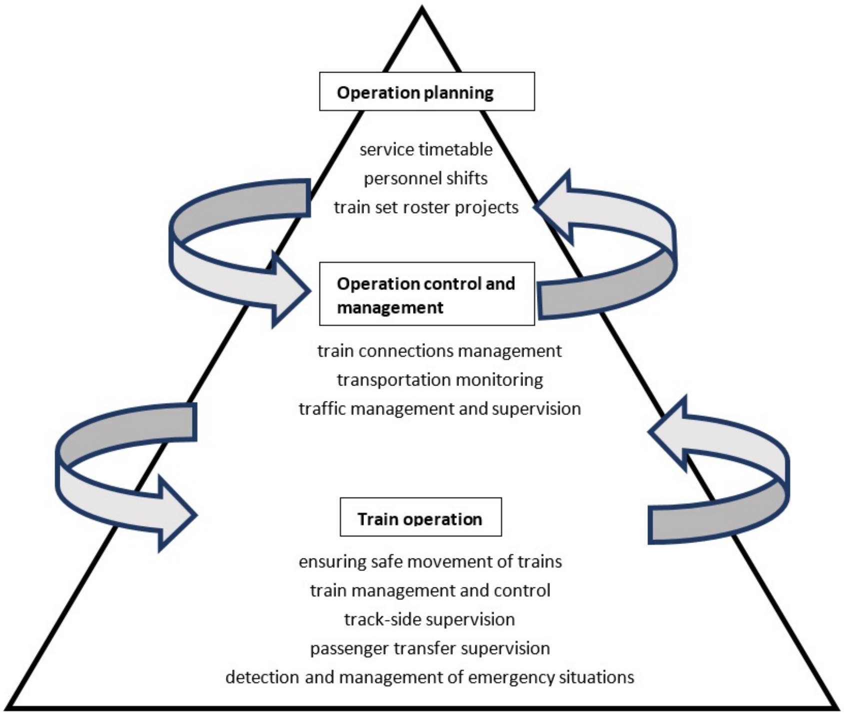

Fig.1 Metro operation organization scheme

Source: [4], edited by authors

For UGTMS systems, both automatic and manual positioning of directions of journey is admissible. Directions of journey are positioned with regard to the routing of the train or operational needs. In order to ensure a safe direction of journey, the authorisation for the movement of the train (movement authority) must be given only after the direction of journey is positioned and after the locking of the direction of journey. The unlocking of the direction of journey occurs automatically or manually after making sure that the whole train has moved past the relevant elements of the direction of journey [4].

[1]OCC – Operations Control Centre

The designated and operational intervals determined by the railway manager are another important safety element securing the safe movement of trains. The designated interval is given by the directional and height arrangement of stations and tracks, by the periods of stalling, by traction properties of trains, arrangement of turning stations and the train operator´s reaction time (for grades of automation GoA0 – GoA2). The UGTMS system ensures the safe movement of trains in the network in the designated interval. Safe train separations can be ensured by fixed or flexible compartments. For each subsequent train, the absolute limit is set for the authorization of movement based on the position of the end of the preceding train [4].

Equipment at all grades of automation controls whether the safety speed limit is kept. Safety speed limits are determined based on the static and dynamic speed profiles. Dynamic speed profile is calculated based on the static speed profile and a safe braking model. The safe braking model must take into account variables such as inaccuracy in determining the position, the length of the train, the deviation of speed measurement, reaction time, reaction time of the emergency brake. A train moving in the controlled area must not exceed the dynamic speed profile, thus ensuring that the train shall not exceed the absolute limit for the authorisation of movement [4].

It is also possible to operate a train without the train-borne system equipment or with a non-functioning train-borne system equipment in the UGTMS-controlled area. However, under this reduced scheme, the UGTMS must ensure safety of operation with the lowest possible human factor dependency and while complying with traffic regulations [4].

2.3 Functionalities for train operation

The ensuing chapter covers basic functions relating to the train operation and its safe movement in the network operated in the automatic mode. The individual elements represent the cornerstones of the system safety.

