



# Advanced Train Control Systems

**Editor: Bin Ning**



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# Preface

Since 1992 I have participated in all of the Comrail conferences. I think that Comrail is one of the most successful conferences in the areas of railways and other transit systems. The proceedings of the conferences reflect the new achievements and applications of computer based technologies in railways. The Conference series establishes a good platform for professional experts from all over the world to exchange their views and achievements.

Professor Carlos Brebbia, one of the conference chairmen for Comrail 2010, suggested that I review the papers on advanced train control systems published in the most recent previous proceedings and select the best papers for the publication of this special volume on Advanced Train Control Systems (ATCS). The idea was to collect the best papers in one of the areas of the conference for publication as a separate volume to help the international reader. I was happy with that suggestion and in particular with being responsible for editing this special volume for Advanced Train Control Systems for signaling engineers, designers, manufactures and operators amongst them. As editor, I hope that I have made the right choice and that readers find this special volume informative and helpful.

Advanced Train Control Systems are playing an important role in improving the efficiency and safety of train operation, acting as their “brains and nerves”. ATCS needs highly reliable and safe systems using complex computer tools. Normally, these systems consist of four parts: the central control system; the station control systems and wayside systems; the on-board control systems and the communication network including mobile communication. From the point of view of the whole life cycle, an Advanced Train Control System includes design and development, re-design for a special line application, simulation verification and test, plus safety assessment of the system and subsystems. These concepts are known to those who are familiar with typical advanced train control systems such as ETCS, CTCS for main line railways and CBTC for transit systems.

When selecting and editing the papers for this special volume, it was my intention to offer the reader a wide picture of the ATCS field based on past



papers presented at the Comprail conferences. I hope that this purpose has been achieved.

Finally, I should thank all the authors of all sixteen papers for their contribution to this special volume. Without their support, this special volume could not have been published.

The Editor

# CTCS—Chinese Train Control System

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## Abstract

There are very similar features between Chinese Railways and European Railways in terms of train operation mode and train control. ETCS (European Train Control System), supported by the European Union and the European Industrials, has been finalized as the technical standard of train control systems in Europe after more than ten years effort. There is more than 71,500 kilometers of railway operation line in China, which includes conventional lines with a speed of 120 kilometers per hour, a dedicated passenger line with a speed of 250 kilometers per hour and the speed-raising lines with a speed of 160 kilometers per hour. A high speed line from Beijing to Shanghai with a speed of more than 300 kilometers per hour will be constructed in the next few years. Due to historical and technical reasons, there exist more than six kinds of railway signal systems for Chinese Railways. At present, there is no technical standard for Chinese train control systems. In order to ensure the safety and efficiency of train operation and to meet the requirements of modern technical development in railways, the concept of CTCS (Chinese Train Control System) was put forward in 2002 as the technical standard of Chinese train control systems by the Chinese Railway Ministry. In the paper, CTCS is introduced. Based on the present situation of Chinese train control systems and their development requirements, both in technical and management aspects, the frame of CTCS is described. The comparison between ETCS and CTCS is also made.

*Keywords:* train control system, automation, Chinese railway, European railway, railway signaling.

## 1 Introduction

At present, Chinese Railways are facing the great challenge. In the next twenty years, the Chinese Railway Network will be through the special periods of the

quick development and extension. There are 71,500 kilometers of line in operation in Chinese railways. With the development of the Chinese Economy, it is estimated that at least another 20,000 kilometers railway line is needed and will be constructed. In addition, the dedicated passenger lines and a high speed railway line will be constructed in the next few years. However, there are more than six kinds of signaling systems and they are not interoperable in the Chinese Railways due to the reasons of historical and technical development. Up to now, there is no standard for railway signaling on Chinese Railways. The existing signaling systems can not be interoperable, and the direction of the new signaling systems is not clear. The situation is very similar with that in Europe before the ETCS (European Train Control System) project began in 1992. There is urgent requirement for the signaling standard of the Chinese Railway. Under the standard, the future signaling systems and the existing signaling systems can be interoperable. The concept of CTCS (Chinese Train Control System) was put forward in 2002 for the Chinese railways by the Ministry of Railway. The working program for CTCS has been started since last year. The event is the milestone in the signaling history of the Chinese railways. It will be playing a very important role in ensuring the Chinese railway network construction and perfection, train operation safety and efficiency, and guiding the future development of the Chinese railway signaling.

CTCS is based on the situation of the Chinese Railways. It is different with ETCS, but it can learn from ETCS. There are very similar features between CTCS and ETCS since there are a lot of similarities in Chinese Railways and European Railways in terms of operation modes and signaling systems.

## 2 ETCS

ETCS is a subsystem of ERTMS (the European Rail Traffic Management System). Sometimes, it is described as ERTMS/ETCS. ERTMS includes ETCS (Euro-cab), GSM-R (Euro-radio), Euro-balise, Euro-interlocking and so on.

The background of ETCS is the requirements of the European railway network development. With development of European high speed railway network, apart from the different languages, there exists the strong barrier to cross-European borders since there are at least 15 different ATP systems in operation in Europe. Moreover, the ATP systems are incompatible and produced by their own suppliers. In order to make the systems be compatible and break the monopolies, the idea of ETCS was put forward. Supported by the European Union, the European researchers and the six main European railway signaling suppliers called as UNISIG, began to work for ETCS ten years ago.

The goals of ETCS can be described as the following seven aspects. The first one is interoperability which means that trains can be interoperable across borders and able to read signaling in different countries in Europe. It also requires the “operator interoperability” and “supplier interoperability”. The second one is safety. ETCS applications, even with level 0, will improve the safety of train operation by providing ATP or cab signaling. The third one is capacity. The simulation figures indicate that the line capacity can be increased

by from 10% to 30% after ETCS application in comparison with the existing line without ETCS. ETCS can especially improve the line capacity in busy areas since the ETCS can provide smoother train operation. The fourth one is availability. Under the ETCS standardization, there is no needs for a train to be installed more kinds of on-board systems. It means less equipment, fewer interfaces and less connection. Moreover, tele-diagnosis and maintenance help dramatically increase the reliability and maintenance of the system. The fifth one is cost-effectiveness. ETCS means fewer products. In this way, its manufacturing cost and maintenance cost could be decreased dramatically. The sixth one is less on-board equipment. It means there is only one on-board system where a single and standardized Man-Machine Interface (MMI) is provided. The last one is open market. It means that monopolies for railway signaling in Europe will be broken. It is also the strong wish of the European Community from the start of the ETCS project.

The applications of ETCS are divided into several levels. They are Level 0, level STM, level 1, level 2 and level 3. Level 0 means that ETCS on-board system (ATP) is installed in locomotives running on the existing line without ETCS or national system or with ETCS system in commissioning. Level STM means that train is equipped with ETCS operating on a line equipped with a national system to which it interfaces by use of a STM. In the application of ETCS Level 1, apart from on-board system, balises or Euro-loops are added to the wayside system, and in-fill information transmission is implemented. With level 2, radio system (GSM-R) is applied between trains and wayside system, and the fixed block system is implemented. With Level 3, based on radio system, a moving block system is implemented.

Now, ETCS is now becoming a reality [4]. It is a very successful solution to railway signaling system in Europe and in the world. Most of ETCS test activities in France, Italy and the Netherlands have been concluded in 2002 or early 2003. ETCS commercial projects are rapidly coming all over Europe. During CTCS specification work, more experience concerning ETCS is expected.

### 3 CTCS

Like Europe, Chinese Railway is facing to remove the incompatible obstacle of the different signaling systems on the network. The European Railway needs ETCS, and the Chinese Railway needs CTCS. It is needed that signaling systems for high speed lines and conventional lines, passenger lines and freight lines are unified as a standardization, i.e. CTCS.

The purpose of CTCS is to define the signaling systems for Chinese Railways. CTCS will become the standard of the signaling systems in Chinese Railways. The existing signaling systems will be interoperable with the new signaling systems. In the future, all signaling systems, imported systems or home-made systems, wayside systems or onboard systems must be in line with the CTCS standardization. Apart from interoperability, the interface standard between the signaling systems, migration from existing signaling to CTCS, data

transmission format between the subsystems, safety and reliability, capacity increase, easy maintenance, lower investment and open market etc. are considered during CTCS working..

Based on the present situation of signaling system on Chinese Railway Network, CTCS will be divided into the several levels, referring to ETCS. CTCS is planned to be divided into the following five levels [1].

CTCS level 0. It consists of the existing track circuits, universal cab signaling ( the digital, microprocessors-based cab signaling that be compatible with the six kinds of track circuits on Chinese Railway Network, designed by the research team of Northern Jiaotong University ten years ago) and train operation supervision system. With level 0, wayside signals are the main signals and cab signals are the auxiliary signals. It is the most basic mode for CTCS. It is not necessary to upgrade the wayside systems for CTCS level 0. The only way to realize the level 0 is to equip with the on-board system. CTCS level 0 is only for the trains with the speed less than 120km/h.

CTCS level 1. It consists of the existing track circuits, transponders (or balises) and ATP system. It is for the train with the speed between 120km/h and 160km/h. For this level, the block signals could be removed and train operation is based on the on-board system, ATP which is called as the main signals. Transponders (balises) must be installed on the line. The requirements for track circuit in blocks and at stations are higher than that in the level 0. The control mode for ATP could be the distance to go or speed steps.

CTCS level 2. It consists of digital track circuits (or analog track circuits with multi-information), transponders (balise) and ATP system. It is used for the trains with the speed higher than 160 km/h. There is no wayside signaling in block for the level 2 any more. The control mode for ATP is the distance to go. The digital track circuit can transmit more information than analog track circuit. ATP system can get all the necessary information for train control. With this level, fixed block mode is still applied. The system indicates the special feature of Chinese railway signaling. It is also called “ a points and continuous system ”.

CTCS level 3. It consists of track circuits, transponders (balises) and ATP with GSM-R. In the level 3, the function of the track circuit is only for train occupation and train integrity checking. Track circuits no longer transmit information concerning train operation. All the data concerning train operation information is transmitted by GSM-R. GSM-R is the core of the level. At this level, the philosophy of fixed block system is still applied.

CTCS level 4. It is the highest level for CTCS. Moving block system function can be realized by the level 4. The information transmission between trains and wayside devices is made by GSM-R. GPS or transponders (balises) are used for train position. Train integrity checking is carried out by on-board system. Track circuits are only used at stations. The amount of wayside system is reduced to the minimum in order to reduce the maintenance cost of the system. Train dispatching can be made to be very flexible for the different density of train operation on the same line.

The division of CTCS is only preliminary. It could be changed a little bit during CTCS working. However, the frame, the goals and the outline of CTCS

has been made out and described. According to the above definitions, the function requirements specification (FRS) and the system requirements specification (SRS) have been started by the Chinese colleagues.

#### 4 Comparison of ETCS and CTCS

Before the comparison is made between ETCS and CTCS, the configuration of railway signaling system is defined. All the working concerning ETCS and CTCS are based on the configuration. As a matter of fact, the configuration of railway signaling system could be classified as the four parts. (1) Onboard system. (2) Wayside system. (3) Control center system. (4) Communication network including mobile communication [3]. It is also shown in the figure 1. As control center system, by the telecommunication network including mobile transmission, it has all the data for the system to calculate and control. For wayside system, it consists of sensors, actuators ( signals and point machines ) and RBC (Radio Block Center) etc. The communication network connects reliably and safely the control center with on-board system in trains, sensors and actuators installed along the line and at stations.

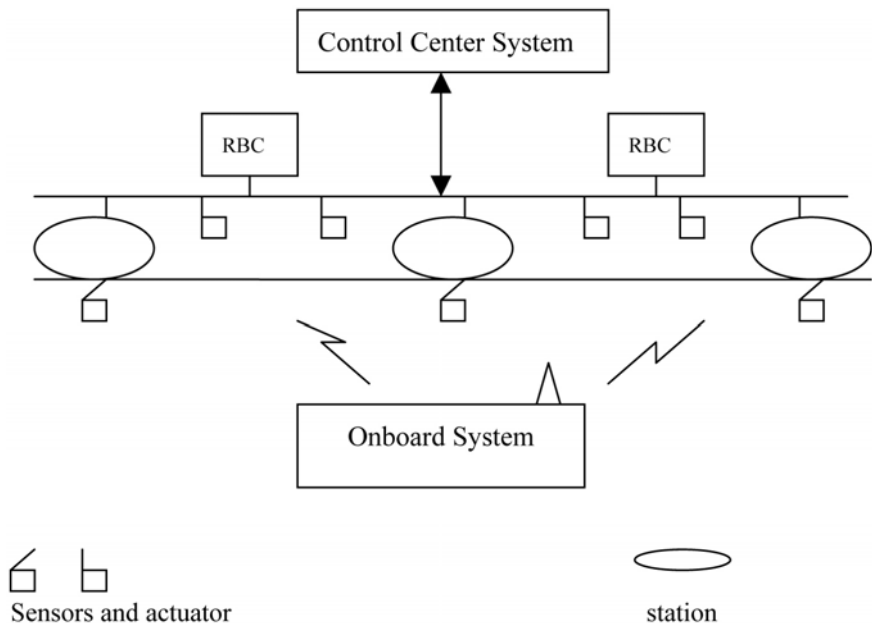


Figure 1.

The architecture of an on-board system is shown in the figure 2. It consists of on-board vital computer units, MMI, train speed measurements unit, train position unit, train integrity checking unit, radio receiver, train data recorder unit, train speed control interface etc.

The two figures give the overview of a railway signaling system as a whole. Both ETCS and CTCS are a universal, future oriented concept, based on the whole system. Their specifications ensure the interoperability of onboard device and wayside equipment in the different lines, in the existing lines and the new lines, produced by the different suppliers.

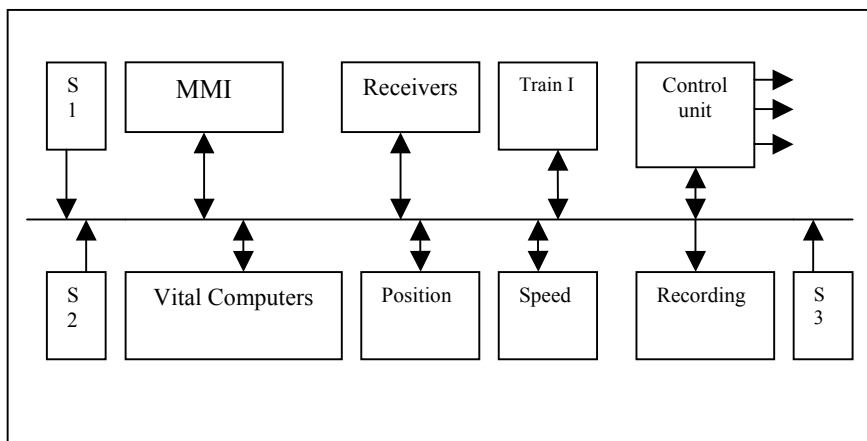


Figure 2.

Background and goals for ETCS and CTCS are very similar. They are respectively the development requirements of the European railway network and Chinese railway network. The key technical issues, such as interoperability, safety, reliability, vital computers for onboard system and control center, easy and less cost investment and maintenance, are the same in ETCS and CTCS.

It is decided by the Chinese Railway that GSM-R will be used as standard of radio system for CTCS.

Both ETCS and CTCS have put moving block systems as its highest level and the final target. This is the result of modern mobile communication development. Based on reliable and fail-safe communication, train control system (moving block system or train control system based on communication) become a close loop safety control system to ensure train operation safety and efficiency.

In CTCS, track circuits still play a very important role. On Chinese Railway Network, track circuit is mostly used and the basis of train control systems. It is not possible to construct CTCS without track circuit. This is the reality of Chinese Railway. The so called “ a point and continuous mode ” will be the special feature of CTCS. Moreover, MMI with Chinese characters is different with the MMI in ETCS. Research on MMI for onboard system have been done in Chinese railways.

In ETCS, balise is a very important device. The communication between onboard train system and wayside systems, positioning can be realized by balise. In CTCS, it is not decided what is used for position after track circuit is removed. We have our own transponder which has not been accepted as standard. Last

year, Euro-balises, produced by Siemens Signaling Company, have been applied in the dedicated passenger line from Qinhuang Dao to Shenyang.

In a word, there are a lot of common points between ETCS and CTCS. However, they are different. CTCS is a standardization of railway signaling system for Chinese Railway. Anyhow, it is true that CTCS could learn from ETCS during its construction process. It is hard and too early to say that ETCS and CTCS would come as a standard for railway signaling system in the world in the future.

## 5 Conclusion

It can be seen that CTCS is required urgently by Chinese Railway. The first step for CTCS is to finalize the FRS and the SRS according to the situation of Chinese Railway [5]. It is estimated that the project needs at least 3 or 5 years. Moreover, the government officials from the Ministry of Railway, the experts from railway industries and researchers from universities and research institutes must be involved in the projects. It is also recommended that some experts on ETCS from the European participate in CTCS project. To speed up the process of the project, the simulation center of CTCS should be built at the beginning of the project. After the finalization of the FRS and the SRS for CTCS, the center will become the test and verification center of CTCS systems and its products.

After 5 or 10 years, all the wayside signaling systems and onboard signaling systems on Chinese Railway will be in line with the standard of CTCS. It could be the domestic making products or imported products. The systems must be in series with the transport requirements of the line and interoperable.

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# Re-signalling with communications-based train control – New York City Transit’s recipe for success

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## Abstract

This paper provides a status report on New York City Transit’s (NYCT’s) Canarsie Line Re-signalling Project which is scheduled to enter revenue service in 2004. Re-signalling an operating mass transit railway represents many challenges, particularly when introducing new computer-based and communications-based train control technologies. This paper focuses on the project and design management techniques adopted by NYCT to ensure the project would be successfully completed on schedule and within budget – NYCT’s “recipe for success”. The paper specifically addresses the techniques used to: understand the needs, evaluate the alternatives, develop the implementation strategy, establish the technical requirements, select the preferred system/supplier, promote a partnering philosophy with the selected supplier, finalise/freeze the system design, and plan the cut-over.

*Keywords: mass transit, re-signalling, communications-based train control.*

## 1 Background

New York City Transit is one of the most extensive and complex subway networks in the world. The first line entered service in 1904 and the NYCT rail network now comprises 22 interconnected lines with 1,100 km of track, 468 stations and over 6,000 railcars. The system operates 24 hours a day, 7 days a week, transporting on average 4.3 million passengers a day.

As part of an ongoing modernisation program, NYCT is pioneering the integration of new computer-based and communications-based technologies to enhance customer service. For example, the initial phase of a modern Automatic

Train Supervision (ATS) system, which will provide centralised control of the rail network from a new Rail Control Centre, is scheduled to enter service in late 2004. NYCT is also modernising its existing voice communication systems and upgrading its passenger information systems, through improved Public Address and dynamic Customer Information Screens. Passenger safety and security is also being enhanced through the increased use of closed circuit television.

NYCT has also initiated a program to replace its existing fixed block, wayside signals/trip stop signal technology with state-of-the-art communications-based train control (CBTC) technology [1].

## 2 Understanding the needs

As with any advanced technology system, NYCT realised that one of the most critical elements in assuring the success of its signal modernisation program was to first establish a clear understanding of the operating needs and benefits to be realised by the new train control technology [2]. To this end, in the early 1990's, NYCT established an interdisciplinary task force made up of all of the users and other stakeholders who would be affected by the new train control system. This task force, with support from a consultant team (lead by Parsons in association with Booz Allen & Hamilton and ARINC, Inc.) experienced in the design and deployment of new technology train control systems, developed the key operating requirements and captured these requirements in a "concept of operations" document.

In developing such a top-level requirements document, NYCT also realised that it was important to balance the needs and expectations of the users with the capabilities and limitations of the available train control technologies. NYCT therefore actively involved potential train control system suppliers, and other transit agencies, in the development of the top level requirements and implementation strategies.

For NYCT, the key operating needs can be summarised as:

- Designing, implementing and operating the new train control system as a logical and practical evolution from current NYCT practices.
- Bringing the existing signal system into state-of-good-repair
- Enhancing the safety of train operations even in the event of train operator error, by providing continuous overspeed protection to enforce civil speed limits on curves and when moving over switches
- Increasing train throughput and passenger carrying capacity, particularly on the major trunk lines in the network
- Improving the reliability and availability of the train control system
- Providing for maximum operational flexibility, to specifically include support of mixed mode operations (equipped and unequipped trains), all under signal protection.
- Supporting both manual and automatic train operations with full automatic train protection (ATP).
- Reducing life-cycle costs

For NYCT, it was also recognised that any implementation strategy for a new train control system would need to accommodate the following constraints:

- The size of NYCT rail network is such that the implementation of a new train control system must be phased over multiple years and involve multiple contracts.
- The new train control system must support NYCT existing operating philosophy of interoperability between lines, i.e. trains that generally operate on one line within the network must be capable of safely operating on other lines within the network.
- The requirement for interoperability over multiple lines, together with the need to phase the introduction of the new train control system over multiple years also generates the need for interoperability between trainborne and wayside elements of the new train control system provided by different suppliers under different contracts, as well as the need to support mixed mode operations
- The new train control system must be capable of being introduced with minimum disruption to existing train operations on a network that operates 24 hours a day, 7 days a week.

### 3 Evaluating the alternatives

Having established the operating needs, the next step in NYCT's recipe for success was to establish the most appropriate train control technology to satisfy these needs.

The evolution of railway signalling for mass transit applications has involved basically four generations of train control philosophy, with each generation providing an incremental improvement in operational performance.

What can be considered the first generation of train control systems philosophy includes track circuits for train detection, with wayside signals to provide movement authority indications to train operators, and trips stops to enforce a train stop if a signal is passed at danger (intermittent ATP). With this train control philosophy, virtually all of the train control logic and equipment is located on the wayside, with trainborne equipment limited to trip stops. Train operating modes are limited to manual driving modes only and the achievable train throughput and operational flexibility is limited by the fixed-block, track circuit configuration and associated wayside signal aspects. This train control philosophy is representative of the technology currently in service at NYCT.

The second generation of train control technology is also track circuit-based, but with the wayside signals replaced by in-cab signals, providing continuous ATP through the use of speed codes transmitted to the train from the wayside. With this train control philosophy, a portion of the train control logic and equipment is transferred to the train, with equipment capable of detecting and reacting to speed codes, and displaying movement authority information (signal aspects) to the train operator. This generation of train control technology permits

automatic driving modes, but train throughput and operational flexibility is still limited by the track circuit layout and the number of available speed codes.

The next evolution in train control philosophy continued the trend to provide more precise control of train movements by increasing the amount of data transmitted to the train such that the train could now be controlled to follow a specific speed/distance profile, rather than simply responding to a limited number of individual speed codes. This generation of train control technology also supports automatic driving modes, and provides for increased train throughput. However, under this train control philosophy, the limits of a train's movement authority are still determined by track circuit occupancies.

The fourth generation of train control philosophy is generally referred to as communications-based train control (CBTC). As with the previous generation of train control technology, CBTC supports automatic driving modes and controls train movements in accordance with a defined speed/distance profile. For CBTC systems, however, movement authority limits are no longer constrained by physical track circuit boundaries but are established through train position reports that can provide for "virtual block" or "moving block" control philosophies. A geographically continuous train-to-wayside and wayside-to-train RF data communications network permits the transfer of significantly more control and status information than is possible with earlier generation systems. As such, CBTC systems offer the greatest operational flexibility and can support the maximum train throughput, constrained only by the performance of the rolling stock and the limitations of the physical track alignment.

In evaluating the ability of each alternative train control philosophy to meet NYCT's operational needs, the primary evaluation criteria included performance capabilities (e.g. safety, reliability, maintainability, availability, headways, operational flexibility, etc.), the ability to implement on an operating mass transit railway, the design and implementation risks, and life cycle costs. The evaluation itself was undertaken by NYCT's interdepartmental task force, drawing on the results of an extensive consultant study and supported by industry feedback. International peer reviews were also used to validate the evaluation findings.

The alternatives evaluation concluded that CBTC technology was the most appropriate solution to NYCT requirements, offering enhanced performance, lowest life-cycle cost and minimum operational disruption during implementation.

## 4 Developing the implementation strategy

Having selected the most appropriate train control technology, the next step in NYCT's recipe for success was to develop a practical and realistic implementation strategy. This strategy included:

- A staged implementation driven primarily by the condition survey of the various lines
- A strategy that is closely coordinated with new car procurements, to minimise the additional costs associated with retrofitting existing trains

- A strategy that in general modernises the lower capacity branch lines first, such that when the higher capacity trunk lines are re-signalled all of the rolling stock have been equipped, thereby minimising the need for support to mixed-mode operations.

NYCT also recognised the importance of an early pilot project to not only validate the operational benefits of the new technology, but also to establish NYCT procedures and working practices applicable to this technology. The Canarsie Line was selected as the NYCT pilot project.

The Canarsie Line is a two track line, 18 km in length with 24 stations and 7 interlockings. Approximately two thirds of the line is underground. Passenger trains typically operate between the two terminal stations in both peak and off-peak periods. .

## **5 Establishing the technical requirements**

Having selected the train control technology, and established an overall implementation strategy, the next step in NYCT's recipe for success was to develop the detailed technical requirements to support procurement of a train control system for the Canarsie Line pilot project. Again, NYCT involved all stakeholders when establishing the detailed performance, functional and design requirements for the new system.