Ensuring safe movement of the train. The positioning and securing of the requested direction of journey is fundamental for the safe movement of the train. The direction of journey must be locked and, subsequently, authorization for the train movement must be given. In terms of train operation, an essential requirement is ensuring the automatic identification of the position of the train when entering the area or when the train is activated on the operated network. Furthermore, the orientation of the train, i.e. the position of its front and rear part, must be ascertained. If this information is not available due to system failure, operation needs to be stopped on the section in question by applying emergency braking of the endangered train. In these cases, the system automatically creates a protective section where no trains can be allowed. The train may also be localised using a back-up system (if one is set up), in which case the movement of the train is organised in fixed sections of the area, where an absolute block condition must be met in order to secure the availability of each given section. If there is no available UGTMS functionality and there is no other technical equipment available to ensure the availability and correct positioning of the direction of journey, traffic needs to be organised pursuant to traffic regulations of the railway manager. The system must still be able to detect unauthorized movement of the train (e.g. unwanted autonomous movement of the train). Should any such event occur, the system must activate the emergency brake of the affected train without delay [4].

Train operation. Automatic trains are operated using driving speed profile. This profile is created with regard to the travelling culture and the energy load requirements and needs to be adapted to the dynamic speed profile in any case. Furthermore, the driving speed profile is based on data on infrastructure, vehicle parameters and critical operational parameters. Critical operational parameters refer to the stalling of trains in stations and on service tracks. The driving profile must change automatically when the input parameters of the calculation are altered [4]. For each train, the train route needs to be created, containing all the data on stopping of the train. However, this route can be changed based on operational needs and the driving profile needs to be adapted to this. The train must stop in all designated stations and there must be a possibility in place to keep it in the station based on the instructions of OCC staff [5].

Guideway supervision. The equipment on the track or on the vehicles must make sure that the train cannot collide with obstacles, i.e. with objects or persons in the clearance envelope. If the equipment detects an obstacle in the clearance envelope, a safety section must be created around this obstacle. The information also needs to be displayed in the OCC. Such a safety section may be called off only by a secure command given by the personnel after making sure that the track is clear. At the same time, if the train equipment detects an obstacle, the train needs to be stopped automatically and may be set in motion only after a secure command of the OCC service staff [3]. If the system is equipped with elements enabling the request for emergency stop by passengers or operations staff, the stations need to be fitted with equipment enabling emergency stop activation. Apart from the stopping of the train, a safety section is also created until it is securely called of by OCC staff [2]. Supervision over platform rails may be carried out using sensors detecting an obstacle on the track. However, in most cases, platform screens are used for AUGT system. In such a case, the closure and securing if the platform screen door needs to be controlled to enable safe entrance of the train to the station. If there is any interference with the system and an unauthorized opening of a door (including doors not intended for passengers), the train entering the area must be stopped and a safety section must be created. Such a section my only be called off by a secure command from the OCC [5].

In case infrastructure maintenance or other works are under way on the operated track, the system must enable the creation of a safe working section. This working section is inserted into the system manually by an OCC staff member who is also authorised to call off this working section after the track is cleared. Entry of the train into the working section may only be allowed by a secure command from the OCC issued individually in each case [4].

Supervising passenger transfer. As a minimum, passenger transfer supervision requirement must be met during the boarding and alighting of passengers, which represents the greatest risk to safety. Safety conditions must be met to ensure a safe boarding and alighting of passengers. The basic prerequisite is making sure that the train is securely stopped and secured in the designated place. Furthermore, the doors must be opened only on the desired side of the train. If the system is equipped with platform screen doors, it is necessary to ensure that these open only after the train safely stops and is secured. If the train is shorter than the platform, only the platform doors enabling to board the vehicle must be opened. The closing of the doors shall be governed by a designated timetable or based on minimum designated time of stay of the train in the station [6].

As soon as the time of departure comes, the system sends a command to close the doors. Such closing of the doors may be accompanied by acoustic or visual signals. The closing of the door of the train and platform screen doors must be synchronised so as to ensure safe boarding and alighting of all passengers. If the security measures are ensured by detection elements, any intrusion of a person into the safe zone must not be indicated [4].