The technical specifications developed by NYCT and its consultants focused on defining "what" functions the new system was required to perform, rather than specifying "how" these functions were to be implemented. The NYCT technical specifications placed particular emphasis on defining the operating modes required to handle the various system failure modes. In developing the technical specifications, NYCT also recognised that the CBTC system was not a "stand alone" system but was required to interface with conventional signalling equipment and other train management and customer information systems. Particular attention was therefore given to appropriately defining such interfaces in the technical specification.

Industry reviews were again utilised at key points during the development of the technical specifications to provide beneficial feedback regarding the identification of potential areas of project risk. Visits to other transit properties using similar systems and technology were also valuable to experience first hand the features of the new technology and to obtain feedback on lessons learned as well as operational and maintenance experience with the technology.

## **6 Selecting the preferred system/supplier**

The next element in NYCT's recipe for success was to select the preferred system, and preferred system supplier, for the Canarsie Line pilot project. The Request for Proposals (RFP) for the Canarsie project was issued in October 1997 and technical proposals were received from six proposers in February 1998. In July 1998, following NYCT's evaluation of the proposals, contracts were

awarded to three shortlisted suppliers for a technology demonstration test program. Installation of equipment on NYCT's test track was completed in December 1998 and the demonstration tests commenced early in 1999, running for approximately 6 months. The demonstrations included RF data communication tests, train location and speed measurement tests, tests of Automatic Train Protection (ATP) and failure management functions, and tests of other miscellaneous operational functions including equipment diagnostic provisions. From these tests, an evaluation of the proposers' Best and Final technical, management and cost proposals, and other relevant information, the train control system consider best suited for NYCT's requirements was selected for installation on the Canarsie Line.

In December 1999, a 5-year, \$133 million contract for re-signalling the Canarsie Line was awarded to a Joint Venture of Siemens Transportation Systems Inc. (formerly MATRA Transports International), Union Switch & Signal, Inc. and RWKS Comstock.

## **7 Promoting a partnering philosophy**

Having selected the most appropriate system and supplier, the next step in NYCT's recipe for success was to implement rigorous design management and project management processes using a fully integrated and co-located project team. The following implementation issues were considered particularly critical:

- Establishing realistic project schedules that draw on "lessons learned" from other similar projects.
- Adopting a structured system development process that includes a system definition phase early in the project to ensure there is a complete and common understanding between the agency and the supplier on the requirements to be implemented.
- Establishing clear requirements for an overall test and commissioning strategy, including use of prototypes, simulation tests and other facilities, to minimise actual field-testing requirements.
- Reaching early agreement between all stakeholders on the safety certification process.
- Utilising well-defined transition plans to develop and implement new operating and maintenance practices and procedures, and to operationally manage the cut-over to the new train control system.

To facilitate the timely flow of information between all project participants, NYCT introduced a Working Group concept to handle Contractor's Request for Information, and to expedite the review and approval of Contractor submittals. Each working group focused on resolving technical issues and problems within their particular technical areas. Working groups were established for overall systems design, trainborne equipment integration, data communication system definition, wayside equipment integration, control centre equipment integration, test and commissioning, safety certification, rules and procedures, and maintenance and training.

## 8 Finalising the system design

During the preliminary and detailed design phases of the CBTC system, NYCT and their consultants have worked closely with the Contractor to establish final system and subsystem requirements and interface specifications. This included approval of the System Functional Specifications and the Systems Design Document which froze the system functional requirements. The resulting functional requirements established the NYCT-specific adaptation requirements to the Contractor's existing service-proven system design. The CBTC system for the Canarsie Line consists of three main subsystems as shown in Figure 1:

- The Central subsystem that supervises operation over the complete line
- The Wayside subsystem, a distributed subsystem that controls individual sections of the line
- The Trainborne subsystem that determines train location, receives movement authority from the wayside, and governs train movements accordingly.

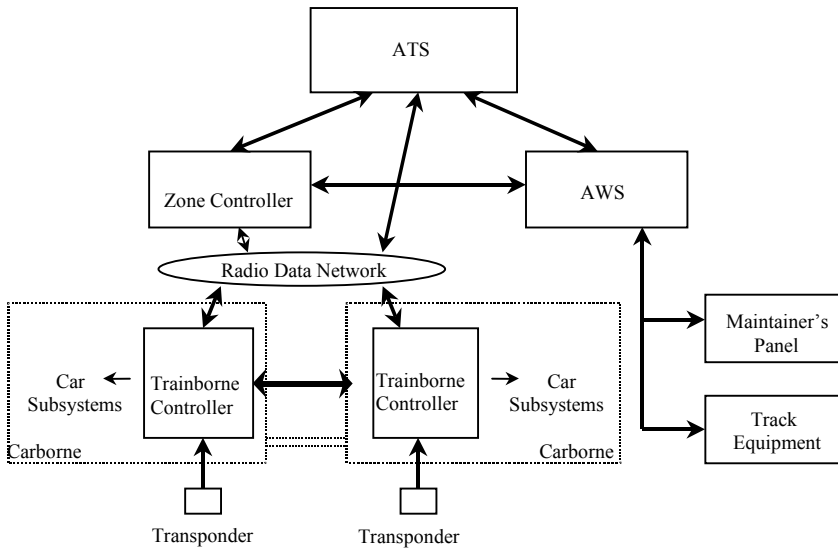


Figure 1: CBTC system architecture.

The Central Equipment is located at NYCT's Rail Control Centre (RCC) and provides the Automatic Train Supervision (ATS) functionality. These functions include all the tools, information and commands needed by dispatchers to supervise train movements, such as: line display, train tracking, trip assignments to trains, automatic routing of trains, regulation of train movements for schedule adherence and recovery from delays, and subsystem and equipment status. The



ATS subsystem can address each train to send regulation commands, such as depart from station, and to monitor train subsystem status for operational and maintenance purposes. The ATS subsystem also controls interlockings, by requesting route clearance and displaying the status of track circuits, switches, and signals, and communicates with the zone controllers to implement control actions affecting equipped trains such as blocking sections of track or setting temporary speed restrictions.

The line is broken down into multiple controlled zones including associated interlockings and radio transmission cells. Each zone is controlled by a zone controller. Zone controllers receive information from and send commands to interlockings. A zone controller also communicates with all equipped trains within its particular zone through the radio communication network. The train communicates various data to the zone controller including its location and the status of equipment on board. The zone controller in turn communicates commands and data to the train including the movement authority. The movement authority is the section of track through which the train is authorised to proceed subject to maximum speed and other limits both permanent and temporary.

Zone controllers can also detect and track unequipped trains by virtue of track circuit occupancies. The zone controller then manages a “map” of all trains (both equipped and unequipped) in its zone and is able to define movement authorities for all equipped trains.

The conventional signalling equipment, including interlockings, signals, switches, train-stops, and track circuits is collectively known as the auxiliary wayside system (AWS). For the Canarsie Line, each interlocking consists of a conventional relay-based set of equipment. The interlockings establish and maintain routes for both equipped and unequipped trains. The route requests are generated by ATS or from a local maintainer’s control panel. For CBTC equipped trains a new signal aspect (flashing green) has been created to indicate to the train operator that movement authority information is displayed onboard.

Trackside CBTC equipment consists of the track-mounted localisation transponders used to provide position fixes to equipped trains. Other trackside equipment consists of conventional signal equipment of the AWS including signals, train stops, single rail track circuits, and switch machines.

Trains are equipped with trainborne controllers that communicate with ATS, the zone controller in which the train is located, and the zone controller for the next zone into which the train is entering. Trainborne radios handle the communication between the train and the wayside. The passenger cars for the Canarsie Line are R143 cars manufactured by Kawasaki Rail Car. Trains can be configured in either 4-car or 8-car units and a complete set of trainborne CBTC equipment is provided on each 4-car unit. Provisions were designed into the cars to make them “CBTC ready” through the use of detailed mechanical, electrical, and functional interface control documents. The interfaces between CBTC and the car equipment consist of a mix of discrete wires and data networks, with train operator displays located in all driving cabs. Data communication links are also provided between 4-car units when coupled into an 8-car train.

## **9 Planning the cut-over**

### **9.1 Test and commissioning**

In developing a cut-over strategy for the new train control system, NYCT recognised that CBTC, unlike NYCT's existing wayside signalling/trip stop technology, requires extensive testing in the field with dedicated trains. The prerequisites for a field test typically include an equipped train with operational CBTC trainborne equipment, train operators and supervisors, fully operable CBTC wayside subsystem, and on an operating mass transit railway the need for alternative transport for passengers (buses or shuttle trains).

To minimise the field test time, significant effort was therefore put into planning for factory testing at various levels of integration. First the subsystems were tested on host hardware. This was followed by testing on the target hardware. The next stage was to connect the target hardware in the factory as close as possible to the configuration of the field, emulating missing components where necessary. For the Canarsie Line, the final in-factory system integration tests involved the central office (ATS) equipment, two adjacent zone controllers, and two trainborne controllers. The communication links between ATS, zone controllers and the trainborne equipment was achieved using actual RF communications. Emulation was used to represent the wayside signalling hardware, and the wayside network.

Once system testing has been completed in the factory, testing can begin in the field. Despite the extent of factory testing, however, problems also have to be anticipated and planned for during the early stages of field commissioning as the complexity of parameters affecting the real system operation is extensive. Field testing therefore typically starts slowly and involves extensive data gathering which must be analysed off-line back at the factory.

CBTC field testing on the Canarsie Line commenced in late 2003 and all cars will be equipped by early 2004 to support the introduction of CBTC revenue service during 2004.

### **9.2 Training**

The introduction of CBTC technology to an organisation of the complexity and size of New York City Transit involves a significant culture change to operations and maintenance. CBTC is introducing microprocessor equipment at every layer of operations; centralised control through ATS, wayside vital computers in equipment rooms along the right of way, radio cases and antennas alongside the track, transponder equipment laid between the rails, and vital computers and complex sensors on board the trains.

Train operators for example must be trained in the new displays, the modified wayside signal aspects, and the recovery mode procedures when CBTC equipment fails. In addition to classroom training, and the use of computer aided training tools, there is no substitute for hands on training on the line itself. This can only be done after system tests are complete and will be done in off-peak

periods on the line between revenue trains operating under conventional signals. With the new train control system, the Canarsie Line will now be centrally dispatched and the CBTC-ATS subsystem provides complex functions for the automated operation of the whole line. ATS training is therefore being provided on a stand alone simulator facility located within the Rail Control Centre.

In addition to train operators, dispatchers and maintainers, supervisory, management and engineering personnel also need to be trained in the new system and the overall training plan is therefore complex as the degree of understanding needed for each category of personnel varies considerably.

It must also be recognised that in addition to the technical and operational aspects of the system, staff must also be trained in the new rules and procedures that have been prepared to cover CBTC operations on the Canarsie Line.

## 10 Conclusions

Implementing any re-signalling project on an operating mass transit line represents significant challenges, particularly when introducing new technologies and operating practices. However, by following a logical and systematic implementation approach – an approach that is focused on risk identification and mitigation – New York City Transit is proceeding with its ambitious signal modernisation program on schedule. The first line to be equipped with CBTC – the Canarsie Line – will be entering into revenue service during 2004.

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# Fully digitalized ATC (Automatic Train Control) system of integrated functions of train-protection and interlocking

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## Abstract

An integrated type ATC (Automatic Train Control) system has been developed. An automatic train-protection function and interlocking function are executed on unified hardware of the ATC logic unit on the ground. Integration of hardware: makes the interface between conventional ground side ATC logic unit and interlocking device unnecessary; simplifies the input/output connection among the safety related facilities; and gives a space margin of a signalling cabin. Fully digitalized two-channel hardware architecture realizes a decrease in the number of electro-magnetic relays and of analog circuits being the bottleneck of reliability and availability of conventional train protection and interlocking facilities. The transmitter/receiver unit is mounted DSP (Digital Signal Processor) chips for the filter function to transfer the train-control signal and the train-detection signal via the track circuit. The wayside controller controls the field facilities such as switch-motors and signals without using the electro-magnetic relays of the conventional way. Integration and digitalization of hardware also give improvements not only in the reliability and availability but also in the quick response of the train control and route control. The developed system named SAINT (Shinkansen ATC and Interlocking system) is going to be put into service for the Shinkansen networks of East Japan Railway Company.

*Keywords: ATC, interlocking, integration, digital, SAINT, Shinkansen.*

## 1 Introduction

Tohoku/Joetsu Shinkansen was opened in 1982, and is continuing safe and stable transportation service till today. However, 20 years have passed since the

opening, the present ATC is aged and it is the time to update. Since the present ATC system is using electro-magnetic relays abundantly, its installation space is large. Moreover, electro-magnetic relay has problem of large influence of failure, because of single channel usage. Then, a new ATC system (DS-ATC) utilizing digital and software technologies had been developed. It had been put into service in December 02 in the extension section in Tohoku Shinkansen (Morioka - Hachinohe). Its architecture will be used as a base of integrated interlocking and ATC device for the existing Tohoku and Joetsu Shinkansen lines. New system is called SAINT (Shinkansen ATC and Interlocking system).

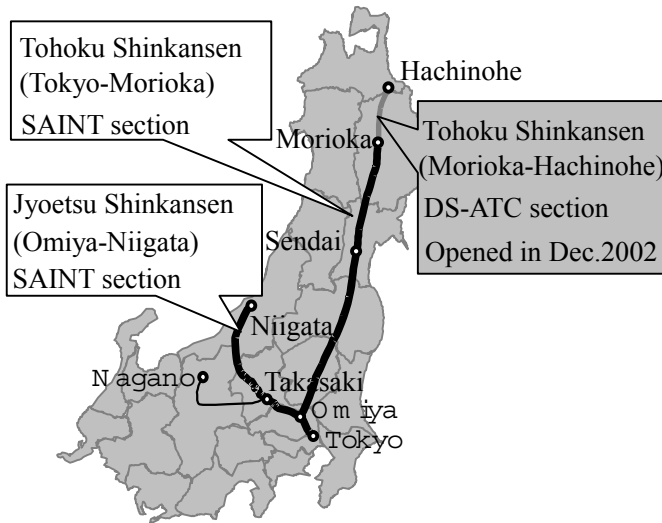


Figure 1: Renewal lines of the system.

## 2 System development plan

### 2.1 Concepts

#### 2.1.1 Requirements

The target lines of the development are the Tohoku and Jyoetsu Shinkansen lines which are of the most important high-speed lines in Japan. The network scale is of 767km length and of 26 stations. There has been a strong need from passengers to shorten the travel time with these lines. At the same time, from the standpoint as a railway operator, it is necessary to: shorten the train headway; to boost the performance of train traffic control because that the section between Tokyo and Omiya stations is of deadly high train frequency; to get higher reliability of ATC system as to keep the availability of the network; and to reduce the initial and the maintenance costs. Adding, compulsory requirement to the next ATC system for successful replacement is that the amount of hardware

of the ground equipment should be small because the setting place is, generally together with the existing ATC system in the common equipment room.

### **2.1.2 Design concepts**

The design concepts are: to apply newest digital and software technologies upon all the devices to minimize the hardware volume; and to take distributed architecture to minimize the influence of local failures. The ground equipment is composed of an ATC logic unit, transmitter/receiver units and signal device controllers for signal lights and switch motors. Adding, a substitute blocking function with a radio communication path will be set against the case of, for example, a track circuit failure between stations.

## **2.2 Examination of the contents of the development**

### **2.2.1 Rationality of functional integration**

An ATC ground system detects occupied tracks. If an ATC system stops by some failure, the location information of trains within the related area becomes unknown, and then the control for switches and signal lights becomes impossible. On the other hand, if an interlocking system stops, the state of switches and routes becomes unknown. The train operation should be stopped in both cases. Therefore, upon the dispatcher's standpoint, it is reasonable to integrate the functions of ATC and interlocking within one device. And of course, the hardware reliability of a station system will be improved surely by the abolition of the interface hardware between an ATC system and an interlocking system.

### **2.2.2 Utilization of last developments**

- (1) Conventional ATC system and interlocking system include many electro-magnetic relays. For example, every control circuits in station field for signal lights and/or switch motors are composed of specific wired-logic circuit of electro-magnetic relays. The influence of a failure in such a circuit is very undesirable for the availability of a railway line because of the single channel circuit architecture. In the meanwhile, recently, the use of electronic field signal device controllers with two-channel architecture is coming to be popular. Then it will be effective for the line availability to apply the technology to the interlocking with minimizing the amount of wired-logic circuits.
- (2) As for the shortening of the train headway, the assured braking technology had been proven upon the DS-ATC system put into the section between Morioka and Hachinohe stations. The section is the extension part of the Tohoku Shinkansen line and it had been opened in December 2002. The digital ATC logic unit on the ground detects occupied tracks and transmits a digital telegram signal to a train via the track circuit. The on-board ATC device controls the train brake according to a parabolic deceleration speed pattern which is effective to realize shorter headway and also better riding comfort. Then the authors decided to apply this technology for the development.

## **2.3 The contents of development**

### **2.3.1 Concentration of devices**

- (1) ATC function and interlocking function work on the same CPU by integrating the two systems.
- (2) Generally the transmitter unit and receiver unit for track circuit have comparably the largest hardware volume in the ground equipment of an ATC system. So that, both has been unified into one with further miniaturization design.

### **2.3.2 Common hardware**

Software processing absorbs the difference in the classification of signal lights or switch motors. So, the number of the types of hardware of device driving interface is minimized. It is expected the cost down of the equipment on the ground and also of the stock of the signal devices for emergency.

### **2.3.3 Ease of system repair**

The software modules and data should be restored according to the change of track equipment. So as to make ease the software and data restore work, the software/data of frequent repair cases are concentrated within an ATC logic unit. On the other hand, the software/data of rare repair cases are distributed upon signal device controllers.

### **2.3.4 Multiplex architecture**

Almost all the hardware devices including the function of previous electromagnetic relay logic circuits have two-channel or three-channel architecture to improve the system's reliability and rail network availability.

## **3 System configuration**

SAINT has distributed architecture which one ATC logic unit is installed in every interlocking station. The peripheral devices for ATC and interlocking are connected by LAN. The system configuration of ATC and interlocking integration type equipment is shown in Figure 2.

Main devices and functions of integrated type ground equipment are as follows.

#### **(1) Logic controller**

It is triple channel and 2 out of 3 system. ATC functions, such as train occupancy detection, train pursuit, and ATC telegram generation, and interlocking functions, such as an open check of setting route, signal lights control, and switch motors control, are processed in the same CPU.

#### **(2) TCS (Track Communication Server)**

It is triple channel and 2 out of 3 system. It has the function to distribute the ATC telegram (it functions as an occupied track detection telegram) which is

received from the logic controller, and send out to a track circuit via a transmitter/receiver unit. And it has the function to judge a train position based on the amplitude of the telegram signal received from the track circuit via a transmitter/receiver unit, and to transmit a result of the judge to the ATC logic unit.

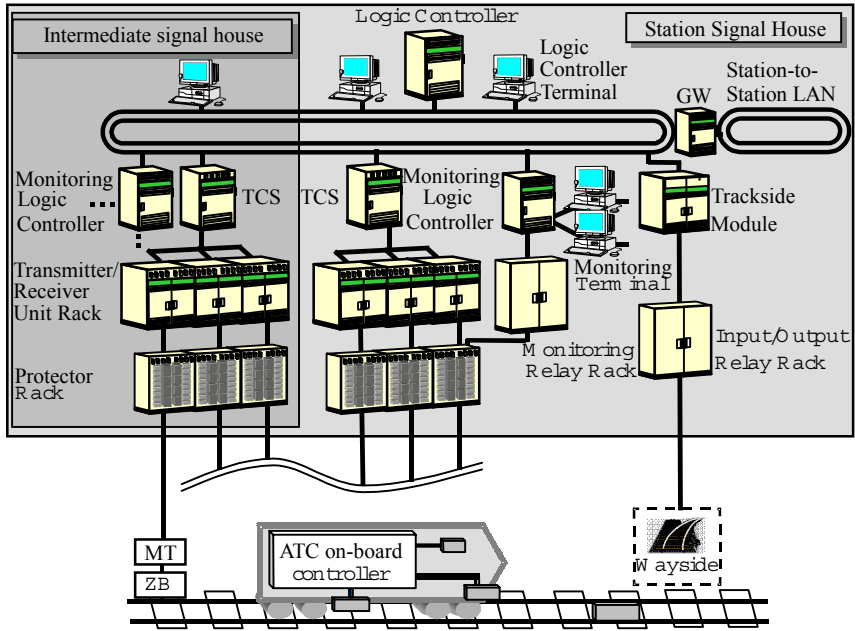


Figure 2: System configuration.

### (3) Transmitter/receiver unit

It is double channel system. It has functions: to modulate a telegram received from the TCS; to send the telegram signal into track; to demodulate the telegram signal received from the track; and to transmit the telegram to the TCS.

### (4) GW

It is double channel system, and composes the necessary data link between the GW of adjoining stations.

### (5) Trackside module

It is double channel system, and controls signal lights, switch motors and input/output interface with external equipment.

### (6) Monitoring logic controller

It collects track signal amplitude and other various state data. It outputs the alarm to require the inspection of the equipment so as to avoid a break down of devices by supervising the drift of track signal amplitude during a long period.



## 4 Transmitter/receiver unit

### 4.1 Miniaturization

The number of the track circuit transmitters and receivers is in proportion to the number of the track circuits, then, it is very effective to miniaturize these to save the installation space. As for the DS-ATC system said above, the logical and weak current analog circuits necessary for the transmitter and receiver had been successfully unified into single circuit-board type transmitter/receiver unit utilizing DSP (Digital Signal Processor) technology. Applying the technology, high power circuits such as power amplifier are integrated together with the DSP part into one unit (DSPA). As the result, the amount of the volume of track circuit transmitters and receivers is remarkably reduced.

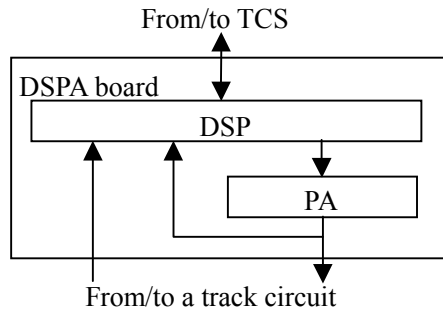


Figure 3: Configuration of DSPA.

### 4.2 Roles of DSPA

A DSPA unit has a DSP part and PA (Power Amplifier) part. The DSP part processes the logical functions and analog signals. The roles of the DSP part are the followings.

- (1) To communicate with the ATC logic unit
- (2) To modulate the digital telegram and to drive the PA
- (3) To supervise the transmitting signal to a track circuit
- (4) To demodulate the signals from a track circuit

## 5 Signal device controller

### 5.1 Signal light control board

#### 5.1.1 Hardware classification

So as to decrease the kinds of the signal light control unit, authors investigated and analyzed all the functions of signal light control used the Shinkansen system. Resultantly, the functions are classified into three such as signal lamp control,

general purpose low level current drive, and general purpose high level current drive. All types of signal light became to be driven by the three kinds of signal light control board.

5.1.2 Control software and data

For the ease of the software and data restore work with the SAINT system said above, signal light control boards are loaded comparatively the fixed control software and data those have not frequent restore cases. The ATC logic unit generates the control command and the classification information of a signal light. The roles of the signal device controller are to control ON/OFF of a lamp and to monitor the state of lamp current.

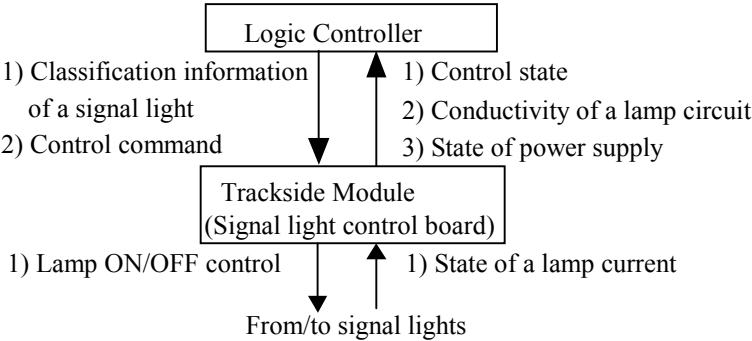


Figure 4: Signal light control.

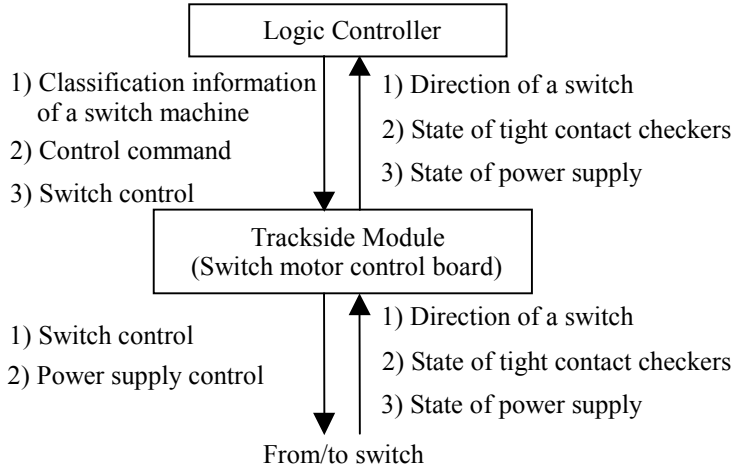


Figure 5: Switch motor control.