If the doors are closed and there is no requirement preventing the departure of the train, the train may leave the station at a time given by the train timetable. For grade of automation GoA3, the command for departure may be given directly by operations staff member, for GoA4, this command is given automatically [2].

2.4 Functionalities serving traffic operation and supervision

System functions necessary for a safe and smooth automatic operation of railway and rail transport represent another important feature of the automatic operation. For traffic operation, it is necessary to ensure that the OCC staff can keep track of all the decisive functions of the system.

Train lines management. UGTMS systems, depending on the grade of automation, require functionalities for the management of individual train lines to meet the projected transport demand. The system must be designed so as to minimize deviations from normal operation even in case of operational irregularities. For grades of automation GoA3 and GoA4, it is necessary to implement the function of systemic train route creation in compliance with train timetables and the correct assignment of the route to a specific train connection depending on its features. Specific assignment of the train connection to a train route may be carried out manually at the OCC or automatically. Each train with an assigned route must have a unique identification number. The system must enable manual adjustment of all parameters of the route, if need be [4]. Each route consists of a set of directions of journey. These directions of journey are positioned fully automatically in case of automatic operation. However, the OCC service staff must always be able to position a direction of journey manually. The direction of journey must be positioned well ahead of time to prevent the intrusion of the route by other trains and ensuing delays. The positioning of the direction of journey is triggered by the system based on data contained in the train route. The internal logic of the system must prevent positioning any direction of journey which would cause mutual blocking of trains. In case of unavailability of a selected direction of journey, the train run must be sorted out by a diversion [7].

Supervising rail transport operation. The system must enable continuous supervision of all trains in the operated area and it must be able to pass on information to service staff. Information on the position of communicating trains is essential. When using the alternative management system using track sections, the system must be able to provide information on the occupancy of these sections by a non-communicating train. UGTMS must keep automatic transport documentation on rail transport management. All train-borne and track-side signalling equipment whose function influences the safety and smoothness of rail transport operation must be supervised by the system and their immediate status must be detected. Information on failures and irregularities must be preferentially communicated to the HMI operation. When communicating the information, its importance needs to be determined so as to show information with higher level of priority first [4].

Functionalities for HMI interface. The system must ensure safe communication between the operation in the managed area and the OCC. The OCC staff must keep track of the status of all elements involved in the UGTMS system which are directly linked to the safety and smoothness of operation. Only locally controlled functions pertaining to system maintenance may be left out of this overview. The system must be able to work safely and pass on all the commands issued by the management staff at the OCC [4].

Passenger information systems and passenger supervision. The UGTMS system may be equipped with voice or audio-visual information system. In order to secure the passenger safety, the system must enable a voice call between passengers and the OCC staff during emergency communication devices (in the train, at the platform). If UGTMS is connected to the external passenger monitoring system, this system must be equipped so as to be able to show the video camera image from the location in question at the OCC in case a dangerous situation is detected [6].

3. The possibilities of introducing automatic operation at metro line B

Introducing automatic operation on a track which is already in operation is a complicated issue. It is a strategic decision requiring a comprehensive change of the organization of operation management. A detailed decision-making analysis needs to be drawn up, assessing all the benefits and drawbacks of the modernization of the signalling equipment. Furthermore, a risk analysis needs to be drawn up, assessing all the risks ensuing from the change of the grade of automation and the related transfer of a portion of responsibility from operations staff to a technical equipment.

Line B is currently equipped with track circuits and the ARS train signalling equipment, continuously controlling the speed of the train. It therefore follows that Line B is fitted with equipment meeting the criteria for the grade of automation GoA1. The transfer to automatic operation would require major adaptations of the station, track and train signalling equipment. At the same time, the operator´s control centre would need adjusting so as to be able to keep track of all the functions required for automatic operation.