## 5.2 Switch motor control board

The control software and data for the switch motor control are separately installed into the ATC logic unit and the switch motor control boards in the same manner of the signal light control case. The ATC logic unit is loaded the data of every type of the switch machines, number of tight contact checker of every point. The roles of the switch motor control board are to control the switch direction and power supply for switch motor and to monitor the state of switch machine.

## 6 Conclusion

An integrated type ATC (Automatic Train Control) system has been developed. Automatic train-protection function and interlocking function are executed on one ATC logic unit on the ground. The system's reliability, availability also the traffic control response are improved. Developed system named SAINT (Shinkansen ATC and Interlocking system) is going to be put into service for the Shinkansen networks of East Japan Railway Company from 2005.

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# Automatic train control system for the Shinkansen utilizing digital train radio

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## Abstract

An ATC (Automatic Train Control) system utilizing digital train radio for the Shinkansen line has been developed. LCX (leaky coaxial cable) system along the track transfers information for train control such as: train location information from the on-board ATC system and distance-to-go information from the ground-side train protection equipment. Applying the developed technology, it is expected that track circuits in the section between switch stations become unnecessary for train separation control. The quality of digital communication by LCX and the accuracy of train location measured by trial tests were both sufficient enough to put the system into practical use. East Japan Railway Company decided to apply the technology for the substitute block system of the Tohoku and Joetsu Shinkansen lines with a future scope that the system will become the major train protection system of Shinkansen lines.

*Keywords: Automatic Train Control, digital train radio, LCX, substitute block system.*

## 1 Introduction

As the Shinkansen trains run at super-high speeds, the cab signal system that sends speed signals to the driving cab has been used. And the Automatic Train Control (ATC) system has been used to control train speeds automatically in accordance with those speed signals. The ATC system of the Tohoku Shinkansen and Joetsu Shinkansen lines has contributed to the safe and stable transportation since the commencement of these lines in 1982. But the system is aged and the replacement of the ATC system is required.

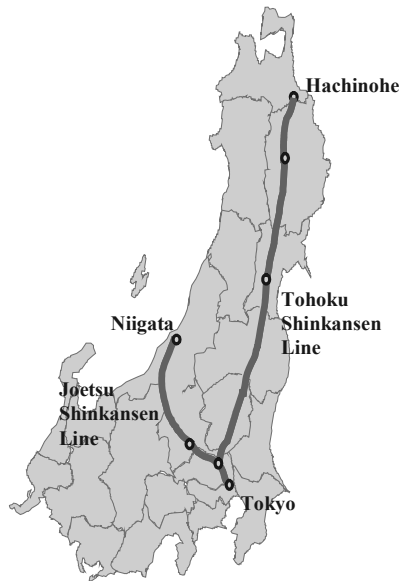


Figure 1: The Tohoku and Joetsu Shinkansen lines.

On the other hand, the mobile technology such as mobile cellular phone has dramatically advanced and it is expected to make use of the technology in railway signalling to reduce the construction cost.

Then we developed the ATC system utilizing digital train radio and decided to use the developed system as a substitute block system for the Tohoku Shinkansen and Joetsu Shinkansen lines.

## 2 ATC system utilizing digital train radio

### 2.1 Digital train radio of the Shinkansen

The digital train radio of the Tohoku Shinkansen and Joetsu Shinkansen lines using a leaky coaxial (LCX) cable laid along the track was put into service on November, 2002. There are fifteen channels for data communications and four channels are assigned to the train control with the data transmission rate of 9600 bps. If a channel is used to control a train, only four trains can be controlled by the digital train radio. So the idea of time slots is adopted. A channel is divided twenty-five time slots per a second and the number of the trains controlled by the radio is increased.

### 2.2 Outline of the developed system

First on-board ATC device of the developed system gets the output of the tachometer-generator and calculates the location of the train at every time period. Then the calculated location information is transmitted by the LCX cable to the

ground-side equipment. Next the ground-side train protection equipment identifies every train's location as the followings.

- (1) When a train is with in a section between neighbouring stations, the train location information described above is used.
- (2) When a train is within a station zone, the train detection information from track circuits is used.

After that the ground-side train protection equipment generates the distance-to-go information in accordance with the trains' location. Finally the ground equipment sends the distance-to-go information to the trains with the LCX cable independent of trains' location.

Applying the developed technology, it is expected that track circuits outside switch stations become unnecessary for train separation control. But there are several problems such as identification of switched off train to apply the developed system to normal block system. Then we used the developed system as a substitute block system.

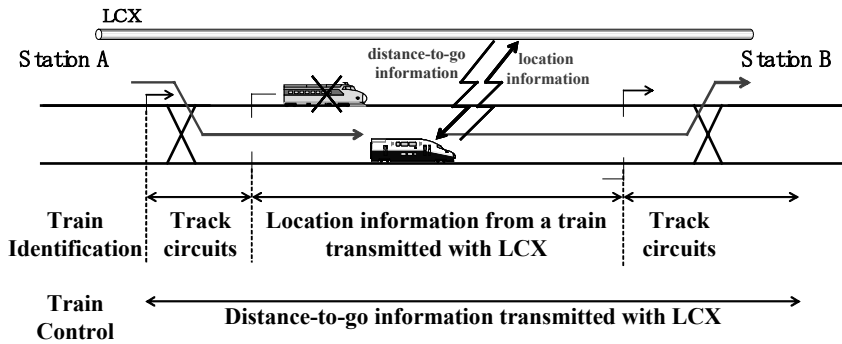


Figure 2: Outline of the developed system.

## 2.3 System configuration and functions

The system configuration is shown in fig.3. The outline of each function is described in the following.

### 2.3.1 Ground equipment

Ground equipment consists of a regular logic controller, a track communication server, a radio logic controller and a radio unit. The radio logic controller, the track communication server and the regular logic controller are connected with the optical cable at speed of 100Mbps.

**2.3.1.1 Regular logic controller** The regular logic controller is an integrated system of the functions of both regular block system and computerized interlocking device. If substitute block method is executed, it would interlock a route that connects a station and a next one and permit only one train to run on the route. The number of trains between neighbouring stations is counted by axle counters.

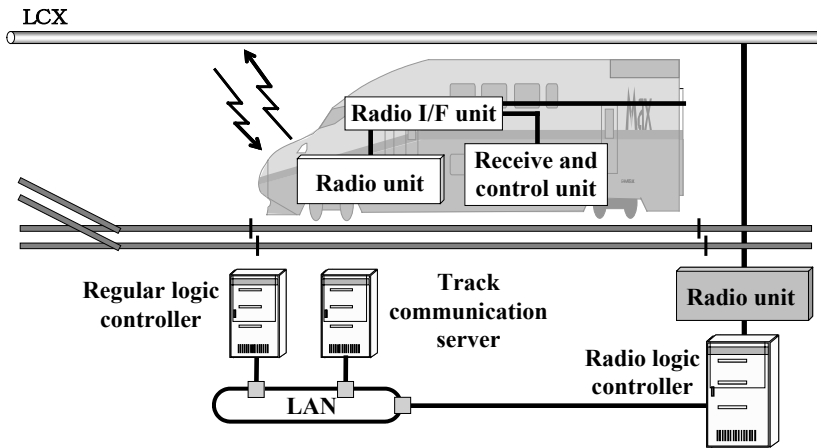


Figure 3: System configuration.

**2.3.1.2 Track Communication Server (TCS)** The TCS performs train detection based on the information received from transceiver furnished to every track. And it transmits the track occupancy state of the track within station zones to the radio logic controller.

**2.3.1.3 Radio logic controller** The radio logic controller is a main controller of the developed system. It identifies the every train's location with the information transmitted through the LCX cable from on-board device and the track occupancy state from the TCS. Then it makes the distance-to-go information in accordance with the trains' location and sends it to the trains through the LCX cable. Furthermore it administers the time slot of the train control channels of the digital train radio.

**2.3.1.4 Radio unit** The radio unit receives the train location information from the on-board device through the LCX cable and transmits the information to the radio logic controller. Furthermore it receives distance-to-go information from the radio logic controller and transmits the information to the on-board device through the LCX cable.

### 2.3.2 On-board equipment

The on-board equipment is composed of the following devices.

**2.3.2.1 On-board radio unit** The on-board radio unit receives the distance-to-go information from the ground equipment through the LCX cable and transmits the information to the radio interface unit. And it receives the train location information from the radio interface unit at every 1350 ms period and transmits the information to the ground equipment through the LCX cable.

**2.3.2.2 Radio interface unit** The radio interface unit receives the distance-to-go information from the radio unit at every 40 ms period. Because the ground equipment sends the distance-to-go information of all trains using a channel, the radio interface unit can receive the null information to itself. Then it must select the distance-to-go information for itself by the distinctive train number contained in the information. And it receives the location information from the reception and control unit and transmits it to the on-board radio unit.

**2.3.2.3 Receive and control unit** The reception and control unit has the both functions of the regular block system and the developed system. It identifies the precise train location by the output of the tachometer-generator and the transponder unit. It also controls automatically the train brake in accordance with a permissive speed profile obtained from the distance-to-go information. The profile data is stored in a database of on-board device beforehand.

**2.3.2.4 Transponder unit** The transponder unit receives precise position information from wayside coils installed approximately every three kilometres and outputs it to the receive and control unit.

Table 1: System specification.

Communication cycle time (per a train)	1350 ms
Data transmission rate (digital train radio)	9600 bps
Data length of distance-to-go information (per a train)	48 bytes
Error check (for the train control channel)	16 bits cyclic redundancy check
Number of channels (per a radio unit)	4 channels (Up and down line have each 2 channels)
Number of time slots (per a channel)	25 time slots
Number of radio logic controller (the Tohoku and Joetsu Shinkansen Lines)	26 units
Number of digital train radio units (the Tohoku and Joetsu Shinkansen Lines)	39 units
Average radio covering area (per a radio unit)	20 km

## 2.4 System specification

The system specification of the developed system shown in table 1 is described in the following.

- (1) The distance-to-information that has the data length of 48 bytes consists of a time slot information, a train number, a preset block number, a stopping block number, a train protection information and so on.
- (2) The communicating information between the ground equipment and the on-board device is subject to a 16 bits cyclic redundancy check (ITU-T CRC 16).



(3) Two time slots of twenty-five time slots per a channel are used as poling-slots that are utilized by the ground equipment to identify a train at the first time that the on-board device is turned on. The remaining twenty-three time slots are utilized as control-slots, so maximum number of trains controlled by a channel is twenty-three.

### 3 Train control using digital train radio

#### 3.1 Train identification

The flow how the ground equipment identifies the train location by the digital train radio is described in the following.

- (1) The ground equipment transmits the poling-information at every 1350 ms period to communicate the trains at the first time that the on-board device is turned on.
- (2) The on-board device that has not been assigned time slots received the poling-information and answers the train's location using poling-slots. The train's location is obtained at first by the ATC telegram for regular block system using track circuits.
- (3) The ground equipment receives the answer on the poling-slot. Then it confirms that the location contained in the answer is correct or not by the information from TCS. If the location information that the on-board device answers corresponds with the information of TCS, it sets the train number information in the answer to control-slot that isn't utilized at present.
- (4) The on-board device compares its train number and the train number of the distance-to-go information. If the result agrees, it would control the train based on the information from the ground equipment.
- (5) The ground equipment has been communicating with the on-board device until the train has run out beyond the range of the radio unit or the ground equipment has not received the answer.

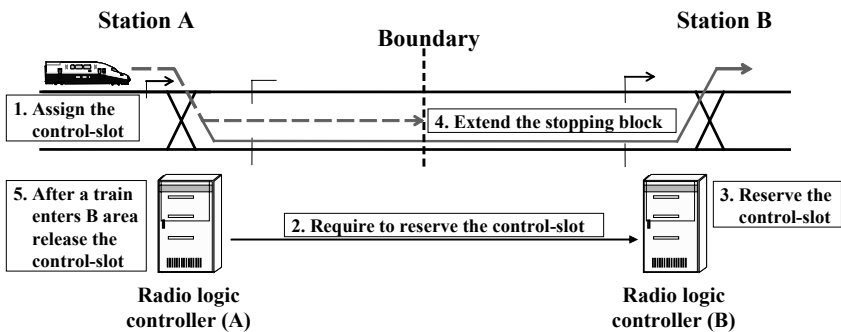


Figure 4: Administration of time slots (Handover).

### 3.2 Administration of time slots

Because the covering area of a radio unit is limited, the logic controller administers the time slot of the train to continue the control of the train even in the boundary section of radio units. This function is generally called “handover”. The handover method is described in the following on condition that the boundary of radio units corresponds with that of radio logic controllers.

- (1) When the on-board device is turned on at station A, the control-slot is assigned as described above.
- (2) If the stopping block of the train which depends on the preceding train position corresponds with the boundary section of the station A and B, the radio logic controller at the station A requires the radio logic controller at the station B through the Gate-Way to reserve the control-slot.
- (3) Then the radio logic controller at the station B reserves the control-slot that isn’t utilized at present.
- (4) After the reservation of the control-slot, the radio logic controller extends the stopping block of the train to the outside of the block occupied by the precedent train.
- (5) If the train controlled by the radio logic controller at the station A enters the area of the station B, the train comes to be controlled by the radio logic controller at the station B using the reserved control-slot. And the control-slot at the station A is released.

Actually the function of the radio logic controller in terms of handover is more complicated because the boundary of radio units doesn’t correspond with that of radio logic controllers.

## 4 Substitute block system

### 4.1 Substitute block operation

A substitute block operation is carried out in the following case.

- (1) Break down of a track circuit between switch stations.
- (2) Catenary trouble on one side.
- (3) Blocking of a route one side by troubled train.

The cases of (2) and (3) have been dominant since the commencement of the Tohoku and Joetsu Shinkansen lines. Especially the substitute block operation using opposite line has frequently carried out because the regular block system can’t carry out the operation using opposite line.

### 4.2 Utilization of the developed system for substitute block operation

In the case of conventional substitute block system, there is no automatic train separation measure between neighboring stations. Therefore the maximum train speed is restricted below 110 km/h depending on attentiveness of a driver.

On the other hand, the train speed is automatically controlled in the developed system. And the developed system has the potential to raise the maximum train

speed. The substitute block operation utilizing the developed system is carried out as follows.

- (1) The substitute operation is ordered by the central headquarters.
- (2) The commander confirms that there is no train between neighboring stations with the train count system using axle counters.
- (3) The route for the substitute block is set.
- (4) In a train, the train operation mode is switched to the substitute block operation by an operator.
- (5) The operator runs the train under control of the developed system.

Developed system makes safer substitute block operation because of the less human errors. If communication error happens, the safety on the developed system would be secured because the interlocking system permits only one train to run between neighboring stations when the substitute operation carries out.

## 5 Trial tests and results

### 5.1 Test system's composition

The test equipment of the developed system was installed at Koriyama and Fukushima stations. The test equipment was composed of the following.

- (1) Regular logic controller, which can set the substitute block route
- (2) Track communication server
- (3) Radio logic controller
- (4) Radio unit

The Radio logic controllers at both stations were connected with ISDN at the speed of 64kbps.

### 5.2 Test results

The bit error rate of digital radio communication was below  $10^{-6}$  and the quality of digital radio communication between ground equipment and trains was good enough for utilization. There was no difference between the location detected by the track circuits and detected by the position information from trains.

The test results show that there is no problem to adopt the developed system as a substitute block system.

## 6 Conclusion

An automatic train control system utilizing digital train radio for the Shinkansen has been developed. Applying the developed technology, it is expected that track circuits outside switch stations become unnecessary for train separation control. Trial tests have been carried out and the results are good enough for utilization. At the first application, we have decided to introduce the developed system as a substitute system which will realize safer substitute block operation.

In the future, the system will become major train protection system of the Shinkansen lines.

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## **CBTC (Communication Based Train Control): system and development**

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### **Abstract**

CBTC (Communication Based Train Control) systems are known as comprehensive, integrated and intelligent control systems for rail systems including mainline railways, light rails and underground lines in cities. With the development of modern data communication, computer and control techniques, CBTC represents the future direction of rail control systems. At present, CBTC has been used in light rail and underground lines in cities. It has not been implemented in mainline railways for many reasons. In future decades, rail systems will be in rapid development periods throughout the world. CBTC is known as the brain and nerve centre of rail systems, and ensures the safety and efficiency of rail systems. It is necessary for CBTC to be researched and developed further. In Europe, there is the ETCS (European Train Control System). In China, there is the CTCS (Chinese Train Control System). In Northern American and Japan, there are advanced train control systems or moving block systems. However, there is no standard for development and design of CBTC in the world at present. In this paper, efforts are made towards the establishment of a CBTC standard which directs the development and design of CBTC systems. The configuration of CBTC systems is first described. The key technical issues are addressed. The fundamental modular of CBTC and its interface requirements are defined. The transit methods from the present train control systems based on track circuits, transponders and other traditional means to CBTC systems are also put forward.

*Keywords: automation control system, rail system, computer and communication, standardization.*

## 1 Introduction

The CBTC (Communication Based Train Control) system has been known as the development direction of control systems for rail systems in the world. In particular, with quick development of modern mobile communication, its implementation and application become more and more easily. At present, CBTC has been used in city rail transportation systems, such as light rail and underground systems. It will be used in mainline railway systems in the near future. Application of CBTC has the following features. It makes the dispatching system more flexible and efficient. The safety and reliability of the system are high. It is easy for CBTC to be transited from the present system. The maintenance cost for CBTC is lower since track circuits are removed from the system. The control system of railway network will be towards intelligent, network and comprehensive system, CBTC is as brain and nerve centre of the railway system. Its development and application will be with the direction of railway operation control system [2].

At present, there are CBTC systems from the different company in the world. For example, SELTRAC from Alcatel has been used in SkyTrain in Vancouver in Canada since 1986, in JFK-Airport Light Rail System in the United States since 2003. Trainguard MT from Siemens will be used in the underground line Canarsie in New York in 2006. URBALIS from Alstom has been used in the Light rail in Singapore since 2003. In addition, there are also CBTC systems from Japan Signaling, GE and CSEE etc. In the world, there are more than 30 light rail and underground systems where CBTC systems have been or will be applied. According to the statistics, most of the CBTC systems are based on cross-loops for train-ground communication, some of the CBTC systems use radio for train-ground communication. In Europe, Radio system will be used for train control (ETCS-2 and Euro-radio) [1]. Nowadays, when the signaling systems need to be upgraded in many cities, such as London, Paris and New York, CBTC system is chose as a new system. It is predicted that CBTC systems will be applied in mainline railway in the near future [5].

However, there is no standardization for CBTC systems. The CBTC systems from the different company cannot be compatible. It is easy for a kind of CBTC system from a company to monopoly the market. It is not good for commercial competition and technical development. For users of a railway network, it is not possible to select the best systems. Meanwhile, it is not easy for the CBTC system to be upgraded with technical development. In the paper, efforts are made to put forward the technical standardization for CBTC in terms of system configuration, function requirements, data format, interface definition and development in order to facilitate development and design of CBTC systems. Meanwhile, CBTC systems from the different companies can be compatible on a railway network and railway users have more choices in the CBTC markets. Of course, for every designer of a CBTC, it is easier for the whole system or part of the system of a CBTC to be upgraded with new technology advent.

## 2 System configuration of CBTC

A CBTC system can be divided into the five parts. The first part is the Central Control System (CCS). The second part is the Station Control System (SCS). The third part is the Onboard Control System (OCS). The fourth part is the Block Control System (BCS), including Radio Block Control System (RBCS) and block sensors etc. The fifth part is the Communication Network System (CNS), including mobile communication system. The figure 1 shows the configuration of a CBTC system. The five parts constitutes the whole system of a CBTC system. However, the five parts are relatively an independent part each other as a subsystem of a CBTC. The fifth part (CNS) connects all other four parts as communication channel, including mobile communication between train and wayside systems in order to ensure real-time, reliable and safe data exchange among them. The functions of a CBTC system should be distributed to the five subsystems. The data format between every two parts should be defined.

The Central Control System (CCS) is the control center of a CBTC system. Train plans and train graphs are generated here. All the train operation is dispatched and commanded in CCS according to train graphs. The state data concerning to station control system (SCS), block control system (BCS), on-board control system (OCS) and train operation should be sent to CCS [1].

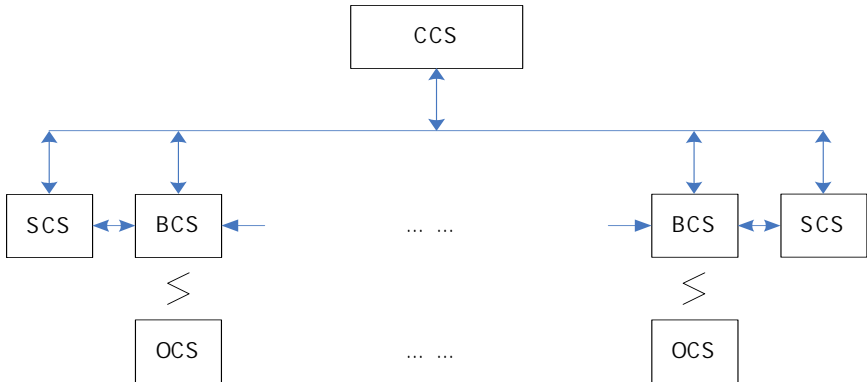


Figure 1: The configuration of CBTC systems.

Station Control System (SCS) is an interlocking system which control switches, signals and routes at stations or in areas. SCS communicate with CCS, BCS and OCS. Station interlocking system is a traditional train operation control system in terms of its functions. There is no special requirement for SCS in CBTC systems. At present, most of SCS are the computer based interlocking systems in CBTC systems [2].

Block Control System (BSC) includes radio block system and wayside sensors for CBTC system along the track. BSC communicate with CCS, SCS and OCS. Its main function is to control train safety operation in blocks. Train operation safety interval is calculated by BCS according to train safety operation



modes on moving block conditions, and then the concerning orders (permissive speed) are sent to OCS by CNS.

On-board Control System (OCS) is a train control system equipped in locomotives. Its main function is to control train speed such as acceleration, deceleration, cruising and braking. Data concerning train position and speed are sent to BCS. The permissive speed of train operation is received by OCS [3]. In a CBTC system, OCS must be safer and more intelligent compared with OCS in the traditional train control system.

SCS, BCS and OCS must be failsafe and reliable. CNS must be satisfied with the requirements of real time, safety and reliable data transmission in CBTC systems. For CCS, there is no failsafe requirement since it does not directly control train operation, but it is reliable [3].

As a comprehensive train operation control system, it is reasonable for a CBTC system to be divided into the five subsystems. Every subsystem is relatively independent and easier to be designed and implemented. The above division is very helpful for a CBTC system to be analyzed, designed and developed.

### **3 The key technical issues and interface requirements of CBTC**

In a CBTC system, the key technical issues can be described as follows. Some of the key technologies are common in every subsystem. The others are relatively independent.

The vital computer is one of the core parts in CBTC systems. In SCS, BCS and OCS, there is a vital computer. From the point of view of application, the vital computer is different with the different subsystems. However, in terms of safety and reliable requirements, the safety platform of the vital computer in the different subsystems is the same. The vital computer can be designed as a series modes which are suitable for different subsystem in a CBTC system. The configuration of a vital computer can be two out of two or two out of three where fault-tolerant design is carried out. The safety platform is transparent to the application in the different subsystems. The vital computer is relatively independent parts in CBTC system. Its configuration and software platform can be upgraded with technical development of computer and fault-tolerant design [6].

Figure 2 shows the configuration of an OCS in a CBTC system. The vital computer is the core part of OCS. Other parts (I, II, III, IV...) are connected to the vital computer by a kind of bus (Can bus or other filed bus). Other parts could be radio receiver and transmitter unit, position unit, speed measurement units, MMI unit, locomotive engine interface, recorder unit etc [3]. It is obvious that OCS is modular configuration, in addition to the vital computer.

The reliable and safety mobile communication system is the foundation of a CBTC system. The concept about moving block system (CBTC is also called as moving block system) was put forward in 1960. It is not possible for a CBTC system to be implemented until the reliable, safe mobile communication appears.

Traditional track circuits cannot satisfy with the communication requirements of train and wayside in a CBTC. In the last decades, cross-cable and leakage cable or leakage optical fiber can be used in CBTC systems. Today, GSM-R and other radio system begin to be applied in a CBTC system. The reliable and safety mobile communication system become the key technology of a CBTC system.

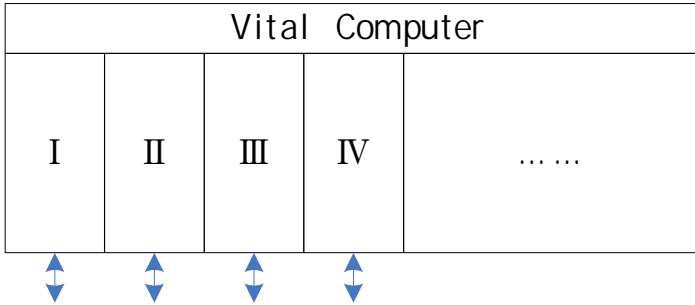


Figure 2: On-board control system configuration.

The accurate position system and the accurate speed measurement system are also the key technologies of CBTC systems. The accurate position and speed is the basic parameters of train operation control. In the position system, position calibration must be considered. In the speed measurement system, it is possible for combination of the different speed sensors (radar and axle generator) to be used to be suitable for the different speed of the train [3].