The advantages and disadvantages of the transfer to automatic operation. The transfer to the automatic operation of trains on line B would require many changes of the current operation concept. Nevertheless, this seems to be an interesting alternative during the transfer to a completely new system. It is possible to go for the combination titled GoA2+ in the article. This presumes the operation of the existing train sets with train operators under ATO supervision and there is also the possibility of using the CBTC technology in combination with specific segments of ECTS which is available in the Czech Republic in terms of technology. This intermediate stage combines the advantages of modern signalling equipment (ETCS L3 moving block) and the current technology (train operator vs. safety screen doors at the stations). The use of ETCS would allow for the shortening of operation intervals and, most importantly, the minimum interval. This has a direct impact on the capacity of the whole metro system, which is already operating at the borderline of its operational capacity. However, this modification does not cover other related parts of the metro system, such as the platform capacity, escalators, ticket stamping machines etc. This would require a separate solution, which needs to be directly related to the modifications of metro operation. The simulation model based on the queueing theory can be useful in this situation. Table 2 gives an overview of the advantage and disadvantages of making use of the GoA2+ intermediate stage.

This system envisages the use of the existing infrastructure combined with train sets supervision using ETCS L3 (moving track sections). The ascertaining of parameters regarding the possibility to increase transport capacity and minimize operational intervals can be done by simulation. The simulation has been carried out but is not included in this article.

Table 2

Transfer to GoA2+

Advantages	Disadvantages
• improvement of operation safety by excluding or mitigating the risks of human failure • increased system flexibility, • improved travelling convenience, • the possibility to increase transport capacity	• investment costs • the necessity to carry out changes of operational regulations of the railway manager.

Source: authors

Table 3 compares the advantages and disadvantages of transfer to the fully automated operation GoA4.

Table 3

Transfer to GoA4

Advantages	Disadvantages
• improved punctuality of train connections, • improvement of operation safety by excluding or mitigating the risks of human failure • increased system flexibility, • improved travelling convenience, • the possibility to increase transport capacity, • minimization of operational intervals, • reduction of traction energy consumption, • fewer operations staff	• track investment costs, • station investment costs, • the necessity to modernize technical equipment of the track and train, • complications while ensuring normal operation during the intermediate stage, • the necessity to change legal regulations (Act on Railways), • the necessity to change of operational regulations of the railway manager

Source: Authors

Requirements regarding the transfer to automatic operation. The basic prerequisite of the transfer to automatic operation is the reliable replacement of the role of the train operator or other operations staff by technical equipment. At the GoA1 grade of automation, the technical equipment is limited to signalling equipment controlling the safety and availability of the guideway, the ascertaining of the safe speed and safe train separation. However, the operations staff is responsible for the safe train guidance, train operation, passenger movement supervision and response to emergency situations. The change to the GoA4 grade of automation means the transfer of these functionalities to a technical equipment.

The existing technical equipment may also be used for the positioning of the directions of journey and secondary detection of the availability and integrity of track. However, the existing technical equipment needs to be integrated into the UGTMS system. Other automatic operation functionalities need to be ensured by a brand new technical equipment. The technical equipment must include functionalities for driving the train, for its safe acceleration and braking, as well as functions for monitoring the availability and free passing of the train track. In terms of passenger safety, functions ensuring the safe movement of passengers are essential. These are functionalities ensuring safe opening and closing of doors and devices, detection of the fall of passengers between train cars and platform and functionalities giving authorization to the train to leave the station only after the passengers have safely boarded and alighted. With regard to train operation, its automatic putting into and taking out of service needs to be ensured, as well as continuous review of the condition of trains and all their functional technical units indispensable for the safety and smoothness of operation.

With regard to the overall safety of operation, functionalities ensuring secure detection of any dangerous situation are vital. Depending on the nature of the situation, the system must enable a remote solution by the OCC or, as a minimum, communicating the information about the necessity of operations staff intervention. A detailed overview of functions for automatic operation is given in chapter 2.3.

Description of the transfer process regarding the introduction of automatic operation. Line B is one of the principal lines of Prague public transport. This implies that its taking out of service during the transfer to the automatic operation would bring about various challenges for the whole transportation system. There are three essential options regarding the solution of the intermediate stage during the modernization of the existing track [3]:

1) Complete shutdown of the existing track and its re-opening only after the finalisation of its conversion.
2) The continuation of operation for passengers using the existing equipment while working on the new equipment. Test runs would be carried out outside operation hours or in areas excluded from passenger transport operation.
3) The continuation of operation for passengers using the existing equipment while working on the new equipment. Test runs would be carried out during operation in a way which would reduce the scope of operation as little as possible (for example, during train breaks).

The work schedule and the conditions for the transfer process must be approved by the supplier of the equipment, the railway manager and the authority in charge of safety issues (*the Office for Railways*). Under no circumstances shall the train operation for passengers be put at risk by the test runs of trains operated automatically prior to their final approval. For these reasons, a risk analysis needs to be carried out including all the potential hazardous situations which might occur during the transformation process. At the same time, the work responsibilities of the operations staff need to be specified for each step of the transformation process. At the same time, the operations staff may be entrusted with interim safety measures applicable only for selected phases of the transformation process.

4. Automatic metro operation systems worldwide

The automation of high-speed railways has been an indisputable trend worldwide. In view of this, this chapter is dedicated to the metro automation trend around the world, including specific cases of application. The chapter goes on to describe particular automatic metro operations, stressing essential track parameters, signalling equipment and operated train sets. In June 2016, a total of 55 automated metro lines were in operation in 37 cities worldwide. A total of 157 cities have their own metro network, which implies that at least one automatically operated metro line can be found in 23 % of cities with metro operation. The overall length of automatically operated metro tracks is 803 km, being14.2 % longer than in 2014. According to existing projects, 2300 km of automated metro tracks will have been built by 2025. As shown in Fig. 2 below, Northern America, Europe and South-East Asia enjoy.

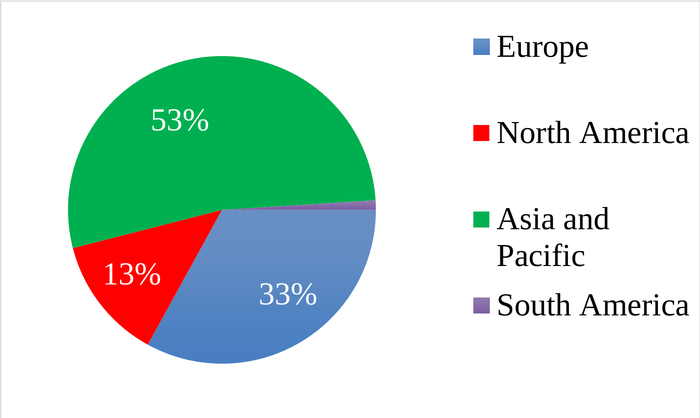

Fig. 2 Shares of the length of automatically operated metro lines worldwide

Source: [8] edited by authors

Countries with major shares of automatically operated lines include France, South Korea, Singapore and United Arab Emirates. Cities with the greatest lengths of automatic metro lines include: Singapore (93 km), Dubai (80 km) and Vancouver (63 km) [8]. Automatic operation was first tested on metro tracks with the capacity of one train for under 300 persons. The first automatically operated metro was opened in Lille, France in 1983 [9]. The shares of different metro lines sorted by train set capacity is shown in Fig. 3.