Train integrity system is very important unit in a CBTC system since track circuits are removed. An axle-counting system or on-board train integrity unit are applied for train integrity checking in a CBTC system.

The dispatching algorithms are the core software in CCS of CBTC systems. Its task is to generate train graphs according to the requirements of train plan and to automatically restore normal train operation when train operation plan is disturbed.

The train operation control model is the key to ensure train to be safe operation in CBTC systems. In a CBTC system, there is no block section. Train following interval is calculated in real time method. The figure 3 shows the principle of train following interval control in CBTC systems. In addition to the safety protection distance ( $d_f$ ), the interval of the two following trains (train 1 and train 2) is the safe braking distance of train 2 in theory.  $V_2(d)$  is the speed curve of the following train 2.  $V_{2e}(d)$  is the emergency braking curve of the train 2, and  $V_{2s}(d)$  is the service braking curve of the train 2. O is the calculated stop point of train 2. O' and O'' are respectively the actual stop point of train 2, caused by the various errors. It is obvious that train operation control mode is the algorithm of train speed and interval control. Cellular Automata model is the newest model for train operation control [4].

Simulation and test platform is necessary for CBTC system development. Since CBTC system is a complicated and comprehensive system, during the development of a CBTC system, it needs a simulation environment to support

the development. After the CBTC system is implemented and put into operation, it needs a simulation platform to test and maintain it.

## 4 Development, implementation and transit

CBTC is a comprehensive system over a rail network. The following principles should be observed in the development and design of a CBTC system.

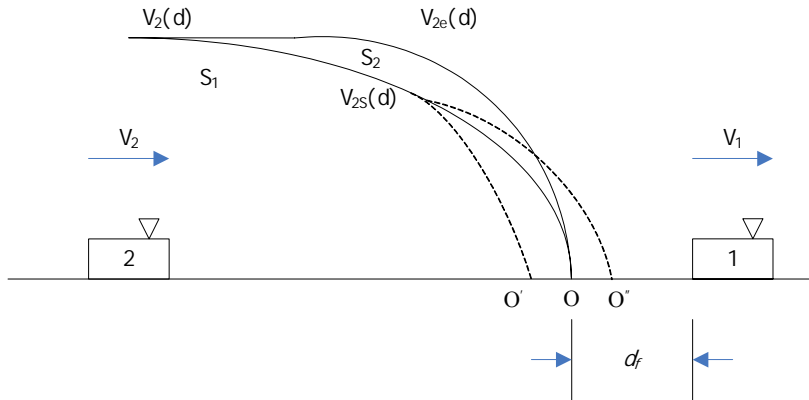


Figure 3: Train Interval control model.

According to the requirements of mainline railway network in an area or a country, light rail network or underground network in a city, the system requirements specification (SRS) and system functions specification (SFS) must be made up. These are the first set of files for a CBTC system, and they are also the basic files for a CBTC system. The files could be different for new lines and old lines upgrading in a network. This is the first step of the CBTC system development.

The second step is the key technical selection of a CBTC system. It includes the communication technology between train and wayside, the type of the vital computer and the system configuration. For communication system between train and wayside, it could be GSM-R, 2.4GHz Direct Sequence Spread Spectrum (DSSS or Frequent Hoping Spread Spectrum-FHSS) system in IEEE802.11 or cross-cable system etc. For the type of vital computer, there are more choices. It could be two out of two system or two out of three systems based on the different commercial computers. Decision on the above technologies is closely related to the cost and reliability of the CBTC systems.

Interface standardization and data format standardization should be defined before the system design. Firstly, the interfaces between CCS and SCS, CCS and BCS, SCS and BCS, OCS and BCS are defined. The data format transmitted among the subsystems and their contents are defined. Development of each subsystem will be relatively independent and the whole system will be modular. For users, the configuration of the CBTC system will be flexible.

After the above design files are finalized, system design and development can be started. Files management and design steps must be line with the requirements of software engineering and safety assessment procedures since a CBTC system is a safety and reliable system. Design and development for subsystems can be carried out in parallel. The chief designer must coordinate the progress of each subsystem [6].

In order to promote and verify the design and development, simulation test will be carried out in the whole process of the design. Normally, a general simulation environment platform is established to test each subsystem. Finally, after the whole system is finished, it should be simulated in laboratory to test its functions and safety features in varied conditions before it is installed in the field.

Before a CBTC system is put in operation, field test must be carried out since the simulation test in laboratory cannot be perfect. Particularly, the physic conditions such as temperature, humidity, vibration and electro-magnetic interference etc are different. The period of field test depends on the laboratory simulation contents and the field conditions.

According to the development of rail transportation system and CBTC systems in the world, it is only the problem of time for the traditional train control system (track circuits based train control system) to be replaced by CBTC systems. At present, CBTC systems have been applied in light rail network and underground systems in the world. Particularly, when the signaling system is upgraded and the new line is constructed, CBTC is their first choice for train control systems. For example, the New York Metro selected Siemens's CBTC and Shanghai Metro selected Alstom's CBTC systems. It is also clear that CBTC will be applied in main line railway network. In Europe, ETCS level 2 has been in trial since 2000 [5].

It is true that transit from traditional train control system to CBTC systems is a long process. It is not possible for the transit to be completed in the short time since the cost and other reasons. However, from the above CBTC system analysis, it can be seen that the transit from the traditional system to CBTC system is very easy. This is one of the biggest advantages of CBTC systems since that can overlap on the traditional systems. Under the certain conditions, the two systems can coexist without interference. Before the CBTC is adjusted into normal operation, the old system can still be used. The traditional system can be removed only after the CBTC is in normal operation.

Since the CBTC system is modular system, the part of the traditional system can remain in the CBTC system. For example, as a relatively independent subsystem, the interlocking system can still be used in the CBTC system as long as the interface is upgraded. Therefore, when signaling system needs to be upgraded, CBTC can be implemented step by step.

## 5 Conclusion

It is very clear that CBTC system will replace the traditional train control system in railway network in the world. Its configuration, interfaces and data format

should be standardized. Its key technical issues are in common. As long as the standardizations can be observed, the CBTC systems manufactured by the different companies can be compatible on railway network. Moreover, CBTC system can be easily upgraded with development of new technologies in the key technical areas. Meanwhile, it is also easier for the traditional train control system to be transited into CBTC systems.

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# Re-signaling the Paris Line 1: from driver-based to driverless operation

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## Abstract

In November 2005, RATP – Paris Urban Transport Operator – awarded Siemens a contract to upgrade the oldest line of the Paris metro to driverless operation (with no driver onboard). This paper discusses RATP's motivations and focuses on the technical challenges for upgrading the ATC from driver-based to driverless operation. This paper also presents the Communications-Based Train Control solution engineered by Siemens.

*Keywords:* communications-based train control, re-signaling, driverless Automatic Train Control.

## 1 Introduction

Since the beginning of the 2000s, RATP, Paris Urban Transport Operator, has undertaken a vast re-signaling program to modernize the automatic train control (ATC) systems installed on its metro network. The overall program aims to increase safety and transport capacity, and improve passenger comfort.

The OURAGAN re-signaling program, focusing on driver-based train operation (Paris lines 3, 5, 9, 10 and 12) to which Siemens Transportation Systems already contributes is part of an overall modernization scheme. In addition to improving safety, capacity and passenger comfort, it aims to achieve high level of parts interchangeability in the communications-based train control system to insure its easy maintainability.

In conjunction with OURAGAN program, feasibility studies have been conducted by RATP to upgrade the existing lines with strong transport demand to driverless lines, following the example of line 14 which is in revenue service since 1998 and driverless from day one.

The automation of line 1 is achieving two goals: the upgrading the PA BF (speed code type of automatic train control solution engineered by Siemens in the early 1970s) to Communications Based Train Control (CBTC), and secondly conversion to full driverless train operation (with no driver onboard), the success on the line 14 is now widely recognized.

The paper explains the motivations of RATP and focuses on the technical challenges for upgrading an existing driver attended line to a driverless one. This paper also presents the Communications-Based Train Control solution engineered by Siemens.

## **2 The stakes of upgrading Line 1 to driverless train operation**

### **2.1 The oldest line but also the most loaded**

Opened to the public in 1900, Line 1 extends across Paris from the east to the west, a distance of over 17 km. It is the oldest metro line, and also the most prestigious metro line because its 25 stations serve most of the places of interest in the French capital, as well as numerous business districts and shopping centers.

The annual passenger traffic on Line 1 is, at 207 million passengers, the highest in the whole metro network, making it the most heavily used line of the Paris metro. One of the reasons for the high ridership lies in the line's strategic layout, serving 16 of the most crowded stations, as well as 5 out of 15 major multimodal nodes of the network.

A fleet of 52 MP89 trains operate daily, with a headway of 105 seconds. 23,500 passengers are transported per hour and per direction. Thanks to a commercial speed of 27 km/h, the estimated travel time from Château de Vincennes (in the east) and la Défense (in the west) is only 35 minutes.

The characteristics of line 1 mentioned above lead to a high request for adaptability of the transport offer, which is hardly reachable with a driver operated line.

Another factor in support of the choice of fully automating line 1 is the necessity of renewing the current equipment before 2010. This particularly concerns signaling, OCC, ATC and interlocking equipment which are 4 major parts of the automation system. Indeed, the current signaling equipment needed to operate the line consists of:

- The Operation Control Center, which was installed in Boulevard Bourdon in Paris, in 1967 and upgraded in 1981.
- The wayside signaling used for safe train separation, which was installed in 1956.
- The PA BF (Pilotage Automatique Basse Fréquence), the speed code solution engineered by Siemens, used for controlling train movement.

The changeover to driverless train operation will increase transport capacity thanks to a time headway reduction from 105 to 85 seconds. The speed of driver-attended trains is currently limited to 70 km/h. With driverless trains, the

maximum speed rises to 80 km/h, enabling the commercial speed to be increased.

The increasing proportion of delays due to passengers also contributes to the choice of line 1 automation. 72% of the delays are due to passengers and among them 69% can be controlled by using platform screen doors (e.g. serious accidents, alarm signal, passenger on tracks, objects on tracks).

Moreover, from an economical point of view, line 1 automation will reduce the operating costs between 10 and 15%, without taking into account the accidents that are avoided doing so.

Finally, the positive feedback of satisfaction from both passengers and operators on line 14 and the above-mentioned elements convinced RATP that line 1 automation is the best solution.

The line 1 automation program consists of different kinds of projects. Most of them obviously deal with technical issues such as the automatic train control system, which is the main subject of this paper, and also the platform screen doors, the rolling stock, the audio-visual equipment. But there is also an organizational project to upgrade the line operation and jobs. As a consequence, this ambitious program, whose objectives and constraints are shared by many transport operators and authorities around the world, requires a complex financial, social and technical process of design and management under the responsibility of RATP. The main milestones of this program are:

- the start of the platform screen doors installation in January 2008
- the commissioning of the new Operational Control Centre in February 2009
- the first operating driverless train in October 2009
- a fully automated line in 2010

## **2.2 The CBTC Line 1 upgrade contract**

On November 7, 2005, RATP and Siemens Transportation Systems France signed a 30.8 million euro contract for upgrading Line 1 from driver-attended to driverless train operation, thus consolidating Siemens' leadership in the design of automatic train control (ATC) solutions for the RATP. This new award follows a number of ATC solutions designed for RATP by Siemens:

- Automatic Train Control for driver-attended lines: PA 135 and PA BF installed on 12 of 13 metro lines.
- Automatic Train Control (SACEM) for RER A and B regional Express lines.
- Driverless Communications-Based Train Control for Line 14 and its extensions to Saint Lazare railway station (in revenue service since December 2003) and Olympiades (in revenue service in 2007),
- Communications-Based Train Control for driver-attended lines as part of the OURAGAN re-signaling program: lines 3 and 5, and subsequently lines 9, 10 and 12.



The upgrading Line 1 to a driverless line presents real technical challenges. The challenges are unique because the switchover from the current operation (using a fleet of trains with drivers under the control of a speed code solution) to driverless operations (using a free-propagation CBTC solution) will have to be carried out without any disruption of passenger service.

The contract comprises the:

- Design and supply of equipment necessary for driverless train operation: wayside equipment and onboard equipment installed on 49 cars.
- Supply of the Data Communication System based on free propagation radio, comprising the wayside backbone network and equipment for wayside-to-train communication.
- The Operation Control Center (OCC), which enables RATP to supervise and manage operations on the line.

The cut-over strategy that enables the switchover from driver-attended train operation to driverless operation consists of three key milestones:

1. Refurbishment of the existing OCC to meet specific requirements of future driverless train operation. The new OCC is then put in service to supervise and manage current driver-attended trains operation.
2. Operation of the first driverless train.
3. Mixed-mode operation: both manual operated and driverless trains run on the line during a interim period. Progressive replacement of driver-operated trains by driverless ones until the entire Line 1 fleet is running in driverless mode.

To achieve these milestones a number of technical requirements must be satisfied:

- The system will have to support mixed-mode operation: During a given time period, driver-operated and driverless trains will share the line during daily operation.
- The installation and testing of the system will have to be performed as transparently as possible with respect to daily passenger service. As a consequence, the only possible interruptions of passenger service have to match the normal daily service interruptions, namely at night during an extremely short three hour time window.

### **3 The CBTC solution designed for Paris Line 1**

#### **3.1 Key assets**

The technical solution designed for Line 1 allows for:

- Simultaneous and safe operation of driver-attended and driverless trains thanks to the tracking of CBTC-equipped and unequipped trains.

- Unequipped trains, operated by drivers, are tracked using the existing track circuits. Movement authorities are delivered to drivers via the existing wayside signaling equipment.
- Driverless trains are tracked based on the location report issued by onboard equipment and delivered to wayside equipment. Movement authorities are then communicated to the trains by wayside equipment based on an exchange of messages. This is the fundamental principle of Communication-Based Train Control.
- Minimal installation work thanks to a significant reduction of wayside equipment as the result of:
  - The use of the free-propagation radio solution engineered by Siemens, adaptable to free ISM band frequencies as well as to narrow proprietary bands. The wayside equipment is installed in stations.
  - The decentralized system architecture, with equipment installed in technical rooms located in stations, thus reducing the cabling along the line.

To reduce the number of tests performed during daily operation and to maximize the time available for testing at night, Siemens devised a system qualification strategy, based on:

- The design of a simulation platform allowing the entire system to be tested in the factory.
- Tests performed during daily operation in so-called “shadow mode”: this permits the observation and analysis of the behavior of the system installed in its real-life environment over a long-time period without impact on passenger service.
- The implementation of sophisticated migration processes, making it possible to switch from the current mode to driverless operation and back again within the time slots available at night dedicated to testing.

### 3.2 Focus on train tracking

The simultaneous, safe operation of driver-attended and driverless trains relies on tracking system based on virtual blocks combined with the moving block principle. This stems from the technical evolution of tracking systems currently in use on the Meteor Line, on the Canarsie Line, on Barcelona line 9 and on OURAGAN.

For the tracking of unequipped trains, the existing track circuits are used. The track is physically divided into “blocks”, which only contain one train at a given time. Entry to each block is protected by a signal light (red/green) that informs the driver whether or not the block is already occupied by a train.

The tracking of CBTC equipped trains does not depend on track circuits. Instead, the track is split into “virtual blocks”, which overlay the existing physical blocks. Each train calculates its own location on the line and transmits it to the wayside CBTC equipment.

The wayside CBTC equipment continuously updates the status (occupied or free) of each virtual block based on:

- The location reported by the onboard CBTC equipment and delivered to the CBTC wayside equipment, using free propagation radio.
- The occupancy status of track circuits.

The wayside CBTC equipment then computes for each train a target point, i.e. a danger point, not to be passed in order to prevent a hazardous situation from occurring. The target corresponds to the first danger point located downstream of a train. It can be a block (a track circuit or a virtual block) occupied by a train, a red signal or the end of a territory under CBTC control.

Using free-propagation, the wayside CBTC equipment delivers the target point to each CBTC equipped train. In the event that the target point corresponds to an occupied virtual block, the target point is set to the last reported position of the train ahead. This is the moving block principle. If the target point corresponds to a track circuit occupied by an unequipped train, the target point is set to the entry to the track circuit.

Equipped trains then compute the ATP (Automatic Train Protection) speed curve (which guarantees that the train will come to a stop before the next danger point) and the ATO (Automatic Train Operation) curve.

In the case of unequipped trains, information about the next danger point is delivered to drivers using the existing wayside signaling. A green light means that it is safe to enter the block as it is not occupied by any train. A red light means that it is forbidden to enter the block as it is occupied by a train.

### 3.3 Focus on the free propagation radio solution

Now in operation on the Canarsie Line in New York City, the free propagation radio product offers outstanding performance in the face of the stringent requirements CBTC in underground railway applications. Indeed, the challenge taken up by Siemens was to adapt the various technical innovations to the specific needs of underground transit applications by favoring system availability in these difficult environments for the propagation of radio waves.

For driverless train operation, availability of the data communication system is essential to enable the CBTC system to safely replace the driver. The radio solution fulfils the following requirements:

- Robustness to guarantee the very high level of availability required, despite the diversity of the environments: alternating between tunnels and open air sections, interference and masking. The signal modulation is based on Direct Spread Spectrum Sequence (DSSS). The demodulation takes into account the energy carried by the various multi-paths to “rebuild” the signal transmitted.
- High performance with respect to message updating and handover constraints. Wayside-to-train messages can be addressed to all the trains or to a set of trains on the line. Messages are refreshed frequently

(approximately every 0.5 s) to ensure maximum performance of the CBTC system.

- Robust intrusion protection to ensure security. As the identity of the communication is determined, there is no need for standardization at the air gap. No interface at the air gap is a guarantee of protection against intentional or accidental intrusion.
- Proven coexistence with ISM band users: no perturbation from WIFI users, no perturbation to WIFI users.

The robustness of the free-propagation radio system was achieved through the thoroughness with which the radio link budget was drawn up in various environments as well as: TDMA and micro-synchronization, diversity, and geographical organization redundancy. As a consequence, it guarantees unrivalled operational availability for a reduced amount of wayside radio equipment. A total of 55 radio equipment installed on 17 km of the Canarsie Line.

For Line 1, this feature is of key importance as it contributes to the simplification and minimization of the installation work since the free-propagation radio system does not require any continuous medium on the guideway and wayside radio equipment is strategically located in stations.

### 3.4 Simulation platform

In order to minimize the number of tests performed on the line during revenue service hours, and so reduce the risk of disruption to passenger service, considerable efforts are dedicated to the design of powerful simulation tools.

These tools allow extensive in-factory testing including the functioning test of an item (which can be software, a piece of equipment, a subsystem or the complete system) and evaluation of its performance in an environment closely resembling that on the line. The tools are based on key modules comprising the OCC, the wayside signaling, wayside CBTC equipment, CBTC equipped trains, platform screen doors and free-propagation radio system and their corresponding interfaces. Behavior of the items will be assessed both in nominal and degraded conditions based on predefined scenarios. It is possible to interact with the simulation at any time in order to generate events or create failures, thereby increasing the relevance of the test performed.

### 3.5 The migration strategy

The major challenge when re-signaling lines in revenue service lies in the validation of the system – in the specific case of Line 1, the OCC and the CBTC onboard equipment – without impairing the quality of service offered to passengers during daily operation and compromising safety. A fundamental feature of this solution is therefore the ability to be operated in “shadow mode”, whereby the system receives and sends all necessary information as if under CBTC control, but without any actual outputs being activated.

A second challenge which makes this project unique is the coexistence of:

- Totally different automatic train control technologies – speed code and CBTC,
- Different modes of train operation – manually operated trains and driverless trains.

The migration strategy is organized into three main time periods corresponding to the three key milestones scheduled by RATP.

- *Period 1* is concerned with all the installation and testing work requested for operating the line with the new OCC. The main technical difficulty lies in testing and commissioning all the functions available in the “new” OCC, while still ensuring the safety of daily train operations under the control of the “old” OCC. This work is carried out during both daily operations and night-time hours. It involves having the two OCC working in parallel: until the first milestone is reached, the “old” one remains active and the “new” one operates in shadow mode; at the end of this period, the “new” OCC becomes active, but the “old” one remains available for operation if necessary.
- *Period 2* focuses on the testing and commissioning of the driverless CBTC solution to enable the first driverless train to operate on the line together with manually operated trains. It should be noted that all the wayside CBTC equipment is installed during the Period 1. The testing covers ATP and ATO functions. The main difficulty is how to perform all the necessary tests and customizations without interfering with work already done. For this, the system will first be extensively tested on the test track in Valenciennes, France. In addition, a CBTC system installed on a MP 89 train will be tested in shadow mode on Line 1.
- *Period 3* is concerned with the progressive introduction into revenue service of the new MP05 rolling stock equipped with the driverless CBTC. Manually operated trains are progressively removed from service. The final functionality of the system is tested, including automatic train regulation and management of the depot.

## 4 Conclusion

The upgrading of Line 1 of the Paris metro from a driver-based to a driverless operation (with no driver onboard) is undoubtedly one of the most important projects RATP is going to realize in the next five years.

After the great success achieved with Meteor Line 14, which demonstrated the undeniable advantages of driverless operation, this project opens up the way to re-signaling and upgrading conventional lines to driverless operation.

Two major stakes are associated with the line 1 project. The first one addresses the unquestionable improvement of the quality of service, resulting from the flexibility of driverless operation. The second one is related to complex political and social issues associated with it.

Switching over from a conventional line operation to a driverless mode of operation is not a simple matter. It includes major technical challenges, i.e. to install, test and commission the complete system in total transparency to daily operation, so as not to inconvenience passengers or reduce safety in any way.

Since its first implementation on Line 14, the solution proposed by Siemens has benefited from the latest technical innovations implemented on the Canarsie Line of New York City Transit, Line 9 of Barcelona metro and lines associated with the OURAGAN program. It not only makes the most of its key features such as the tracking of both equipped and unequipped trains, the free-propagation radio, the system's ability to operate the system in "shadow mode", but also integrates state-of-the art simulation tools allowing the testing in real-life scenarios without disrupting operation to successfully take up the technical challenges.

As for RATP, the success of Line 1 Automation relies on the skills and the technical control of the selected suppliers as well as on the experience and the expertise of the RATP in the operation control, the project management and the system risks management.

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# Application of communication based Moving Block systems on existing metro lines

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## Abstract

The unique features of Communication Based Train Control (CBTC) systems with Moving Block (MB) capability makes them uniquely suited for application 'on top' of existing Mass Transit or Metro systems, permitting a capacity increase in these systems. This paper defines and describes the features of modern CBTC Moving Block systems such as the *Bombardier\* CITYFLO\* 450* or *CITYFLO 650* solutions that make them suited for 'overlay' application 'on top' of the existing systems and gives an example of such an application in a main European Metro. Note: \*Trademark (s) of Bombardier Inc. or its subsidiaries.

*Keywords:* CBTC, Moving Block, CITYFLO, TRS, Movement Authority, norming point, headway.

## 1 Introduction

The use of radio as a method of communication between the train and wayside in Mass Transit systems, instead of the traditional track circuits/axle counters and loops is gaining popularity. The radio based CBTC systems are uniquely suited for application 'on top' of existing Mass Transit or Metro systems for increased traffic capacity as CBTC systems normally do not interfere with the existing systems. This allows an installation of the CBTC system in a line in operation whilst maintaining full safety and capacity during the process.

The fact that CBTC systems also allow Moving Block operation adds to the possible increased traffic capacity that can be achieved with such systems.



## 2 Definitions

### 2.1 Communication Based Train Control (CBTC)

Although the term Communication Based Train Control in theory allows for any ‘contact-less’ communication between train and wayside, in this paper the term is used to designate the more modern type of CBTC system using radio as the communication medium.

### 2.2 Moving Block (MB)

The traditional Mass Transit systems using track circuits or axle counters as a method for detecting the presence of the train are ‘fixed block’; the block being defined as the fixed length of the track circuits and axle counters. In CBTC systems radio is used as the communication medium, enabling the position of the train to be sent by the train itself and in turn making it possible to have a ‘moving block’ operation (or more accurately a ‘moving and variable block’ operation) as there is no equipment with fixed lengths in the system.

A moving block system allows the trains to run closer to each other compared to a conventional fixed block system, thus reducing the possible headway.

However, CBTC systems may also operate within a ‘fixed block’ mode, if so desired, thus permitting increased compatibility with traditional systems, while compromising on the headway.

### 2.3 Movement Authority (MA)

A Movement Authority is defined as the authority for a train to safely proceed up to a certain point where it has to stop. In fixed block systems, the Movement Authority consists of a locked train route starting at a certain signal with a proceed aspect and ending at another signal with a stop aspect, passing through one or more track sections.

In a CBTC *fixed block* system the Movement Authority is set from the predetermined block point where the train is to a predetermined point on the track, normally the end of a track circuit or similar.

In a CBTC *moving block* system the Movement Authority is set from the exact point where the train is to a ‘conflict point’ in the track ahead of the train.

In a CBTC system with constant update of information about the train’s position and constant renewal of the Movement Authority the train will be allowed to proceed without braking as long as there is no conflict point within braking distance ahead of it.

### 2.4 Conflict Points (CP)

A Movement Authority for a train always ends at a ‘conflict point’ ahead of the train. A ‘conflict point’ is defined as:

**A location along the track beyond which a train *NOT* permitted.**

A CBTC system utilizes these conflict points to properly and safely manage the movement of trains throughout any metro line. A conflict point can either be *static*, meaning that its location in the track is fixed or *dynamic*, which means that its location is a moving train. An example of a static conflict point is a buffer stop at the end of the line and an example of a dynamic conflict point is the end of the train in front.

Furthermore, a conflict point can have two states - *mutable* or *immutable*. A mutable conflict point can be either *active*, meaning it is a conflict point, or *inactive*, meaning it is not a conflict point. Immutable conflict points are always conflict points.

Examples of typical conflict points are:

Table 1: Typical conflict points.

Conflict Point	Type of Location	State	Active/Inactive
Rear of Train in Front	Dynamic	Immutable	always active
Buffer stop	Static	Immutable	always active
Point	Static	Mutable	active / inactive

3 Elements of a typical modern CBTC system

Broadly speaking, a modern CBTC system can be said to consist of four parts:

- the **Control Centre System** which controls the operation
- the **Wayside System** which receives train positions and issues Movement Authorities to assure the safe running of the trains
- the **Vehicle System** that generates the train position and receives the Movement Authorities and assures the compliance of the Movement Authorities and
- the **Communication System** which allows the transfer of messages to and from the train.

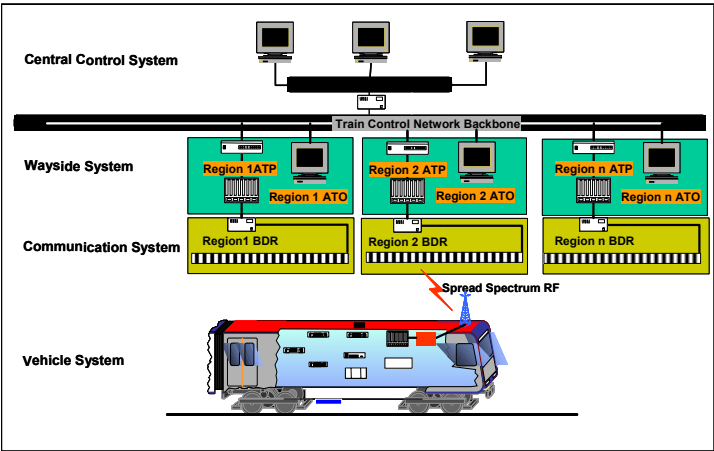


Figure 1: Block Diagram of a modern CBTC system.

### 3.1 The Control Centre System

The Control Centre System normally consists of ‘off the self’ servers and operator’s work stations that run the CBTC application. The Control Centre System allows operators to direct trains from one location to another, turn them around at the end stations, or in the middle of the line, and permits trains to leave and enter the depot(s).

All modern CBTC Control Centres also have programs for automatic driving of the trains without operator intervention, allowing either regulation by time table or by headway.

Furthermore a modern Central Control System also has control of auxiliary functions like Passenger Information Systems (PID), Telephone Systems and CCTV systems. In many cases the Central Control System also contains the SCADA systems for control of auxiliary systems such as traction, escalators and air conditioning.

The Central Control System is always duplicated in modern systems in order to achieve the availability needed.

### 3.2 The Wayside System

For Mass Transit lines of normal lengths, the wayside equipment is distributed along the line and divided into parts, often called *Regions*. Each region is responsible for safe movement of trains within its boundary of control and safe handover of the trains to adjacent regions.

The size of each region depends on the length of the line controlled by it and the maximum number of trains that need to be handled within the region.

The regions contain the ATP and ATO parts of the CBTC system responsible for issuing Movement Authorities and communicating train positions to the Central Control System.

The Wayside System components are operationally redundant for the highest availability.

### 3.3 The Vehicle System

#### 3.3.1 ATP and ATO System

The Vehicle System mounted onboard the train contains the equipment needed to acquire all the information from the train and the track, to process it and to transmit the train position to the Wayside System. It also contains the equipment that receives the Movement Authorities from the Wayside equipment and displays this information to the driver and controls the driving of the train through the ATP and ATO.

The Vehicle System is designed in such a way that the systems installed in each end of the train can be used as replacement for each other thus creating a duplication of equipment, in order to achieve the highest availability.

#### 3.3.2 Train Position System

Since the train in a CBTC system is transmitting its position to the Wayside System, the train must know where it is in the network. This is achieved using

the regions and then subdividing the regions into segments. Within the segments, the train is using its onboard tachogenerator and/or other sensors to measure the distance from the start of the segment (offset). The figure below shows how regions, segments and offsets are used to define the train's position.

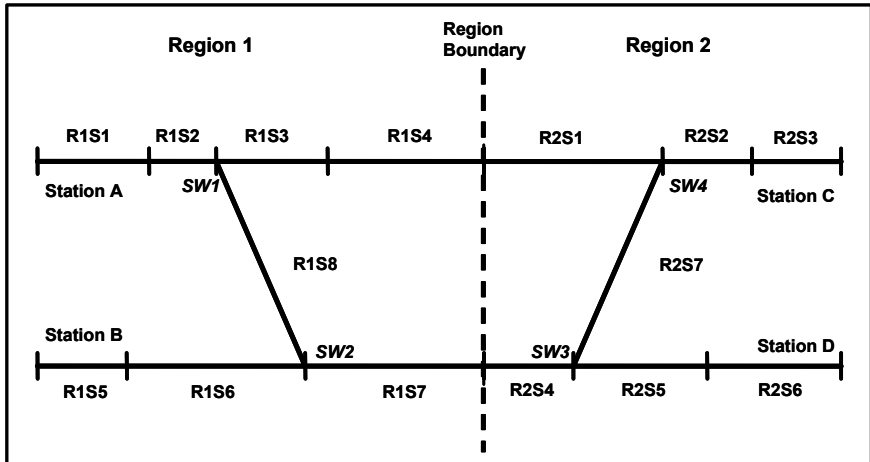


Figure 2: How regions and segments are used for train positioning.

In a *CITYFLO* 450 or *CITYFLO* 650 system, the train's position is sent to the Wayside System as region number, e.g. 'R1', segment number, e.g. 'S3' and offset from the start of the segment, e.g. 500m. The complete position would then be: 'R1, S3+500'.

To correct any errors in the position measurements made by the tachogenerator 'Norming Point' balises are used which are mounted along the track. When a train passes over such a balise it provides an exact location of the train and the Vehicle System can correct for any errors in the position of the train. As the train moves away from the 'Norming Point', the position error will start to increase and this will again be corrected at the next 'Norming Point'.

### 3.4 The Communication System

The communication system in modern CBTC systems is based on radio transmissions, often in the 2.4 GHz ISM band and often using a spread spectrum technique to reduce the chances of interference from other systems.

The communication medium can be based on 'line of sight, or leaky coax using a RADIAX cable, or both depending on the application.

All communication system components, except the antennas or the RADIAX cable, are also duplicated.

### 3.5 The Train Registry System

One of the few drawbacks of CBTC systems is at 'cold' start-up. When the system is started again after a total system power-down, the CBTC Wayside

System is unaware of the position of the trains. In earlier CBTC systems it was often necessary to have drivers board the trains and drive them manually to the next station in order for the CBTC system to ‘acquire’ the position of the trains in a safe way. Although system stops in CBTC systems are unlikely due to the fact that nearly all components are duplicated, having to drive the trains manually could be very time consuming, sometimes taking an hour or more for larger metro systems.

The *CITYFLO* 450/650 systems offer the Train Registry System (TRS) feature, which registers the identity of the trains as they pass in and out of the regions independent of the *regions*. In case of a ‘cold’ start or after a brief communication failure, the TRS system will provide the train IDs for each region to the CBTC Wayside System so that the communication can be re-established instantly thus making any start-up a matter of minutes.

## 4 Application example, overlaid CBTC system for European Metro

### 4.1 Background

Most European metros were established some time ago and by now many of them will need a modern signalling system for one or several of its lines in order to increase their transport capacity. Normally there is in such a metro an existing fixed block, speed-step signalling system, with an older ATP and ATO which is working at full capacity and can not be upgraded.

Many such metros recognize that to install a moving block CBTC system is the only way forward. The solution they often arrive at is to overlay a CBTC moving block system ‘on top’ of the existing signalling system in order to achieve a ‘dynamic headway’ of down to 40 seconds, i.e. a headway calculated without the station dwell times, and to be installed without affecting the passenger safety or transport capacity in the process.

As this often is their first experience with CBTC systems, most metros would like to have a conventional system as ‘fall-back’, should the CBTC system fail. Finally, although often the proposed CBTC system would have a driver onboard, the system itself is more often than not required to be capable of being upgraded to a fully driverless system.

The selection of the *CITYFLO* 450 system from Bombardier Transportation to re-signal a metro line with these requirements will lead to the following system solution.

### 4.2 The system solution

The requirements of overlaying the CBTC system on the existing signalling system along with providing a fall-back system, to assure full safety and transport capacity during the installation and to be able to meet the dynamic headway requirement of 40 seconds lead to a system solution shown below, and which uses several of the unique features of the *CITYFLO* 450 system.

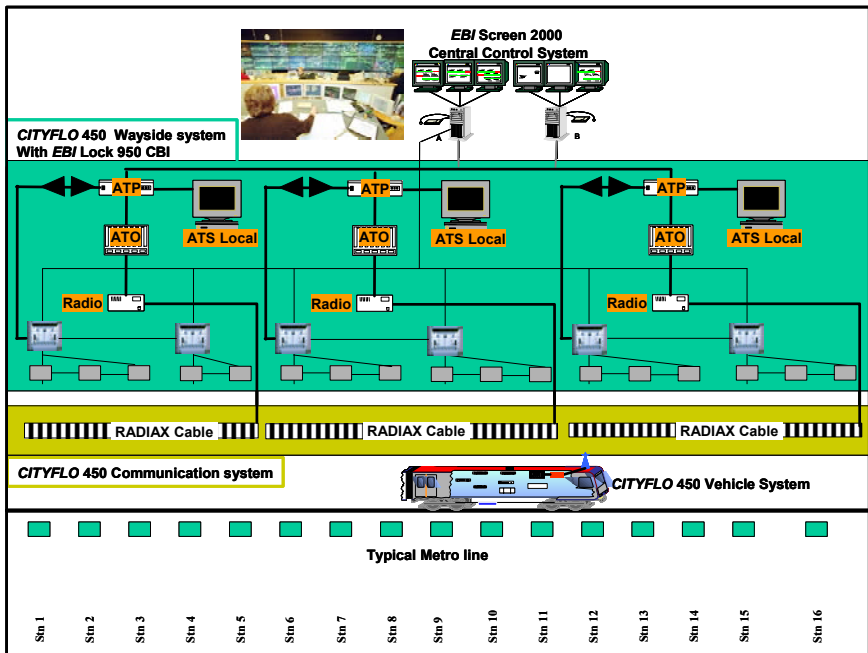


Figure 3: Typical Metro System solution.

#### 4.2.1 Meeting the ‘overlay’ requirement

The *CITYFLO 450* system uses radio for communication between wayside and train. The train position is determined by the onboard ATC equipment and communicated to the wayside ATC over the radio. The system does not need track circuits or other form of wayside interface for safe operation and therefore, can be easily ‘overlaid’ on top of an existing signalling system.

#### 4.2.2 Meeting the ‘fall-back’ requirement

CBTC is relatively new technology and even though metros around the world are beginning to embrace this new technology for the obvious benefits it is likely to bring, the approach is cautious. Choosing to operate the system with drivers initially is a result of such caution even though there are a number of metros which already operate driverless trains using CBTC systems. Requirement for a ‘back-up’ signalling system is another example of such cautious approach. Even though modern radio systems are highly reliable, due to the nature of the CBTC systems, a single loss in the communication chain can bring any system to a grinding halt. Even though highly unlikely, metros often require the system to continue to operate under such a situation.

In such cases Bombardier proposes a full secondary signalling system using the conventional track circuits, interlockings and wayside signals. The solution is based on the *Bombardier\* EBI\* Lock 950* Computer Based Interlocking (CBI) and TI21 jointless track circuits. *EBI Lock 950* CBI was first introduced in 1976 and is currently in its fourth generation. The interlocking has certain special

features that make it ideal for Mass Transit applications and especially for co-operation with the *CITYFLO* 450 system. Note: \*Trademark of Bombardier Inc. or its subsidiaries.

In particular, as the interlocking allows the outputs to the wayside objects like signals, point machines and object controllers to be located at practically any distance from the central interlocking unit, it has been possible to use the capacity of each central unit in two to three metro stations using fibre optic cable as communication medium. This has allowed the number of interlockings needed for each line to be reduced.

The *EBI* Lock 950 CBI and the *CITYFLO* 450 systems communicate with each other over a safe serial link. While the *EBI* Lock 950 interfaces with the wayside objects, the *CITYFLO* 450 manages the communication between the trains and wayside ATC. The movement authority is generated as a safe and optimum balance between the trains' reported position and the actual track occupancies. In normal operation when the *CITYFLO* 450 system controls the operation of the trains, the computerized interlocking will act as little more than a conduit between the CBTC system and the object controllers controlling the wayside objects, with only basic functionality.

Should the *CITYFLO* 450 system fail, the affected trains will still be able to operate using the movement authority generated by the *EBI* Lock 950 interlocking and conveyed by means of the wayside signals.

For this back-up mode, it is possible to choose longer track sections in order to reduce the number of track circuits. Therefore the headway in fall-back mode will obviously be much higher than with the CBTC system.

#### **4.2.3 Meeting the requirement to maintain safety and capacity during installation**

The existing onboard ATP/ATO equipment in the trains will be removed when the *CITYFLO* 450 vehicle equipment is installed on a train. Therefore, it is necessary to choose a system solution that allows safe 'coexistence' between trains equipped with the old ATP/ATO and trains equipped with the *CITYFLO* 450 ATP/ATO without affecting the performance.

To this end, the *CITYFLO* 450 system will have information from the existing track circuits and will therefore distinguish between a train with the old ATP/ATO occupying a track circuit and a train with the *CITYFLO* 450 ATP/ATO occupying a track circuit. The latter train is also sending information via radio about its position while the former is not. This leads to four driving mode cases:

1. A train equipped with the old ATP/ATO equipment following another train equipped with the old ATP/ATO equipment will follow the existing rules and leave two un-occupied track circuits between them.
2. A train equipped with the *CITYFLO* 450 ATP/ATO equipment following a train equipped with the old ATP/ATO equipment can advance up to the end of the track circuit before the one occupied by the previous train.
3. A train equipped with the old ATP/ATO equipment following a train equipped with the *CITYFLO* 450 ATP/ATO equipment must also follow the existing rules and leave two un-occupied track circuit between them.

4. A train equipped with the *CITYFLO* 450 ATP/ATO equipment following another train with the *CITYFLO* 450 ATP/ATO can use the Moving Block capability in the CBTC.

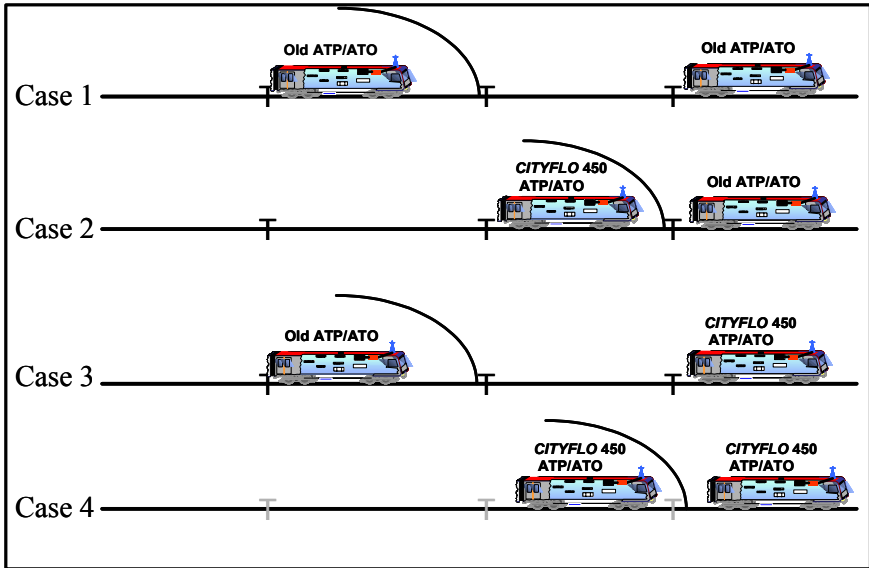


Figure 4: The four driving mode cases during system installation.

#### 4.2.4 Meeting the headway requirement

If the dynamic headway requirement set up is 40 seconds, i.e. with a dwell-time of zero seconds in each station, the trains working in CBTC moving block mode would be separated by 40 seconds.

A modern CBTC system with moving block operation where the train 'footprint' or part of the track considered to be 'occupied' by the train is the train length plus a speed dependent 'buffer' area around the train. Moving and variable block, by its nature allows the trains to circulate closer to each other than fixed block system. The *CITYFLO* 450 system with its efficient radio communication has a demonstrated dynamic headway of about 15-20 seconds in other projects. Taking into consideration, the track and rolling stock characteristics of a typical metro it is nearly always possible to demonstrate in an operational simulation that the required dynamic headway will be met with *CITYFLO* 450 system.

#### 4.2.5 Meeting the requirement for upgrading to a driverless system

The *CITYFLO* 450 CBTC moving block system with a driver is a version of the *CITYFLO* 650 CBTC moving block driverless system belonging to the same system family. It is therefore relatively easy to upgrade the signalling system itself to driverless operation.

Signalling systems have been capable of operating trains without driver for over two decades now. The issue is the compatibility of the infrastructure, i.e.



stations, tunnels and trains for driverless operation, especially the perceived security aspect and emergency procedures. Significant investment will be required for upgrading an existing metro system in order to adapt to the operational requirements of a driverless system.

## 5 Brown field Installations, a challenging implementation

For many European metros it will be their first experience in installing CBTC on an existing infrastructure although several CBTC systems have been installed in other metros in new lines. In such an installation we normally have to deal with a number of challenging issues such as:

1. The *CITYFLO 450* system uses Radiax cable as a medium for train to wayside communication. The cable can be mounted between the tracks, on the tunnel wall or overhead. While mounting the Radiax hanging from the tunnel roof between the two tracks would be logical, in many cases it is not considered feasible due to access restrictions, and instead the location is often changed to the tunnel wall. This requires two sets of Radiax cables to be laid – one on each sidewall impacting the cost and schedule of installation.
2. During the proposal phase, it is often envisaged to interface the onboard ATC equipment to two, three or more different types of trains. On detailed survey, it is often revealed that the interfaces are not uniform even on each type of train, which certainly increases the scope and complexity of the adaptation task.
3. The biggest challenge that awaits a project team is implementation of the system without affecting the existing operation. Most metros, operates 20 hrs each day and therefore only a short time window is available to access the track to perform installation activities. A meticulous planning, rigorous project management and strict organisational regime will be necessary in order to exploit this short access effectively.
4. Our experience on delivering similar application of CBTC to the LRT project in Philadelphia (SEPTA), USA suggests that the driver training for any new system is an onerous task. While, the normal train drivers are familiar with ATP/ATO operation, they will have to be trained in using the new operator console. The effort required in educating the different operational modes of this implementation, i.e. driving under CBTC (without signals), and under ‘fall-back’ mode (with signals), can not be underestimated.

## 6 Conclusion

The paper has demonstrated that a modern CBTC system with moving block capability and using modern computerized interlockings can be ‘overlaid’ in order to increase the transport capacity (throughput) of an existing Metro or Mass Transit line while maintaining the safety and the capacity of that line during the installation process.

# An algorithm for braking curve calculations in ERTMS train protection systems

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## Abstract

The European Railroad Transportation Management Systems standard for train protection, ETCS, includes several advanced features for predicting the safe speed from a number of target locations ahead of the train. The braking system can have a different braking capability in different speed segments. The area in front of the train can contain a number of targets with different target and release speeds. The area in front of it is also segmented according to the gradients, in a way which is independent of the targets. The variables that shall be input to the braking curve algorithm therefore have three dimensions. Since permitted speed shall be calculated, rather than time to intervention, square roots are needed for the calculations, which require some computational power. The article suggests an algorithm where the gradients and the targets are combined in one table. This makes the input variable area two-dimensional instead of three-dimensional, which simplifies calculations and reduces the necessary number of square root calculations.

*Keywords:* ETCS, ERTMS, braking curve, ATP.

## 1 Introduction

The European Train Control System – the new European standard for automatic train protection, uses basically a three-dimensional set of data as input to the supervision algorithms. The three dimensions are: a table of speed restrictions, a table of gradient sections, and a table of deceleration abilities in relation to speed. The output from the algorithms is expressed in the form of speed values; e.g. which is the highest possible speed the train can run, in order to be able to

obey all speed restrictions on the track ahead of the train? The three dimensions of data input may require a large number of calculations. The requirement for output to be expressed in the form of a speed, requires square roots to be used, which requires comparatively large computational power for each calculation, especially since real-time CPU'S are not normally equipped with dedicated floating point processors.

Enough computation power must be allocated to be able to supervise the maximum possible number of restrictions, gradients and deceleration segments, plus an ample safety margin, in order to satisfy the safety requirements of a train protection system. All calculations shall be repeated according to changes in input data, such as train position, train speed and when information about new speed restrictions becomes available.

This paper describes an algorithm using a two-dimensional approach for the calculation of the output speed values.

Section 2 will describe the basic requirements for train speed supervision in ETCS. In section 3, the two-dimensional approach and algorithm will be described. In section 4, additions to this algorithm to be able to handle various special ETCS requirements will be described. Finally in section 5, the conclusions of this work will be summarized.

## **2 Basic requirements for train speed supervision in ETCS**

The following is a simplified description of the requirements for train speed supervision in ETCS. Beside the following requirements, there are also other requirements such as separate service and emergency brake supervision, consideration to position measurement uncertainty, and numerous other requirements which are needed in ETCS, but which are not necessary for describing the basic algorithm for supervision of targets ahead of the train. Possible algorithmic solutions to some of the more detailed requirements are however discussed later in this article.

### **2.1 Speed restriction table**

The speed restriction table can contain up to 31 restrictions ahead of the train (30 static speed restrictions and one distant signal speed restriction). (See `n_iter` in packet 12 and packet 27, in subset-026 chapter 7 and in subset-58.) The restriction speeds can vary between 0 km/h and 600 km/h in steps of 5 km/h. (See variable `v_static` and `v_loa` in packets 12 and 27 in subset 026 chapter 7 and in subset-058).

### **2.2 Gradient section table**

The gradient section table can contain up to 31 sections defining the gradients on the track in front of the train. The gradient on one section can be between  $-25,4$  and  $+25,4\%$  in steps of  $0,1\%$  (see variable `g_a` om packet 21 in subset-026 chapter 7 and subset-058).

### 2.3 Deceleration ability table

The deceleration table describes the trains' ability to brake, as a function of speed. The use of such a table makes it possible to brake later in certain situations, since the known differences in braking ability related to speed are taken advantage of. The table cannot be longer than 31 speed segments. Each speed segment defines the trains braking ability in a certain speed range. The braking ability can be between 0 and 2.55 m/s/s in steps of 0.01 m/s/s.

### 2.4 Brake delay time

Two models for brake delay are allowed. One assumes that the braking ability is zero during the brake delay and 100% after the brake delay. The other model uses two delay intervals. The braking ability is assumed to be zero during the first interval. During the second interval, braking ability is assumed to be gradually increasing to 100%. The algorithm described in this paper uses the first, simpler brake delay model.

## 3 A two dimensional approach and supervision algorithm

The supervision algorithm shall calculate a palette of speeds for various purposes, from the input data in form of speed restrictions, gradient sections, deceleration table and brake delay time. This palette includes:

- Service brake intervention speed SBI: Which is the highest speed that the train can run and still be able to obey all speed restrictions ahead of the train, using only the service brake?
- Emergency brake intervention speed EBI: Which is the highest speed that the train can run and still be able to obey all speed restrictions ahead of the train, using the emergency brake (which has significantly shorter brake delay time)?
- Warning speed W: Which is the highest speed that the train can run and the driver has still a few seconds margin before the SBI speed is exceeded (considering that the SBI speed becomes lower and lower when the train approaches a the start of a speed restriction)?
- Permitted speed P: Which is the highest speed that the train can run and the driver has still a few seconds margin before the W speed is exceeded (considering that the W speed becomes lower and lower when the train approaches a the start of a speed restriction)?

This article will describe an algorithm that can be used to calculate either of the above measures, depending on which brake delay time is used, which position uncertainty is added and which restriction margins are selected. A plausible strategy would be to first calculate the EBI and then use the same algorithm again to calculate SBI, W and P, this time focusing on the restriction which showed to be most restrictive for EBI. The calculation of SBI, W and P can be done in one pass, so a total of two passed would then be necessary, where only on restriction would be considered in the second pass.

### 3.1 Basic steps in algorithm

When calculating the trains braking ability towards a restriction, only the allowed speed and starting point of the restriction are of interest. These are in the following called targets. A target is thus a combination of a position and an allowed speed (beginning at that position). That implies that the restriction table is seen as a table of speed targets which the train must be able to brake to.

The first obvious step in the algorithm is to remove all targets which cannot possibly be the most restrictive target. That is the case when a more distant target allows the same or a higher speed than a closer target. After this first step, the target/restriction table will contain a down slope stair where each more distant target has a lower allowed speed than the previous. The first step is obvious and will not be further discussed in this article.