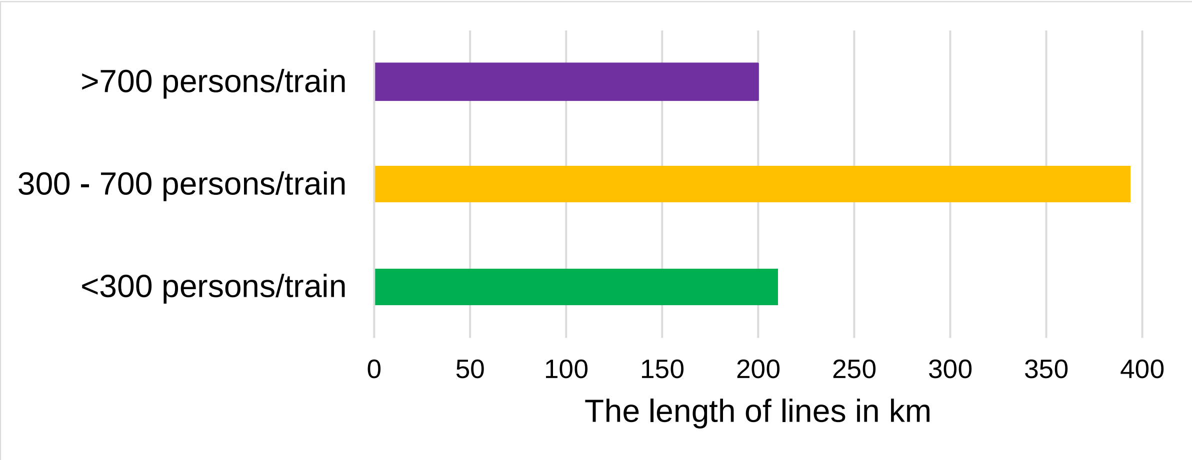

Fig. 3 Lengths of lines sorted by train set capacity

Source: [8] edited by authors

More than 30 years after the commissioning of the first line of automatically operated metro, the past decade has seen a significant growth of the share of automatically operated metro lines worldwide. Europe and Central and South-East Asia have enjoyed the most significant advancement of this technology. The greatest number of automatically operated metro projects are currently being developed in China. Further on, this chapter covers several specific European automatically operated metro lines on which enough relevant sources of information can be found, enabling their detailed description. The greatest emphasis is put on operational indicators, deployed vehicles and types of signalling equipment.

5. Signalling equipment for automatically operated metro

Currently, the CBTC type signalling equipment is the most widely used equipment for automatic metro operation, securing about 68 % of the total length of automatic metro lines worldwide. The most important CBTC supplier is the company Thales, closely followed by Siemens [8]. The share of individual CBTC producers according to the length of lines they supplied with signalling equipment is shown in the graph in Fig. 4.

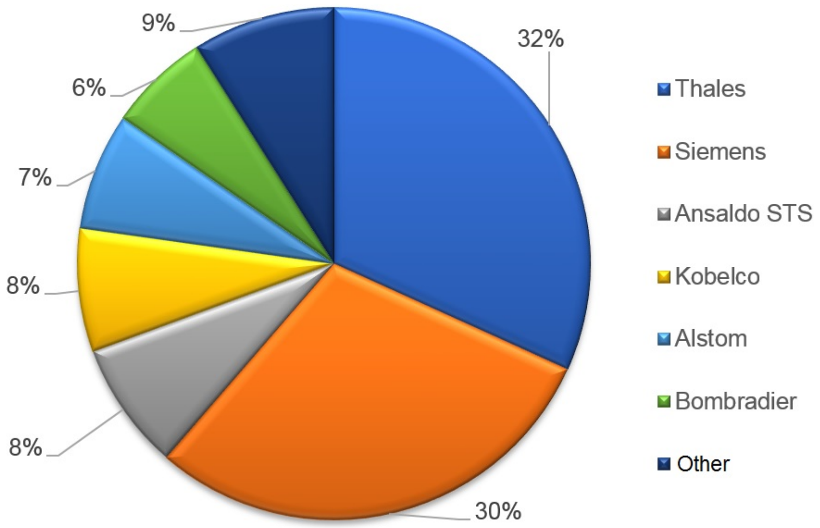

Fig. 4 The share of CBTC producers per length of lines

Source: [8], edited by authors

The CBTC equipment was developed primarily for high-capacity rail transport. This equipment is well suited for segregated tracks being used by trains with identical or very similar parameters and for tracks with a low risk of the endangering of transport by external influences (e.g. weather conditions, unauthorized movement of persons etc.) It follows from the above that the tracks suited for CBTC implementation include metro lines, or, as the case may be, tracks of other segregated urban and suburban lines. The CBTC system differs from the conventional signalling systems mainly by the possibility to operate trains in moving track sections. Conventional signalling systems use the signalling system with track-side or train-borne signalling devices for transport management and the track circuits or axle counter equipment is used for the detection of the position of the train. This is why they do not provide the possibility of operation in moving track sections, but only in fixed track sections marked by signalling devices or individual track sections. The CBTC system sorts this problem out by direct communication between the train-borne and track-side part of the signalling device.