The second step in the algorithm is to merge the target/restriction table and the gradient table into one table which contains both target speeds and positions in the track where the gradient changes.

The third step in the algorithm is to calculate the brake delay distance, that is how long the train would run without any braking, given the train speed and the braking delay. Later in the article I will argue that why it is not the trains actual speed that shall be used to calculate the brake delay distance, but rather the previous result from using the algorithm (the highest possible speed which would make it possible to obey all targets in front of the train).

The fourth step in the algorithm is to calculate the allowed speed at all positions in the target/gradient table, starting with the last position and working stepwise backward towards the position of the train. At each step, a target speed to current allowed speed calculation is done. In this calculation, the gradient (which affects the trains braking ability) is fixed, since all gradient change positions are included in the table. The trains braking ability relative to speed may however be non-fixed. The trains' deceleration ability at the result speed may differ from the ability at the target speed. Therefore, this calculation is in itself divided into steps, one for each involved segment in the deceleration ability table. The resulting allowed speed shall be compare with the target speed at the new position if there is one and the lowest of both selected as allowed speed at that position. If there is not target speed at the new position (the new position represents a gradient change), then the result of the calculation shall be used as allowed speed at the new position.

The fifth step is to interrupt the calculations when the position becomes closer to the train than the brake delay distance, since the trains braking ability is assumed to be zero here. Targets on the distance where braking ability is zero, shall instead be directly compared with the calculated allowed speed, and the lowest value selected.

### 3.2 Step 2: merging the targets/restriction and gradient tables

The merging of the target/restriction and gradient tables can be illustrated by the following example:

Table 1: Example of a target/restriction table.

Position	Allowed speed
500 m	100 km/h
1000 m	50 km/h
1500 m	0 km/h

Table 2: Example of a gradient table.

Position	Gradient up to this position
700 m	0%
1200 m	-1.0%
1700 m	-2.0%

Table 3: Example of a merged target/restriction + gradient table.

Position	Type	Allowed speed	Gradient up to this position
500 m	Restriction	100 km/h	-
700 m	Gradient change	-	0%
1000 m	Restriction	50 km/h	-
1200 m	Gradient change	-	-1.0%
1500 m	Restriction	0 km/h	-
1700 m	Gradient change	-	-2.0%

### 3.3 Step 3: calculating the brake delay distance

The braking ability is assumed to be 100% closer the targets. But before a certain position, the braking ability is assumed to be zero. This position is calculated as the current position plus the brake delay multiplied by the train speed:

$$pos_{delayend} = pos_{train} + brakedelay \cdot v \quad (1)$$

For the sake of knowing when to issue an automatic ATP brake, the actual train speed can be used in this algorithm. If however the speed result from the calculation shall also be used as information to the driver, then we must use the resulting speed from the calculation when calculating the brake delay distance. A larger train speed will result in a larger brake delay distance which in its turn will result in a lower allowed speed from the algorithm. This means that there is a circular dependence in the algorithm. Is this a problem? Assume that the allowed speed is calculated periodically as the train advances on the track. When the train approaches a target, the allowed speed will gradually decrease. If the algorithm used the result from the previous calculation when calculating the brake delay distance, then the dependence on previous cycles result may in this case cause a minor underestimation of the allowed speed which is showed to the driver. The error can be approximated as the trains braking ability during the time between two calculations. If, for example, the braking ability is 0.8 m/s/s, and the calculations are done with 0.25 s intervals, then the error would be 0.7 km/h, and it would be in the safe direction. If for example a future restriction suddenly

disappears, for example because a signal ahead of the train changes from stop to clear, then however the calculated allowed speed would be too high, because it would be based on a too short brake delay distance, and the error could be rather large. This problem can however be solved by limiting how much the allowed speed may increase from one calculation to the next, or by delaying the display of the new information until one the calculation has been performed two times (this could for example result in a delay of the increased speed display by 0.25 s).

### 3.4 Step 4: calculating the allowed speed at all positions in the table

The basic formula for calculating the braking distance from one speed  $v_1$  to a lower speed  $v_2$  is:

$$dbr = \frac{v_1^2}{2 \cdot dec} - \frac{v_2^2}{2 \cdot dec}, \quad (2)$$

where dec is the trains' deceleration ability, in  $\text{m/s}^2$ .

When dbr, dec and  $v_2$  are available,  $v_1$  can be calculated as:

$$v_1 = \sqrt{2 \cdot dbr \cdot dec + v_2^2} \quad (3)$$

So, if the allowed speed at position p is known, then the allowed speed at position p-1 can be calculated as:

$$v_{p-1} = \sqrt{2 \cdot (pos_p - pos_{p-1}) \cdot dec + v_p^2} \quad (4)$$

The trains' deceleration is dependent of the gradient and of the train speed. However, we know that the gradient over the distance is fixed and available as the next gradient change in the table (in tablerow (p) or later).

The relation between gradient and deceleration is defined by the following formula:

$$dec = dec_0 + g \cdot \frac{grad}{100} \quad (5)$$

where  $dec_0$  is the zero gradient deceleration,  $g \approx 9.8186 \text{ m/s}^2$  (free fall acceleration) and gradient grad is expressed in %. The formula can be easily understood if we consider the case when the  $dec_0$  is zero and the slope is 100%. The deceleration would then become  $-9.8186 \text{ m/s}^2$ , which represents free fall acceleration.

As mentioned earlier,  $dec_0$  is dependent on the trains' speed, in accordance with the deceleration ability table. If we assume that there is a function  $f_{vto\text{dec}}$  available which looks up the table and returns the  $dec_0$  deceleration as function of train speed, then we know that the  $dec_0$  is equal to  $f_{vto\text{dec}}(vp)$  at position p.  $dec_0$  at position p-1 is however unknown at the moment, but we assume tentatively that it is the same as at position p, and can then calculate dec as

$$dec = f_{vto\text{dec}}(v_2) + g \cdot \frac{grad_p}{100} \quad (6)$$

Using dec above,  $v_1$  is now tentatively calculated. If  $v_1$  has the same deceleration  $dec_0$  as  $v_2$ , then  $v_1$  is correct. To check this, we assume there is a function  $f_{rangehigh}$  which again looks up the deceleration ability table and returns the highest speed which has the same deceleration as its argument. The condition for  $v_1$  to be valid is:

$$f_{rangehigh}(v_2) \geq v_1 \quad (7)$$

If this is not the case, then a stepwise process is used to calculate the valid  $v_1$ . First we calculate the position where the allowed speed =  $v_2' = f_{rangehigh}(v_2)$  using the basic brake distance formula (2) above:

$$pos_{v_2'} = pos_p - \left( \frac{v_2'^2}{2 \cdot dec} - \frac{v_2^2}{2 \cdot dec} \right) \quad (8)$$

where dec is calculated according to formula (6) above. We now know the allowed speed at position  $pos_{v_2'}$ . We can then do a new tentative calculation of  $v_1$ , again using equation (4) but now substituting  $v_2$  by  $v_2'$  and  $pos_p$  by  $pos_{v_2'}$ . The new tentative  $v_1$  is then compared with the new (higher)  $f_{rangehigh}(v_2')$ . The process is continued until we reach a value  $v_1$  which is  $\leq f_{rangehigh}(v_2')$ . Once the valid  $v_1$  is calculated it shall be compared to the target speed at the new  $pos_{p-1}$ , if there is one. The lowest value shall be regarded as the allowed speed at  $pos_{p-1}$ . The process continues towards the train, and is interrupted when the end of the brake delay distance is reached.

### 3.5 Step 5: to interrupt the speed calculation when the end of the brake delay distance is reached

Since the braking ability is zero over the brake delay distance, the calculation of allowed speed shall be interrupted when the end of the brake delay distance is reached, which happens at position  $pos_{enddelay}$  as defined in equation (1) above. This means that if  $pos_{p-1} < pos_{enddelay}$ , then  $pos_{enddelay}$  shall be used instead of  $pos_{p-1}$  in the last calculation according to step 4. When the allowed speed at  $pos_{enddelay}$  is calculated, this will not be updated anymore, except that it is replaced if there is a target speed which is lower (between the train and  $pos_{enddelay}$ ).

## 4 Additions to the algorithm to be able to handle various special ETCS requirements

In chapter 3, a basic algorithm to calculate the highest possible speed a train can run while still being able to obey the speed restrictions in the restriction table and considering the impact of gradients (the gradient table) and speed (the brake ability table) to the trains deceleration. In ETCS, and any other ATP system, there are many other requirements which need to be satisfied, e.g.

- The system shall be able to calculate allowed speed both for service brake and for emergency brake, the emergency brake being a minimum delay backup, should the service brake fail



- Various speeds for informational purposes, such as permitted speed P and warning speed W shall also be possible to calculate
- Targets may have speed margins for different purposes (e.g. for service brake intervention and emergency brake intervention), and the supervision shall be interrupted when the target speed + speed margin is reached.
- A stop signal position ahead of the train may have a release speed associated with it, in order to make it possible for the train to reach the position where new signal information (possibly clear) becomes available. This is the case when transponders are used to convey the signalling information from the track to the train.

#### 4.1 Allowed speed for service brake and for emergency brake

Service brake and emergency brake have different brake delays and their own deceleration ability tables. The allowed speed to avoid service brake and emergency brake can be calculated by running the above algorithm twice, once with the service brake delay and deceleration table and once with the emergency brake deceleration table. Another method which requires fewer calculations would be to first calculate the allowed speed to avoid emergency brake and then disable all restrictions except the one which was found to be most restrictive for the emergency brake before the algorithm is reused again for the service brake. If however, there is a stop signal among the targets, then this should always be included in the service brake calculations even if it is not the most restrictive emergency brake target, since such a target may be positioned significantly closer for service brake calculations than for emergency brake calculations (at least in ETCS). This is necessary in order to make sure that the train stops before the stop signal even when there is a large safety distance behind the signal.

#### 4.2 Various speeds for informational purposes

In ETCS, the driver has to breach two speed limits before an automatic service brake is issued. The first limit is the permitted speed P, which is showed to the driver during normal operation. As long as the driver runs the train below the P speed, he or she will have at least 5 second margin before ETCS would issue an automatic brake. If the driver exceeds the P speed with a certain margin, the ETCS system will issue a visible and audible warning to the driver. When ETCS issues the warning, the driver has still 3 seconds to react and start braking, before ETCS issues an automatic brake. Since W and P are defined in delay time units, they can be calculated by adding the W and P margins to the brake delay time before running the algorithm. To do this, two extra fictive delay end positions are calculated, one for W and one for P:

$$pos_{enddelayw} = pos_{enddelay} + 3s \cdot v$$

$$pos_{enddelayp} = pos_{enddelayw} + 2s \cdot v$$

where v is the same speed as discussed in chapter 3.3. The calculations are carried out in one pass, but they are interrupted at different positions for the

calculation of  $W$  and  $P$  than for the allowed speed to avoid service brake. This will cause  $W$  to be lower than the “allowed speed” and  $P$  to be lower than  $W$ , and it results in the desired time margins for the driver to react.

### 4.3 Speed margins and release speeds

For a signal speed or static speed restriction, there is a margin from the nominal speed to the speed when automatic service brake intervention is issued. There is also a margin between service brake intervention and emergency brake intervention. Unnecessary service brake intervention is thereby avoided as long as the driver drives close to the nominal speed, and unnecessary emergency brake is avoided when service brake is sufficient to do the job.

When the train approaches a restriction which has a margin, it is not necessary to brake the train down to the nominal speed – it is enough to brake it down to the nominal speed plus margin. Release speeds are similar to speed margins – the release speed is a speed margin above zero which enabled the train to approach the transponder close to the main signal.

Speed margins and release speeds are handled by calculating a position before the actual target where the allowed speed is equal to the target speed plus margin (or equal to release speed). The margin targets are used instead of the real targets in the calculations.

## 5 Conclusion

The ETCS requirements that gradients and targets shall be independently separated, and that the trains deceleration shall be defined in tables related to speed introduces considerable complexity in the supervision algorithms needed. This article suggests a method of combining the gradient and target tables, in order to master this complexity and to limit the necessary number of square root calculations. The allowed speed is calculated from the most distant target and backwards towards the position of the train. Fictive train delay times are used to produce the different speeds that are required for informational purposes.

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# A new ground-to-train communication system using free-space optics technology

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## Abstract

We propose a new ground-to-train communication system using free-space optics between a train and the ground. In the proposed system, a cylindrical concave lens spreads the incoming beam from transmitter (Laser Diode, LD) horizontally to form a wide fan-shaped beam. The fan-shaped beam is projected to a train and the width of the projected beam is equal to the length of a typical bullet-train car. This transmitter with cylindrical concave lens and a receiver (Avalanche Photo Diode, APD) are installed on a train and the ground, and the horizontally spread beam is received continuously by the corresponding receiver. The train can keep a communication link continuously to the ground thanks to this spread beam. We analyzed the performance of the proposed system by experiments. The experimental results show that a sufficient received Signal-to-Noise Ratio (SNR) can be obtained when a train is not moving; therefore, the signal can be received continuously even when the train is moving. Furthermore, in order to keep a continuous communication link even when the train vibrates or shifts vertically, the vertical spread angle of a laser beam is adjusted between 0.1 degrees and 0.5 degrees. These experimental results lead to the conclusion that this system is expected to be a Giga-bit class high speed communication technology between the train and the ground.

*Keywords:* train communication, optical wireless communication, visible light communication, horizontally spread beam.

## 1 Introduction

In recent years, the environment of the ubiquitous society is being developed by rapid expansion of high-speed communication infrastructure such as Asymmetric

Digital Subscriber Line (ADSL) and Fiber To The Home (FTTH). We can use many services in hotspot and internet cafe. There is a high demand for the infrastructure to provide enough service to customers in a train. Leaky Coaxial cable (LCX) and millimeter-wave have been used for wireless communication between a train and the ground. However, the data rate of LCX is only 2.56 Mbps [1]. Millimeter-wave can increase the data rate up to 1Gbps when a train is not moving, but the data rate is decreased to 6.3 Mbps when the train is moving [2]. Therefore, these systems cannot provide high-speed data transmission in the moving train.

The equipments of optical wireless communication such as LD and LED are developed rapidly, and it is possible to achieve high-speed communication with these equipments. Since frequency of lightwave is very high, optical wireless communication is suitable for high-speed communication [3, 4].

We propose a new train communication system using free-space optics technology between a train and the ground. In the proposed system, a cylindrical concave lens spreads horizontally the incoming beam from LD horizontally to form a wide fan-shaped beam. The fan-shaped beam is projected to a train and the width of the projected beam is 25 m which is equal to the length of a typical bullet-train car. Owing to this spread beam, the train can continuously keep a communication link to the ground.

In this paper, we analyze the performance of this system experimentally. We investigate the received SNR in stationary condition and received signal amplitude at moving environment. Moreover, we examine the received power with the expansion of vertical beam angle in order to have a continuous communication link. Finally, we conducted the outdoor experiment using the test train.

The rest of the paper is organized as follows. In section 2, we describe LD with variable Numerical Aperture (NA) lens and cylindrical concave lens. In section 3, we describe the proposed system model. In section 4, we evaluate the system performance experimentally. Finally, the conclusions are given in section 5.

## **2 Design of transmitter**

### **2.1 LD fixed with variable NA lens**

LD is a device that emits the light by induced emission and laser oscillation and outputs the coherent light. The light of LD has isolated wavelength and high directivity, and the transmission power of LD is higher than that of LED [5, 6]. Even though the light of LD has high directivity, the width of the beam projected to a train is diffused and the sufficient received optical power cannot be obtained.

To obtain sufficient power of LD at the train, a variable NA lens which can change focal distance is attached in front of the LD. Since the incident beam angle from LD can be adjusted, the transmitted power can be controlled locally. Figure 1 shows the photograph and the concept of LD fixed with variable NA lens. The vertical beam angle of this LD is set to between 0.1 and 5.72 degrees, and the horizontally spread beam angle is fixed to 4.62 degrees.



## 2.2 Cylindrical concave lens

Various types of lens are categorized by configuration. There are many types of lens such as spherical lens, paraboloidal lens, and cylindrical lens. Among various types, cylindrical lens have a shape of cylinder, and can bring about an effect of lens in one direction. Since horizontally spread beam is projected to a train in the proposed system, we select cylindrical concave lens which spreads horizontally the incoming beam from LD to form a wide fan-shaped beam. Figure 2 shows the effect of cylindrical concave lens, and Figure 3 shows the photograph of a laser beam which is spread by the cylindrical concave lens. In this paper, we select three beam angles spread horizontally by cylindrical concave lens such as 20, 30, and 40 degrees.

## 3 Description of proposed system

### 3.1 System model

The proposed system model is illustrated in Figure 4. The width of the projected beam is 25 m which is equal to the length of a typical bullet-train car. Since the horizontal distance between a bullet-train and LCX is 1.9 m, if it is possible to communicate at this distance, LD and APD can be installed instead of LCX. Because of this, the horizontal distance between train and ground is 2 m (the height of LD and APD is the same). The down-link communication from the ground to the train and the up-link communication from the train to the ground use the same transmitter (LD) and receiver (APD) so that the speed of down-link and up-link are designed to be the same.

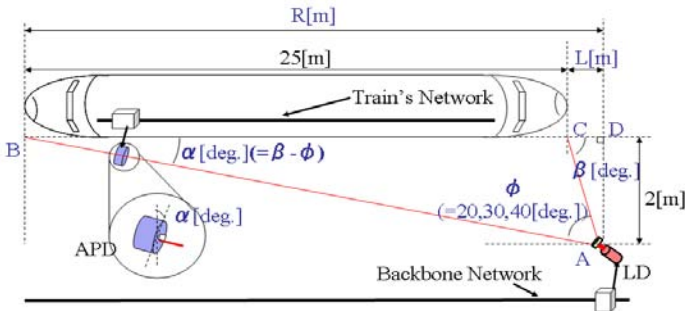


Figure 5: Proposed layout model.

### 3.2 Layout model

The proposed layout model is shown in Figure 5. Figure 5 shows only down-link, but up-link is also designed in a similar manner. We calculate various parameters to set up the layout. The calculated values of the various parameters with the width of the projected beam of 25 m are listed in Table 1, where  $\phi$  is

horizontally spread beam angle and is set to 20, 30, 40 degrees,  $\alpha$  is the angle which received at the longest point B and  $\beta$  is the angle which received at the shortest point C. In other words,  $\alpha$  is the angle at which APD is tipped. L is the distance between point C and D, and R is the distance between point B and D.

Table 1: Parameters of layout model.

$\phi$ (degrees)	40	30	20
$\alpha$ (degrees)	4.3	4.1	3.9
$\beta$ (degrees)	44.3	34.1	23.9
L (m)	2.05	2.95	4.51
R (m)	27.05	27.95	29.51
AB (m)	27.12	28.02	29.58
AC (m)	2.86	3.56	4.93

Table 2: Experimental parameter.

Bit rate	100 (Mbps)
Transmission power of LD	100 (mW)
Wavelength of LD	670 (nm)
Frequency of LD	400 (MHz)
Horizontally spread beam angle (with lens)	20/30/40 (degrees)
Vertical beam angle	0.1-5.72 (degrees)
Receiver	APD
Diameter of receiver	0.5 (mm)
Material of cylindrical concave lens	Synthetic fused silica
Condition of room	Dark room
Received signal amplitude of ambient noise	4 (mV)

## 4 Experimental results

In this section, we evaluated the system performance experimentally. In particular, we show the received SNR in a stationary condition, received signal amplitude in a moving condition, the received power with the expansion of vertical beam angle. Table 2 shows experimental setup.

### 4.1 Received SNR in a stationary condition

Measurement environment and result of the received SNR in stationary condition are shown in Figure 6. With  $\phi$  as a parameter, LD is installed in order to make the width of the projected beam to 25 m, and the tipped angle of APD is 4 degrees. We measured the received SNR between 1 m point and 25 meter point at 1 m intervals using a miniature train. It can be seen from this result that even though the received SNR decreases gradually as the distance becomes longer, sufficient received SNR level can be obtained at 25 m point irrespective of  $\phi$ .



Furthermore, we can find that optimal value of  $\varphi$  is 20 degrees. Therefore, we can say that a sufficient SNR can be obtained for the 25 m train length.

4.2 Received signal power in a moving condition

Measurement environment and result of the received signal power at moving situation are shown in Figure 7 with  $\varphi = 20$  and the tipped angle of APD of 4. We measured the received signal amplitude in a moving condition between 1 meter point and 25 m point using a miniature train. It can be seen from this result that the received signal amplitude declines gradually when the train is moving. However, it is confirmed that the signal amplitude can be received continuously for the communication area.

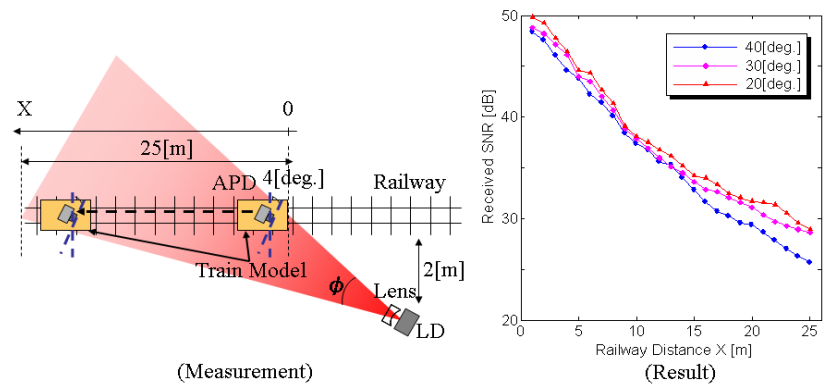


Figure 6: Measurement and result of the received SNR in a stationary condition.

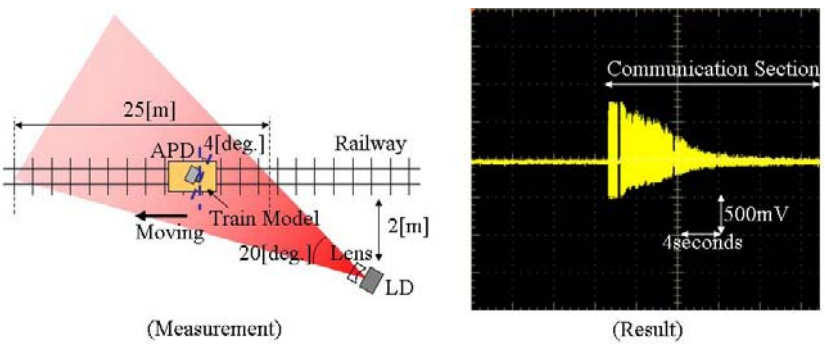


Figure 7: Measurement and result of the received signal amplitude in a moving condition.

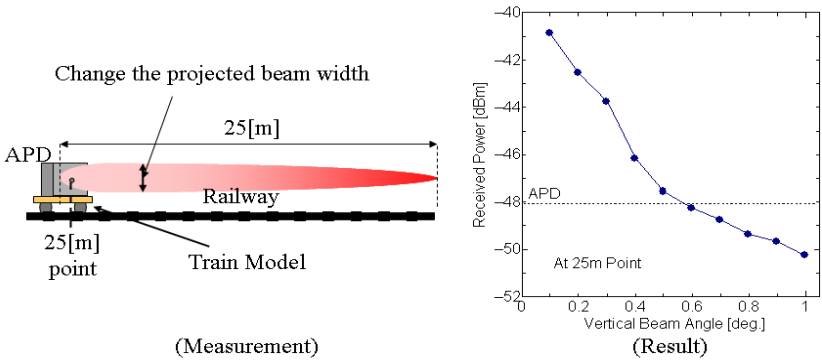


Figure 8: Measurement and result of the received power at 25 m point with the expansion of vertical beam angle.

### 4.3 Received power with the expansion of vertical beam angle

When a train vibrates and shifts vertically, the sensor of APD sometimes jolt out of alignment from the projected beam. We measured received power at 25 m point with expanding the vertical beam angle of LD. Measurement environment and result of the received power at 25 m point with the expansion of vertical beam angle are shown in Figure 8 with  $\phi = 20$  and the tipped angle of APD of 4. A dotted line in Figure 8 shows the minimum sensitivity of APD assuming 1 GHz optical signal. It can be seen from this result that at the vertical beam angle of 0.5 degrees the sufficient optical signal can be received. Therefore, we can say that by adjusting the vertical beam angle between 0.1 and 0.5 degrees, the vertical vibration and shift of a train can be absorbed.

### 4.4 Outdoor experiment using test train

We conducted the outdoor experiment using test train. We measured the received signal amplitude in the down-link and up-link when the train is moving at a speed of 15-20 km/h. Measurement environments of the outdoor experiment using test train are shown in Figure 9. Photograph of the outdoor experiment is shown in Figure 10. Table 3 shows experimental setup. In this experiment, a lens which works as optical concentrator and an interference filter are attached in front of APD. The length of platform is 20 m and that of test train is 19.6 m. The width of the projected beam is 25 m, the horizontal distance between LD and APD is 2 m.  $\phi = 20$  degrees, and the tipped angles of APD is 14 degrees because Full Width at Half Maximum (FWHM) of lens is 17.3 degrees. Furthermore, the vertical beam angle is 0.3 degrees. Figure 11 shows the result of the outdoor experiment. It can be seen from these results that the received signal amplitude declines suddenly at the certain time when the train is moving. We think that these results from effect of FWHM of lens on sensor of APD and interference

filter. However, it can be seen that the signal amplitude can be received continuously for 25 m. Therefore, from these results, we can say that the proposed system will be a promising candidate for train communication.