The on-board part of the CBTC is able to determine the precise location of the train on the track with high precision and provide detailed data on the status of the train at the same time. This is how the CBTC systems can enable operation in moving track sections, thus reducing the distance between subsequent trains on the track. In these systems, the distance between subsequent tracks is determined as per the position of the end of the preceding train, the braking distance of the subsequent train and a safety margin. For the distance calculated this way, the system grants a so called *movement authority* [10]. A general diagram for determining the distance between subsequent trains is shown in Fig. 5.

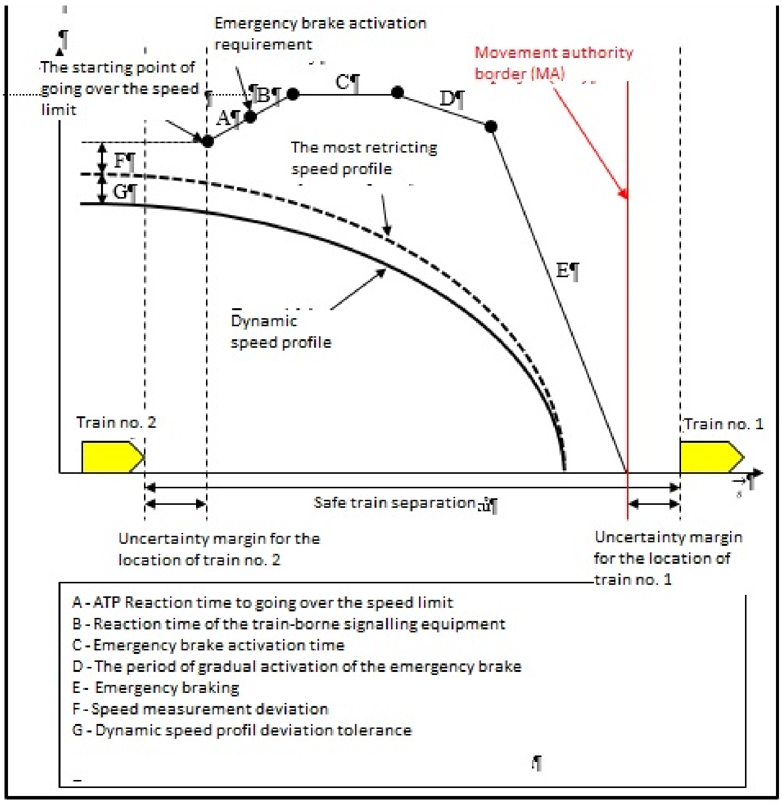

Fig. 5 Diagram showing the process of determining a safe train separation

Source: [11], edited by authors

The CBTC control system always provides accurate information on the position and speed of the train. Based on this information, the onboard part of the signalling equipment calculates the dynamic speed profile in order to ensure safe train separation. The specific part of the signalling equipment responsible for calculating this curve and for making sure that the train does not exceed the calculated speed curve is called the automatic train protection (ATP) [10]. With regard to system architecture, CBTC systems can be classified into two principal parts: the mobile part placed on the train, and the track-side part placed on the track and in the stations. The CBTC system must control the condition of the train exactly like a human train operator would, and, moreover, it controls train integrity and its exact location on the track. This activity is ensured by the automatic train protection (ATP) subsystem together with automatic train operation (ATO) subsystem and automatic train supervision (ATS) subsystem. The ATS subsystem controls all the trains in the network, controls the compliance with speed limits and timetables, as well as the functioning of information systems.

The CBTC system may also control the functions of other related systems, such as the function of track circuits, traction equipment and other infrastructure elements [10]. The CBTC system may function using two different mutual data transmission systems to transmitting date between the train and track-side part of the signalling equipment. The first option is the implementation of a radio network or inductive loops along the entire track. The other, more economic option is placing communication elements continuously monitoring train operation at isolated points along the track [11]. Mutual communication of individual trains is another feature provided by CBTC. This means that the safe separation of trains is optimised using operational information exchanged between individual trains. The underlying principle here is guiding the train set onto a non-conflicting route, similarly to GTN. Information on train delay and its current speed and the scope of movement authority is also passed onto the subsequent train which can optimize its speed accordingly. This effect is further strengthened by using the moving block. Literature available on this subject covers this principle in greater detail [12].

International CBTC system standards. Two basic international standards are defined for CBTC system. The first one is *Institute of Electrical and Electronics Engineers (IEEE) 1474.1* standard, the second one is the *IEC 62290*. IEEE

1474.1 was adopted in 2004. It regulates the functional and performance requirements for CBTC systems. In particular, the standard covers the train signalling equipment a such, id est the ATP subsystem. The ATO and ATS functionalities are defined as optional under this standard. The standard also sets out the principal safety requirements for the system. The standard does not cover only metro systems, but other rail transport systems, too.

Other IEEE standards regarding CBTC include the following: IEEE 1474.2 defining CBTC user interface, and IEEE 1474.3 and IEEE 1474.4, defining CBTC testing standards. The IEC 62290 standard was adopted in 2007. This standard sets out basic terminology, general requirements and the description of functionalities of the control and management CBTC subsystems. Speaking of CBTC, the relationship between the CBTC development and the ERTMS/ETCS also needs to be mentioned. These systems use a number of identical components and are governed by the same standards and system and safety requirements. Item on the literature list number 9 describes the CBTC function, adapted using ETCS L3 for simulation purposes. The development of ETCS components also enables their use in CBTC after partial adaptions. In the Czech Republic, the company AŽD Praha, s.r.o. is engaged in this development.

Basic components of the CBTC communication interface. Optical cables represent the basic fixed component of the communication network. These have sufficient capacity for the transmission of all necessary data. Cable design must be resistant to external influences, inter alia: fire resistance, resistance to humidity, resistance to acids and alkaloids, as well as mechanical resistance. In technical service rooms and cable exchange rooms, the cables must be sorted by their functional group. This measure is of particular importance in order to simplify the detection of failures and damage and to make maintenance easier [13].

The components of the radio network are another key component of the signalling equipment. The CBTC system implements the IEEE 802.11 a/g/p/n protocol (also used in common WiFi/WLAN networks). The greatest advantage is the fact that this is an open and widely used standard, which makes it possible to use various technical solutions for the radio network while maintaining mutual compatibility. The CBTC radio network functions with frequencies of 2.4 GHz or 5.8 GHz.

Both of these frequencies provide good characteristics and the range required for operation in metro tunnels [13]. In case the radio network is made using radio beacons positioned at specific points along the track, the system communicates with the train using vehicle aerial. The train unit exchanges messages with the track-side part continually. If signal is lost or there is another failure (such as the incomprehensibility of the message), the train unit immediately commences high-speed braking. As with all signalling equipment, the communication branches are led along the entire track dually, where only one of these maybe active at any given time. Apart from the redundancy of individual components of the signalling equipment, these components are protected from the weather influences and mechanical damage. The track-side part of the signalling equipment consists of radio beacons positioned along the track within several dozens or even hundreds of meters of each other, covering all the locations of the track. The distance of the radio beacon is mainly influenced by local conditions, such as the directional guidance of the track and the tunnel parameters. Radio beacons may be mounted on separate posts or on other suitable track-side components. Radio beacons are interlinked using a dual optical fibre network. In addition to their high capacity, their principal advantage is their resistance to electromagnetism. The jumper connectors with a robust and durable design represent another important part of the communication network. Usually, class IP 67/68 is used.

The interconnected nodes of the communication network are usually placed in technical service rooms at stations. Apart from optical cable ports, radio beacons are fitted with a connection for electrical power for supplying their aerial. The radio beacon aerial must be resistant enough to external influences, such as: vibration, fire, shock waves, electrical discharge, humidity, changes in temperature and vandalism [8]. The train-borne part of the signalling equipment has redundancy of key elements, same as the track-side part. The aerials of the train-borne part of the signalling equipment may be dual and are connected to modems passing on or receiving data to or from the ATP. The ATP, including its cables, must be resistant to any assumed external influences [13].

6. Conclusion

The area of automatic train operation (ATO) is a modern trend in the field of rail transport. For the time being, it is mainly used in the field of urban underground railways. This article illustrates the options available for Prague metro in terms of automatic operation with regard to its expansion by line D. As part of the article, the possibility of transfer of the existing operation to automatic operation by adjusting of the signalling equipment and using new vehicle was considered. However, this option seems to be complicated and inefficient.

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