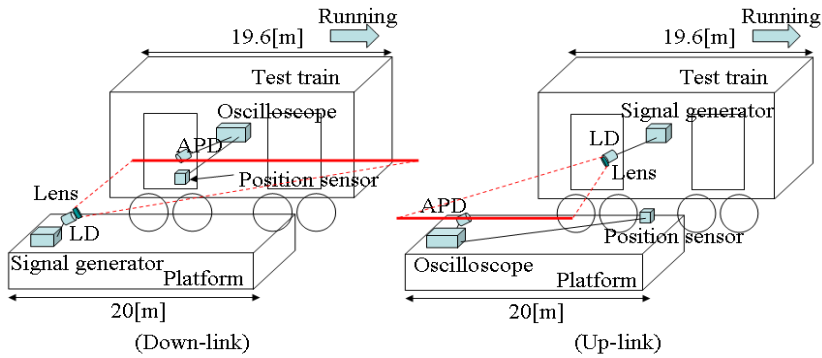


Figure 9:     Measurements of the outdoor experiment using test train.



Figure 10:    Photograph of the outdoor experiment.

Table 3:       Experimental parameter of the outdoor experiment.

Bit Rate	100 (Mbps)
Transmitted power of LD	100 (mW)
Wavelength of LD	670 (nm)
Frequency of LD	400 (MHz)
Horizontally spread beam angle (with lens)	20 (degrees)
Vertical beam angle	0.3 (degrees)
Receiver	APD with lens
Angle of receiver	14 (degrees)
Diameter of receiver	0.5 (mm)
Material of cylindrical concave lens	Synthetic fused silica
Weather	Fine day
Received signal amplitude of ambient noise	20 (mV)

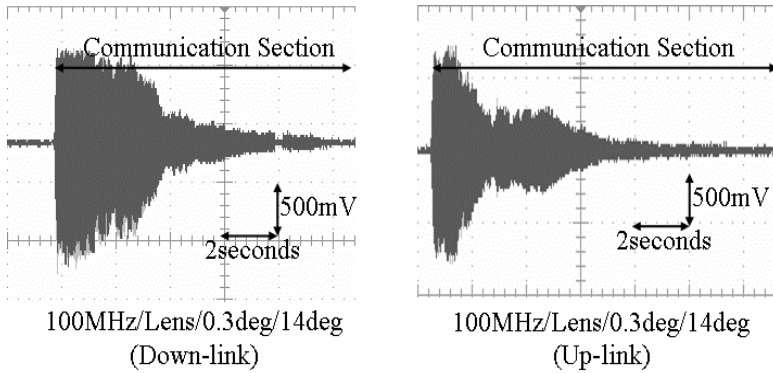


Figure 11: Results of the outdoor experiment.

## 5 Conclusions

In this paper, we proposed a new ground-to-train communication system using free-space optics technology in order to increase the transmission rate between a train and the ground. We investigated the system performance experimentally. It was shown from the experimental results that a sufficient SNR at stasis could be obtained for 25 m train length, and it was found that the optimal horizontal beam angle is 20 degrees. Moreover, the signal amplitude was more sufficient than the signal amplitude of ambient noise and a train can keep a communication link continuously for a 25 m train length. Furthermore, it was shown that by adjusting the vertical beam angle between 0.1 and 0.5 degrees, the effect of the vertical vibration and a shift of a train can be absorbed. Finally, we conducted the outdoor experiment using a test train. We believe that the proposed system is a promising candidate for train communication.

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# Automatic train operation system for the high speed Shinkansen train

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## Abstract

In train operation over 300 km/h, drivers are supposed to operate the handle for acceleration or deceleration quite often due to speed restriction at the curve. To ensure on-schedule operation and lighten the burden imposed on drivers under high speed operation, we developed the automatic train operation system for the Shinkansen train. This system automatically controls the speed to follow the target speed of operation as well as obey Automatic Train Control (ATC). The target speed is set by taking account of the ATC restriction, on-schedule running, and energy-efficient operation. The system was applied to running tests using a series E2 Shinkansen train from Morioka to Hachinohe, about 100 km, on Tohoku Shinkansen line. The test results tell that the accuracy of on-schedule operation is 4 s longer than the simulated running time, and the accuracy of following the target speed is within 2 km/h at the maximum speed of 320 km/h. We conclude that the system performance is satisfactory for the secure speed control and on-schedule operation.

*Keywords:* automatic train operation, automatic train control.

## 1 Introduction

East Japan Railway Company is developing the Shinkansen train with the concepts of high speed, safety, stability, environmental compatibility, and comfortableness. As for high speed, it plans to operate the train at the maximum speed of 360 km/h. To ensure on-schedule operation and lighten the burden imposed on drivers under the high speed operation, we developed the automatic train operation system for the Shinkansen train and carried out the running test on Tohoku Shinkansen line.

## 2 System outline

Automatic Train Control system (ATC) helps to keep train intervals fixed by braking the train, but in the high speed Shinkansen it is necessary to control the train in the shortest running time by powering and braking. This system automatically controls the speed by powering and braking to follow the target speed of operation as well as obey the ATC. The target speed is set by taking account of the ATC restriction, on-schedule running, and energy-efficient operation. The basic action of the system is as follows. Firstly, it accelerates up to the speed just below the ATC restriction. Secondly, it keeps the train at the maximum permissible speed with extreme accuracy. Thirdly, it stops accelerating at the point allowing on-schedule operation to the destination as it runs. The accurate operation at the maximum permissible speed reduces the loss of running time and produces the marginal time to the scheduled running time. According to the marginal time, it stops accelerating to save energy consumption, fig. 1.

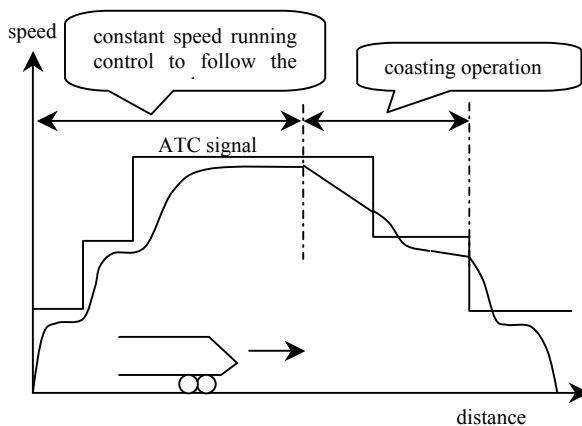


Figure 1: Running pattern image.

## 3 System constitution

This system consists of a switch in the drivers cab and the operation system connected to some devices, fig. 2. The switch in the drivers cab is pushed to start the automatic train operation. The operation system is connected to monitoring equipment in order to get information of kilometre and ATC signal aspect by way of ATC equipment, so it recognizes the train location and the restriction speed. It is also connected to a tachometer generator to get information of the train speed, so it controls notch for powering and braking to follow the target speed. The notch means steps for powering and braking.

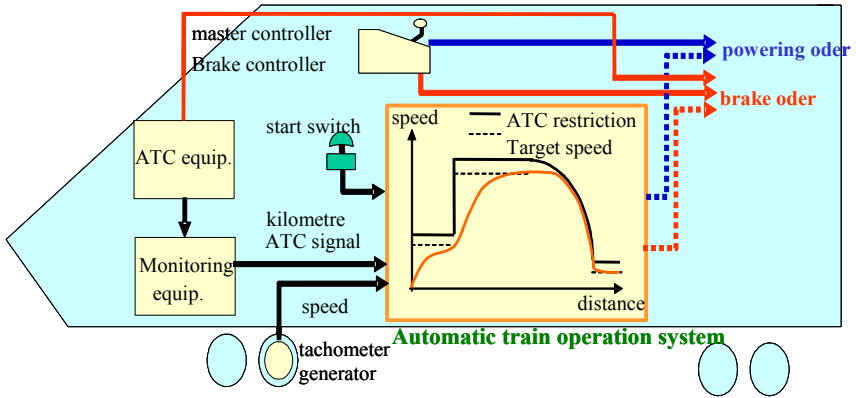


Figure 2: Constitution of automatic train operation system.

## 4 Function

### 4.1 Target speed

The system receives the ATC signal aspect from the monitoring equipment and sets the target speed of operation as the speed below the ATC signal aspect by 3km/h. Using information of kilometre, it can set the target speed according to the train location.

### 4.2 Constant speed running control to follow the target speed

The system controls to keep the speed constant to follow the target speed of operation until the target speed changes. The accuracy of constant speed control is set by within 2 km/h over or below the target speed. Concretely, it orders notch control to absorb changes of the train acceleration or deceleration by gradient resistance and running resistance, and keep riding comfort as it is. For this control, it has data of notch choice set by the train location and running speed zone and calculates relevant notch forward and back according to the changes of train acceleration or deceleration.

### 4.3 On-schedule operation

The system counts the time passed from leaving a station and calculates the difference between running time left and the target running time. When the difference is plus, it stops accelerating to shift to coasting operation for punctuality and energy saving. The accuracy of on-schedule operation is set within 10 seconds more or less than the target running time. The basic control routine for coasting and efficient operation is as follows, fig. 3:

- (1) In the fastest operation pattern, the time to arrive at a next station by coasting from a point is defined as  $T_{ex}$ . The system has  $T_{ex}$  data by simulation in advance.



- (2) The system calculates the time passed from leaving a station,  $T_{sx}$ . It compares a sum of  $T_{sx}$  and  $T_{ex}$  with scheduled time,  $T_t$ . At a point where the sum of  $T_{sx}$  and  $T_{ex}$  is equal to  $T_t$ , it starts coasting operation.
- (3) In case of driver's manual control, it cancels the operation once and start again coasting operation when the condition is satisfied.

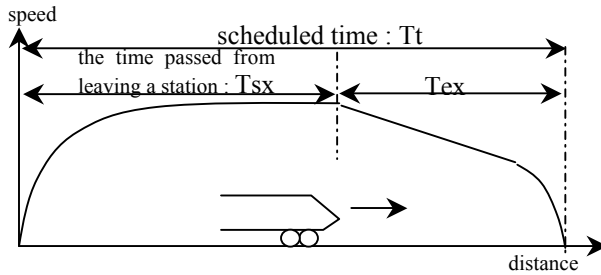


Figure 3: On-schedule operation image.

## 5 Test result

The system was applied to running tests using series E2 Shinkansen train from Morioka to Hachinohe, about 100km, on Tohoku Shinkansen line.

### 5.1 Constant speed running control to follow the target speed

The accuracy to follow the target speed was within 2 km/h in almost all section of running tests. There were two points where the accuracy was 2.2 km/h over or below the target speed. It is because of gradient fluctuation such as from plus 9 to minus 8, so it is improved by adjustment of control parameters of notch choice data.

### 5.2 On-schedule operation

Firstly, the fastest operation under the ATC restriction was tested. Secondly, we set the marginal time as 30 s. On-schedule operation was tested with the target running time as a sum of the running time of the fastest operation and 30 s. As table 1 shows, the running time of the fastest operation was 1591 s. The target running time was set as 1621 s. The running time of 30 s marginal time operation was 1625 s, so the difference between the target and result was 4 s accuracy. Figure 4 shows the result of running test with marginal time of 30 s.

## 6 Evaluation

### 6.1 Constant speed running control to follow the target speed

It is a satisfactory result that the accuracy of constant speed running control was within 2 km/h over or below the target speed in all section except for abrupt gradient fluctuation. The system performed stable control to absorb gradient resistance and running resistance from lower to higher speed zone, so it helps to

lighten operating load of drivers, who are supposed to operate the handle for acceleration or deceleration quite often, and realize constant patterned operation in all time.

Table 1: The accuracy of on-schedule operation and energy consumption (running section: Morioka to Hachinohe).

	The fastest operation	Marginal time 30 sec.
Target running time (second)	-	1621
Running time (second)	1591	1625
Powering energy (kWh)	2443	2173
Regenerative braking energy (kWh)	353	230
Consumption energy (kWh)	2090	1943

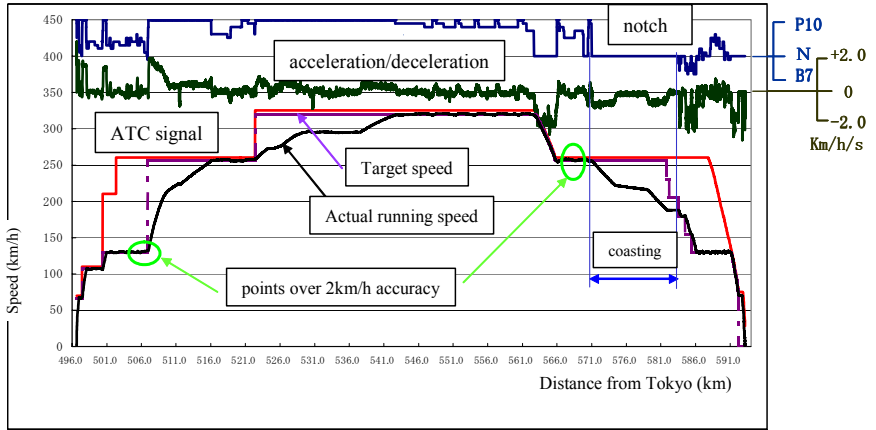


Figure 4: The result of running test from Morioka to Hachinohe.

6.2 On-schedule operation

On-schedule operation was realized by shifting accelerating to coasting according to marginal time of running. The accuracy of punctuality was 4 s, which means that the simulation data about target running time was highly accurate. It satisfies what we set at a target, and we regard the on-schedule operation as possible in the high speed Shinkansen.

7 Conclusion

It is concluded that the system performance is satisfactory for secure speed control, constant speed running control, and on-schedule operation. The system also realizes energy saving operation. For the practical use, we will accumulate

the data of various running patterns in the high speed Shinkansen test train aiming at 400 km/h running.

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## The opportunity to improve software RAMS

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### Abstract

Software is at the heart of many safety critical systems in the railway sector. The development of systems that include software modules requires the correct evaluation of software RAMS (Reliability, Availability, Maintainability and Safety) in order to obtain the correct value of the overall system RAMS.

In order to obtain appropriate software, the standards propose the performance of a set of activities in the different phases of software development, as well as tasks to control their correct accomplishment. They ensure the developed software is of adequate quality. However, it is necessary to go further and try to obtain a quantitative measure of RAMS for each software module as is usually done in hardware development. There are several techniques for the assurance of software reliability and safety that have been in use for years and must be analysed to find their real potential. These techniques are: reliability growth models, artificial intelligence techniques, Markov chains, Software Fault Tree Analysis and Software Failure Mode and Effect Analysis, among others.

This paper is an update of the previous one presented at the COMPRAIL XI Conference. Two circumstances emphasize the strategic time the railway sector is undergoing and the opportunity to adopt the most promising software techniques in order to improve reliability and safety. (1) The development of high-performance railway networks that interconnect different countries and the liberalization and opening of the national markets demand new European global agreements. In this regard, the European Railway Agency has asked its Safety Unit to develop the new Common Safety Methods (CSM) and Common Safety Targets (CST) to be used in all European countries. (2) The IEC 61508 standard (from which some parts of CENELEC EN 50128 are derived) is now under

revision, with the primary aim of ensuring the safety of the developed software by hardening the requirements and promoting the use of the most promising techniques. Moreover, the CENELEC EN 50128 standard is also under revision.

*Keywords: software safety, software reliability, RAMS, railway standards.*

## 1 Introduction

In the present world, our professional and private lives are surrounded by systems governed by software programs. Moreover, software is at the heart of many safety critical systems in the industrial sector. However, this meteoric rise of software applications has not been accompanied by the indispensable evolution in its development process that would allow one to have total confidence in it.

The development of systems that include software modules requires the correct evaluation of software RAMS in order to obtain the correct value of the overall system RAMS. But how do we evaluate software RAMS? Moreover, what techniques should we use in order to provide the software with the best RAMS values?

To obtain safe and reliable software, most of the standards propose the performance of a set of activities in the different phases of software development, as well as tasks during the development to control their correct accomplishment. These standards include the generic safety norm IEC 61508 [2], as well as the CENELEC standards for the railway sector (EN 50126 [3], EN 50128 [4] and EN 50129 [5]).

Development activities and control tasks seek to ensure that the developed software is of adequate quality, sufficient to reach the required degree of confidence. However, it is necessary to go further and try to obtain a quantitative measure of safety and reliability for each software module, as is the usual practice in hardware development. In fact, there are several techniques that have been in use for years, although the standards do not reflect them as mandatory.

This paper emphasizes the intrinsic characteristics of software and briefly defines system RAMS in the first place. Then, it gives an overview of the current state of the standards regarding software RAMS, bringing to attention the strategic moment that faces the railway industry with the ongoing unification and opening of the railway market. In this respect, the paper highlights the development of CSMs and CSTs within the European Union, as well as the most significant improvements that the second edition of the standard 61508-3 and the new edition of EN 50128 include. Finally, it enumerates a series of new techniques that would be interesting to analyse thoroughly so as to confirm the quantitative and qualitative improvements that their application brings in terms of reliability and safety.

## 2 Software RAMS

It is a fact that the techniques used nowadays for the evaluation of hardware RAMS indicators are much more advanced and provide measures closer to the

actual system performance than software RAMS indicators. Given the increasing importance of software components in the overall values of RAMS of a system, this represents one of the more active research areas.

In order to understand this, it is necessary to highlight some of the most significant characteristics that make hardware and software inherently different and partially explain the uneven evolution of techniques for the evaluation of RAMS indicators in hardware and software. The following differences are among the most significant ones:

- In hardware components, physical connections are established when the system is designed and remain unchanged during operation. However, in software components connections among the different modules are “chosen” while the system is operating, normally depending on the different values of input data. Connections in software systems are logical ones, which implies that multiple connections are possible, making it harder to analyze the whole component and carry out a complete testing of it. In this respect, we could argue that the flexibility associated with software turns out to be an additional problem in terms of safety and reliability assurance.
- As a result, given the problems that arise when analyzing and testing software components, it is of the utmost importance to avoid errors in the specification of requirements. It has been proved that a high percentage of software failure is due to an inaccurate specification, to an erroneous interpretation of the desired operation of the system, to a lacking specification regarding the performance of the system under certain operating conditions, or to a specification which can lead to system hazards.
- The interpretation and conversion of requirements when carrying out the design and subsequent implementation of the system is another important source of system failure.
- In many occasions, software experts are not sufficiently knowledgeable in system safety and reliability, and the other way round, engineers whose area of expertise is system safety and reliability are not software experts. However, most companies nowadays employ a group of experts in RAMS who are in charge of the control of all the elements involved, which minimizes the problem.

At this point, it is necessary to briefly define the four characteristics comprised by the term RAMS so that the focus of this discussion can be shifted to the current state of affairs regarding RAMS in the railway industry:

- Reliability (R): is defined in Storey [6] as ‘the probability of a component, or system, functioning correctly over a given period of time under a given set of operating conditions’ i.e. the probability that a system will perform the functions it was intended for when operated in a specified manner under specific conditions, for a specified length of time and for a specific purpose.
- Availability (A) of a system is defined in Storey [6] as ‘the probability that the system will be functioning correctly at any given time’ i.e. the probability to perform the operations that are required from it whenever they are requested. This characteristic is closely related to system reliability: for a

system to be reliable, that is, for it to operate according to its specifications, it will have to deliver the services that are required from it at any given time.

- Maintainability (M) in Storey [6] is defined as ‘the ability of a system to be maintained’ and ‘Maintenance is the action taken to retain a system in, or return a system to, its designed operating condition’. Maintainability is thus crucial for system availability, as the latter depends not only on the frequency of system failure but also on the time necessary to return it to normal operation.
- Safety (S) is defined in IEC [2] as the ‘freedom from unacceptable risk’. It is, then, the avoidance of situations which compromise human, environmental or material integrity.

This paper focuses on reliability and safety, since availability and maintainability are deeply connected with reliability, and the latter could be said to comprise both of them taking into account methods and techniques that are beyond the scope of this discussion.

### 3 CENELEC standards related to RAMS

In the railway sector, the standards that deal directly with the assurance of system RAMS are CENELEC EN 50126 [3], EN 50128 [4] and EN 50129 [5]. These standards are all based on IEC 61508 [2], which is a generic international standard applicable to all kinds of industry. IEC 61508 is divided in seven parts; the third part (IEC 61508 – 3: Software Requirements) deals with software development requirements, and the seventh part (IEC 61508-7: Overview of techniques and measures) explains in greater detail the different techniques and measures mentioned in part 3 which can be used throughout the software development process. Some parts of standard EN 50128 are based on it.

EN 50126 defines a development process which facilitates efficient reliability, availability, maintainability and safety management (RAMS management). This standard illustrates a series of activities to be carried out throughout the development of a system in order to achieve the levels of reliability, availability and maintainability that are required for a particular level of safety. However, only those stages that are directly related to safety (preliminary hazard analysis, hazard log, etc.) appear to have more specific recommendations. The rest of the stages of the development process (in the case of SIL1 and SIL2) do not significantly differ from those commonly followed in general projects with a high quality management. Standard EN 50126 is also being thoroughly revised at the moment.

In order to achieve the required safety level, the standard 50126 proposes a lifecycle which is, to a great extent, based on hazard analysis in the wider sense of the term, that is, understanding hazard analysis as a set of tasks that are carried out throughout all the stages of the development of the system, starting with a preliminary hazard analysis and the creation of a hazard log, establishing a plan for hazard mitigation, carrying out a fault tree analysis, etc. However, as Leveson [7] highlights, hazard analysis techniques have a series of limitations:

- Limitations related to model construction:
  - They often make unrealistic assumptions; for instance, that the system is developed according to appropriate engineering standards, testing is perfect and repair time is negligible, operators and users are experienced and trained, operational procedures are clearly defined, key events are independent and random and so on.
  - Unknown phenomena cannot be covered in the analysis.
  - Discrepancies between the written documentation and the real system mean that important causes of accident may not be considered.
  - The boundaries of the analysis are drawn incorrectly and relevant subsystems, activities, or hazards are excluded.

In general, there is no way to assure that all factors have been considered.

- Limitations related to simplifications of the modelling techniques: continuous variables treated as discrete variables, the ordering of events, inability to represent particular aspects of the system, and so on.
- Limitations related to the fact that the analysis represents the analyst's interpretation of the system, who may inadvertently introduce bias, especially when the system under analysis is complex.

The standard EN 50129 specifies the requirements for the acceptance and approval of electronic safety systems in the field of railway signalling. Moreover, it states what evidence of safety and quality management must be provided, as well as the required functional and technical safety levels, so that the system can be accepted and approved.

The standard EN 50128 is specific for railway software. It defines the software development process and its requirements, specifying the techniques and methods that have to be used in order to satisfy system requirements depending on the appropriate safety integrity level. Nevertheless, these techniques and methods, particularly those specified for levels 1 and 2, are not very demanding to comply with, so it would be reasonable to work on this area in order to establish a set of more specific requirements that guarantee a better overall system performance. The EN 50128 standard is also under revision.

The deficiencies mentioned above make it necessary to research into further techniques and methods for the development of software that ensure a safer and more reliable final product.

## 4 Strategic opportunities

Two relevant circumstances have configured the opportunity to make up for the deficiencies referred to in the previous section.

- All parts of the most important functional safety standard, IEC 61508, are under revision. In particular, dealing with software RAMS, it is interesting to highlight parts three (IEC 61508-3/Ed.2) and seven (IEC 61508-7/Ed.2), from which an important part of CENELEC EN 50128 is derived. Sometime after the start of the process of writing the new edition of IEC 61508, the update of CENELEC standards EN 50126 and EN 50128 has also started.



This update also involves the creation of new parts of each of these standards.

- New European documents about the Common Safety Methods (CSMs) and Common Safety Targets (CSTs) must be created by the Safety Team of the European Railway Agency (ERA): One of the objectives of the railway sector nowadays is the interconnection of railway networks within the European Union. This has led the European Commission to request that a set of common safety criteria are created for all Member States to abide by. The ERA has accepted this commission to develop the Common Safety Methods (CSMs) and Common Safety Targets (CSTs) that shall apply to all systems once they have finally entered into force in the near future.

Given the fact that these two circumstances will necessarily imply the adaptation of the railway sector of European industry, the time is ripe to carry out a detailed analysis of the more promising techniques and methods and to highlight those that prove effective.

#### **4.1 IEC 61508-3/Ed.2 versus EN 50128**

The IEC 61508 [2] is the general standard for the functional safety of electrical/electronic/programmable electronic systems. This standard consists of seven parts, most of them directly related to the railway standard EN 50128, though the latter is differently organized and is also related to other standards.

Annex A of EN 50128 [4], which is normative and is entitled ‘Guide to the selection of techniques and measures’, consists of a series of tables associated with all the clauses defined in the standard, which identify the techniques and measures that help develop a system that conforms to the standard. To the right of each of these techniques and measures, there are recommendations for or against them for each of the safety integrity levels (mandatory M, highly recommended HR, recommended R, no recommendation for or against -, or positively not recommended NR). This annex is based on annexes A and B of IEC 61508-3, though it has more severe recommendations for SIL3 and SIL4. For this reason, changes to the recommendations of techniques and measures in IEC 61508-3/Ed.2 may lead to changes in the tables of Annex A of EN 50128.

Besides the changes to annexes A and B, IEC 61508-3/Ed.2 incorporates several new annexes (C to G), which could also have a direct impact on a hypothetical new edition of EN 50128, even though these new annexes are of informative nature. Among them, Annex C (‘Properties for systematic software safety integrity’) is considered to be of special relevance. It relates the techniques and methods defined in annexes A and B to the properties for systematic software integrity; these properties are achieved according to the degree of rigour with which those techniques and methods are applied.

The most significant differences between the second edition of IEC 61508-3 and the previous one are briefly stated below, together with references to the way standard EN 50128 ([4]) deals with these issues:

- Greater emphasis on traceability between different stages of the development process (set to HR for all SILs), e.g. between system safety and

software safety requirements, between software safety requirements and software architecture, between software safety requirements and software design, etc. EN 50128 recommends the use of a traceability matrix in verification for SIL1 and SIL2, and considers it highly recommended for SIL3 and SIL4.

- The use of automated software generation is recommended in Table A.2, which deals with software architecture design. No reference to this is made in EN 50128.
- Object oriented design is marked as either recommended or highly recommended in Table A.4 on detailed design, while the first edition of the standard made no reference to it at all. EN 50128 simply categorizes it as recommended.
- The use of test management and automation tools is recommended in Table A.5, which covers software modules testing and integration. EN 50128 does not comment on these tools.
- Software failure analysis techniques are explicitly added among failure analysis techniques (Table B.4) under the heading 'Software functional failure analysis'. However, no particular techniques are described, so they remain to be specified. No allusion to these techniques is made in EN 50128.
- Among semi-formal methods (Table B.7) new techniques on entity-relationship-attribute data models and message sequence charts are mentioned for the first time. EN 50128 does not refer to them.
- Static analysis of run-time error behaviour and techniques related to time analysis, such as worst-case execution time analysis, are added to static analysis (Table B.8). These are not considered in EN 50128.
- New techniques related to the modular approach are mentioned for the first time in the second edition of IEC 61508-3 (Table B.9 on software complexity control), recognizing that reliability is negatively affected by complexity. There is no allusion to this whatsoever in EN 50128.

Some of the new techniques and measures have not yet been defined in detail (marked as 'TBA' -to be announced- in the text). They are supposed to be described in a new edition of IEC 61508-7, since all the techniques and measures mentioned in part 3 are explained in part 7 (EN 50128 [4] includes them in Annex B).

One of the highlights of the new edition of EN 50128 (prEN 50128:2009) is the inclusion of the new criteria for the selection of techniques and measures proposed in IEC 61508-3/Ed.2. Another interesting improvement is the incorporation of a series of new annexes, such as annex B (normative) – Key software roles and responsibility, and annex C (informative) – Documents control summary and document flow diagrams. Being normative, Annex B includes new requirements for the development process, considering the different professional roles involved in it. Another annex, D, compiles the new techniques proposed in this standard (similar to those of IEC 61508-7).

Standard EN 50126 is also being thoroughly revised at the moment. One important modification related to software development is the inclusion of a new part which is specifically focused on software (EN 50126-5: Railway

applications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Part 5: Functional Safety – Software). However, the authors of this paper have not had access to the draft by the moment of writing this revision. The new version of the standard will presumably be available by 2011.

The publication of IEC 61508/Ed.2 is due on April 2, 2010, whereas the new edition of EN 50128 will be published in January 2010. Given the simultaneity of their update processes, it is unlikely that there will be significant differences between the two standards. EN 50128 might be more demanding or restrictive than IEC 61508-3, but not the other way. The publication of the new parts and the update of the existing ones of EN 50126 is due in March 2011. It will be interesting to analyze the contribution of EN 50126-5 to software functional safety with regard to the requirements established by then in the two standards mentioned above.

It is important to highlight the fact that the new versions of these software safety-related standards will bring about significant improvements in reliability and safety in the railway sector.

## 4.2 CSM-CST

The European Commission has established a series of regulations and set a new policy that aim at unifying the railway sector in order to improve its performance and competitiveness. An important objective of this policy is the development of a common approach to railway safety, which comprises the setting up of Common Safety Methods (CSMs) and Common Safety Targets (CSTs). Both CSMs and CSTs are being gradually introduced in order to ensure that a reasonable level of safety is maintained throughout the process and that the means to improve that level are provided when necessary.

According to the European Railway Agency (ERA), CSMs define risk evaluation and assessment methods that help to determine whether the required safety level has been achieved. They cover different areas:

- Risk assessment, consisting of the identification of hazards and the specification of safety measures associated with them, as well as the safety requirements that result from those measures and the demonstration that the system complies with the safety requirements specified.
- Hazard log management. All significant changes made to the system have to be registered in a hazard log whenever they are produced and their progress has to be tracked; hazard logs will also register new hazards or new safety measures when they are identified.

The projects SAMNET and SAMRAIL were launched at the request of the European Commission for the improvement of European railway safety. The results of these two projects have been used by ERA as a starting point for the development of the CSMs (Mihn [8]).

CSTs are the safety levels that the railway system, as a whole, and each of its parts have to reach. These levels have to be specific, measurable, achievable and realistic, and have to be reached within a certain period of time.

According to the agenda proposed by ERA, the final results of the project will be available in 2010. Previous results were published in 2007 and 2008 ([9, 10]).

## 5 New techniques for the assurance of reliability and safety

The aim of this section is to highlight some techniques that look promising in a first approach, though they only represent a fraction of the many possible techniques available:

- Software Fault Tree Analysis (SFTA) (Lyu [11]). Fault tree analysis (FTA) is a widespread technique used to ensure the safety of safety critical systems. It considers all the potential damages associated with a system and tracks them backwards so as to determine the events which could have caused them. Incidents records from similar systems are crucial as a starting point for the analysis. Although this technique has traditionally been applied to hardware analysis, it can provide excellent results if used to analyse the software component of systems. Each potential failure of the software can be considered, evaluating its possible causes and representing them in a fault tree model. Tracking the events which may lead to an undesired consequence helps to define the module or modules of the system affected by it, so that appropriate action can be taken to minimize or eliminate the risk.
- Software Failure Mode and Effect Analysis (SFMEA) (Storey [6]). Failure Mode and Effect Analysis is a methodology that attempts at identifying all possible failures of a system or a component or feature of a system, often at different levels, considering their possible causes and studying their consequences. In FMEA, a categorization of failures is made according to the seriousness of their consequences, so that the measures taken to reduce failures focus on those with a higher priority first. Even though this technique is commonly used for the assessment of safety in hardware systems, it can prove very useful too if applied to software systems or components.
- Artificial Intelligence for Software Reliability Engineering (Lyu [11]). There are different artificial intelligence techniques that are used for estimating software reliability, such as neural networks or fuzzy logic. Neural networks are mathematical models that interconnect and process information. They consist of nodes, which represent processing units, connected by means of mathematical functions. Their strength lies in the possibility to apply them to make predictions given a set of preliminary observations and solutions. This technique could bring about very positive results if it is applied to the assessment of software reliability.
- Markov chains (Lyu [11]). Markov chains represent the transitions between different states (failure-success) in systems, assuming that the probabilities of those transitions do not depend on previous states, but are only determined by the initial and final state. It is a useful technique to predict the reliability and availability of a system.

- Software reliability growth model [11]. The aim of reliability growth models is the construction of a model that represents the evolution of system failures detection, based on data of failures detected during the previous testing stages in order to predict the reliability of the system in operation. Because of the particular characteristics of software, it may not be possible to use traditional system reliability growth models to predict software reliability, so it would thus be interesting to adapt these reliability growth models.

Over the last few years, the most predominant approach in research focuses on the automation of the techniques for the improvement and the assurance of safety. Most of these proposals combine the automation of one or more techniques for safety analysis, such as SFTA or SFMEA, with model driven development (MDD) so that the analysis of system safety is fully integrated into the development.

There are various different lines for the development of these ideas, each of them focusing on a different stage or group of stages of the development process. Among them, the following ones can be highlighted: the work of M. Towhidnejad, D.R. Wallace and A.M. Gallo [12] whose proposals focus on the analysis of software at the design level, the approach of M.A. de Miguel, J.F. Briones, J.P. Silva and A. Alonso [13] who use several tools for modelling and in order to implement a UML profile for the representation of safety characteristics, the work of Y. Papadopoulos and D.J. Parker [14] on the automatic synthesis of FMEA from diagrams which have component failure information attached to them, and the methodology for the evaluation of software risk at the requirements level proposed by the team of K. Appukkutty, H.H. Ammar and K.G. Popstajanova [15].

## 6 Conclusion

As this paper has highlighted, software is becoming the most critical part of safety critical systems. The use of new techniques for the attainment of higher software reliability and safety values is necessary in order to get a better performance of the system as a whole in terms of reliability and safety.

Some of the techniques that have been mentioned in previous sections have already been in use for years. It is necessary to analyze them thoroughly to check what their actual effect on systems is, at least in the industrial sector. In fact, it would be interesting to study them in the context of the railway sector, which is the area of focus of this paper.

- Since system failures are very often due to faulty requirements specifications, the improvement of the system's specification would lead to higher software reliability and safety.
- Analysis of experiences for safety assurance in the European railway sector, as well as in other areas, such as the nuclear and the aeronautic sectors.
- The techniques and methods specified in the first and second sets of CSMs.
- The study of other standards, such as 60300, which also discuss techniques and methods for the improvement of system reliability and safety.

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## ERTMS Level 2: effect on capacity compared with “best practice” conventional signalling

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### Abstract

This paper reviews potential capacity benefits attributable to ERTMS Level 2 compared with UK Multiple Aspect Signalling (MAS), tests scope for their exploitation against the practicalities of preparing a comprehensive timetable for a suburban rail network, and proposes simulation experiments to confirm the benefits.

The UK is preparing for adoption of ERTMS Level 2, System D, as its standard signalling system. At the same time growth in passenger demand deriving from privatisation and socio-economic factors is continuing at levels beyond those forecast by conventional planning models, and major expenditure to cater for demand is becoming necessary. It is widely hoped that ERTMS will offer capacity benefits to help cater for demand in the medium term. A variety of claims for the potential capacity increases deriving from ERTMS Level 2 have been made. Many are felt to be simplistic or optimistic.

Effects of ERTMS Level 2 System D are seen to arise principally in the context of reduction of line headways. Compared with UK MAS, headways are expected to be reduced by cab signalling normalising block boundaries once lineside signals are eliminated, and from division of the train safety separation into shorter signalling blocks. However, line headways are only one factor in determining the capacity of a network, and other crucial factors are largely unaffected by the chosen signalling system.

The practical potential of the likely benefits is then tested for plausibility against the example of the commuter operation serving London's Charing Cross station. A 10% increase in capacity is found to be plausible, but only so long as outputs from unrelated projects can be assumed, and track circuit arrangements are redesigned for the purpose. Some methods of operation, and public expectations of the type of service, must also be modified.

*Keywords: signalling, operations, capacity, ERTMS.*



## 1 Introduction

Pressure on capacity of the UK rail network continues to increase. Passenger journeys in 2007 amounted to 1.2 billion, an increase of 7.8% on the previous year, whilst passenger miles exceeded 30 billion for the first time since 1946. The point appears to have been reached at which major expenditure to increase capacity is becoming inevitable, initially through lengthening of trains and through infrastructure work at bottlenecks. Work to increase the capacity of the Thameslink cross-London North-South route with improved signalling and additional tracks at London Bridge is in hand, and a project to create the new London East-West Crossrail route has been authorised.

In the longer term there is growing pressure to consider new capacity in the form of high speed lines for long-distance services, although double-deck solutions for existing lines are probably ruled out by infrastructure constraints and the relatively small capacity benefit achievable within UK vehicle dimensions.

Against this background, it is essential that capacity benefits attributable to ERTMS are on the one hand exploited to the full as an option for comparison with other major infrastructure solutions, and on the other hand are soundly based, to ensure that theoretical benefits can be realised in practice.

ERTMS Level 2, System D, is emerging as the preferred UK option. Although the principal benefits on which its adoption is predicated are safety and the reduced cost of equipment compared with conventional signalling, it is likely that some capacity benefits will need to be identified in order to formulate a positive business case for the adoption of ERTMS.

A variety of estimates have been made for the potential capacity benefits of ERTMS. However, in simply assuming that benefits claimed will transfer in practice to the UK context, considerable uncertainty is encountered. For instance, Invensys [1] suggests that ERTMS Level 2 on the High Speed Line Córdoba-Málaga will enable 24 trains per hour, compared to the current Spanish national system capacity of 7.5 trains per hour. However, the figure suggested for ERTMS seems to be a theoretical maximum, whilst the comparison appears to be made with a historic actual figure, rather than with best practice conventional signalling if applied to the new line. In the UK, the Strategic Rail Authority and Railway Safety and Standards Board [2] describe the potential capacity benefits of System D as “significant”, offering an “increase by potentially up to 1 in 10 train paths”.

First, the basis for comparison of many claims needs to be clarified. UK 4-aspect signalling has been in use since 1925. Since then, standards for the system have evolved to find a sophisticated balance between safety and capacity. In intensively-worked areas such as the South London suburban lines, the signal engineers have become extremely skilled in exploiting the system to best advantage. So long as the signals are located exactly as required to provide the braking distance for the intended maximum speed, and trains actually run at that speed, theoretical headways are remarkably low, around 90 seconds on 4-aspect signalling for 160 kph trains, and little over a minute at half that speed [3]. In

claiming benefits for ERTMS, comparison needs to be made with this highly-evolved best practice.

Then, contrasting with many networks, that of the UK retains a widespread mixed traffic capability operating over complex track layouts. The South London suburban system sees significant, and growing, use by freight trains, serving both Channel Tunnel and seaborne container flows, and domestic traffic such as aggregates for distribution in the London area, or dredged from the Thames Estuary for use outside London. Many routes are limited to double track, but still have to carry both fast and stopping passenger trains, and frequent junctions with only limited grade-separation are a legacy of the evolution of the network.

## 2 What is “capacity”?

Many assessments of capacity are simplistic, using the technical headway to calculate line capacity glibly in terms of “trains per hour”, and are inadequate in the face of the realities of a complex, multi-purpose network.

For each line in a network, the signalling system sets the “headway” - the minimum possible interval between trains that avoids restrictive signal aspects. The headway is constrained by the realities of lineside signals, which must be clearly visible to drivers of approaching trains, not just the wrong side of bridges or tunnels, or out of sight round curves in cuttings. We tend not to place signals in the middle of station platforms so as not to stop trains frustratingly half in and half out of stations. Access for maintenance may militate against placing them in tunnels or on viaducts, which also avoids the risk of trains being stopped at locations that passengers might find unnerving. As signal sections cannot be shorter than is necessary to give braking distance, all these problems can only lead to longer sections and thus longer headways, and the worst group of sections sets the headway for the route.

All in all, once the signalled headway has been rounded off for the convenience of timetable planners, and some allowance made for robustness in practice, a 200 kph line will probably end up with a planning headway of 3 minutes, and line on a suburban route, 2 minutes.

That is all well and good for one line in isolation, and for a continuous flow of trains running at the full permitted speed, but hardly describes any real railway system. In practice, trains stop at stations, so that their dwell time, which is completely independent of the signalling, adds to the separation. And some trains stop at stations while others don’t, so that a wedge of unusable capacity builds up between a through train and a following stopping train.

This loss of capacity can be mitigated by “flighting” - running trains of the same speed in pairs or batches. However, intermediate stations may then find their stops concentrated into short periods, and a more passenger-friendly pattern may be laid down in franchise specifications at the expense of capacity.

Other factors combine to reduce the calculated capacity further. Flat junctions destroy opportunities to run trains simultaneously on conflicting routes. At each end of the line, trains need to turn back at terminal stations - the rate at which this can be done, determined largely by the turnround time and the number of

platforms, is normally much less than the rate at which each approach line might feed trains in or out. Finally, reality suggests it is unwise to work continuously to the limits of capacity.

So line capacity measured in “trains per hour” is really a technical abstraction, useful for comparing some details of signalling schemes, but for little else. In fact, terminal capacity is probably the binding constraint on usage of much of the UK national network.

The UK Institution of Railway Operators’ definition of network capacity, adopted in the Department for Transport’s Rail Technical Strategy [4] is:

*“The number of trains that can be incorporated into a timetable that is conflict-free, commercially attractive, compliant with regulatory requirements, and can be operated in the face of anticipated levels of primary delay whilst meeting agreed performance targets”.*

### 3 Charing Cross – a practical example

London’s Charing Cross station caters for inner suburban trains from South-East London and outer suburban trains from the county of Kent. The intensity of operations was recognised as long ago as 1922, when the South Eastern & Chatham Railway introduced its “parallel working” timetable, optimising the train service around critical junctions approaching Charing Cross where trains diverged to serve the “City” terminus at Cannon Street. This style of working persisted until 1975 when extensive track and signalling alterations, with a limited application of grade separation, allowed trains for Charing Cross and Cannon Street to be allocated to separate tracks 9.6km out, at Parks Bridge Junction.

Key features of the infrastructure approaching Charing Cross are:

- **Charing Cross station:** 6 platforms, worked as two groups of three, each group served by a pair of approach tracks, known as the “Fast” and the “Slow” lines, although the permitted speed on both pairs is 40 kph;
- The two pairs of lines continue through **Waterloo East station**, 1km from Charing Cross, with one platform per track. This is a major interchange location with trains at Waterloo Main Line station as well as the London Underground, and also serving directly growing employment areas in Southwark, and the areas North of the River Thames accessed by way of Westminster and Waterloo bridges. Passenger usage demands a typical dwell time of 1 minute;
- At **Metropolitan Junction** (2.2km), the two pairs of tracks converge into one at an at-grade double junction, and run as such for 0.26 km to just short of London Bridge station;
- Approaching **London Bridge station** (3km) the two tracks fan out into four “paired by direction”. The station provides interchange with Cannon Street services, and with the London Underground to access the growing employment areas in the former London Docklands. Passengers transferring off inner suburban and outer suburban trains from South London and Sussex also transfer onto Charing Cross and

Cannon Street trains. For commercial reasons, the objective is to maximise the number of trains that stop at London Bridge, although one of the two tracks in the “Up” (to London) direction has no platform face and is only used by through trains. Again, passenger usage including interchange is such that a dwell time of  $1\frac{1}{2}$  minutes is called for at peak times;

- Between London Bridge and **Parks Bridge Junction** (9.7km from Charing Cross) the Charing Cross lines reduce to a single pair once more, and run adjacent to a pair of tracks for Cannon Street trains. At Parks Bridge Junction itself, at-grade connections allow exchange of trains between the Charing Cross and Cannon Street lines, with some very limited grade-separation to access branches of the suburban network;
- Between Parks Bridge Junction and **Orpington** (22.2km from Charing Cross) the four lines run in pairs segregated “by use”, with the extension of the Charing Cross lines catering for through trains and stopping trains allocated to the extension of the Cannon Street lines. After Orpington, where many inner suburban trains terminate, the four lines converge into two;
- This double track continues to **Sevenoaks** (35.6km from Charing Cross), carrying outer suburban trains and remaining inner suburban trains serving intermediate stations. The section features two long tunnels and three intermediate stations. Sevenoaks is the limit for inner suburban services.

The net effect is a complex network with many at-grade junctions, carrying a mix of fast and stopping trains through two major interchange locations to a relatively small terminus.

Today, 30 trains arrive at Charing Cross in the busiest 60-minute period of the morning peak, even though, based on planning headway alone, the Fast and Slow lines immediately outside the station could feed in 48 between them (the situation is of course complicated by the short stretch of double-track between London Bridge and Metropolitan Junction, offering just one line for Up trains).

As Figure 2 shows, the three Slow line platforms work continuously through the peak of the peak at the minimum turnround of 7 minutes. With 3 minutes between occupations of each platform, this comes to 18 trains. This is just 75% of the theoretical capacity of the Up Slow line, which is set by the station stop at Waterloo East. Meanwhile, the three Fast line platforms handle only 12 trains, largely as many trains work back in service according to a clockface timetable rather than just at planned arrival plus 7 minutes. Even so, an average of 4 trains per platform per hour is fully comparable with other London terminals such as Victoria and Waterloo, and free time in the busiest hour equates to less than 5 minutes per platform.

Amongst the figures that have been suggested for the potential capacity benefits of ERTMS is 10%, a nice round number. So for 30 train-per-hour Charing Cross, that means three more, or 33 trains per hour on 6 platforms. Is that possible?

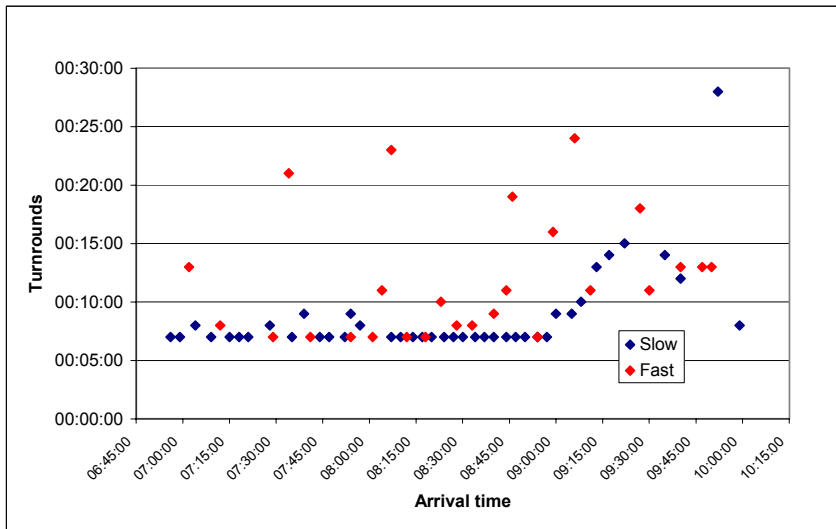


Figure 1: Charing cross morning peak turnrounds.

## 4 How might ERTMS help?

The features of ERTMS relevant to capacity derive essentially from cab signalling and Automatic Train Protection.

If lineside signals are done away with, the message to drivers becomes simply a safe speed at which to drive, calculated by the on-board computer and displayed in-cab. So a practical system could have shorter blocks, and more of them between trains, without the need to display different aspects and expect a driver to comprehend them - perhaps the equivalent of 10-aspect signalling. Some things follow immediately from this:

- Any fixed block system puts one more section between free-flowing trains than is actually required for braking distance. With a given separation provided by a large number of short blocks, this extra section adds less to the total separation – in effect, the benefit of 4-aspect signalling compared with 3-aspect, taken to extremes.
- By decoupling block boundaries from the constraints of sighting lineside signals, block lengths can be closer to the theoretical minimum, minimising excess separation. We might, however, still be reluctant to split tunnels into more than one section, but is this really valid in these days of central door locking, good lighting, open stock and public address systems?
- With lineside signalling, trains running on greens are separated by the full braking distance for the maximum permitted speed, even if their own permitted speed is lower and their required braking distance shorter. ERTMS can give an unrestricted “movement authority” to a slow train on the basis only of the braking distance it actually needs,

rather than the worst case (probably the fastest) train, so a flight of slow trains can run with less time-separation than fast trains.

- Given the Automatic Train Protection functionality of ERTMS, the risk of misjudged braking is virtually eliminated, so signal overlaps might be reduced significantly or even abandoned, further reducing separation.

So ERTMS potentially reduces headways, if track circuit arrangements and block boundaries for ERTMS Level 2 are redesigned specifically, rather than simply being ported over from the previous conventional schemes. All things considered, a 3-minute planning headway on 4-aspect signalling might become 2 minutes under ERTMS.

That sounds excellent - line capacity goes up from 20 trains per hour to 30. The problem is that very few lines with 3-minute headways now actually carry anything like 20 trains per hour, for all the reasons of junctions, differing speeds, and terminal capabilities outlined above. ERTMS will do very little for those problems.

With regard to the mix of train speeds, the underlying issue is one of differing running times, not of headway. True, at the point where trains enter a “corridor”, a slow train might follow a fast a bit more closely to start with, but the lost capacity on route will not change. Perhaps once the fractions of minutes mount up, another complete train might be run, but which sort of train – another fast, another stopper, or what? The benefit of improving headways is only felt when trains of the same speed and stopping pattern follow each other.

At junctions, some benefit might be found. Without signal overlaps, the last block boundary before a junction can be closer to the point of conflict than a fixed signal would be. With route set only as far as necessary for braking distance, slow trains could approach the point of conflict more closely before the interlocking needs to “deny” it to other trains. “Advisory speeds” may allow regulation of trains short of the junction so as to coincide with a free path at the junction rather than stopping clear of the junction to wait for a path - particularly beneficial for freight trains with low rates of acceleration, and also offering environmental benefits by mitigating fuel consumption for restarting after a stop. But using one route over a point of conflict still prevents trains running on all conflicting routes.

And the ability of terminals to accept, turn and despatch trains will not change. In a suburban operation, the limiting factor is the time taken for drivers to change ends (crew changes at the terminus in the peak are not a good idea). For long distance trains, other factors come into play, such as servicing, as well as a greater robustness allowance.

## **5 Can these benefits be exploited in practice?**

Now consider the actual constraints on capacity in the example of Charing Cross and the lines that feed it. ERTMS may well improve line headways, but can this show a benefit given other constraints such as terminal capacity, junctions, and the mix of train speeds?

In terms of platform capacity at Charing Cross, the answer is easy – the Fast platforms will have to work as hard as the Slow platforms. The clockface timetable will be at risk, and outer-suburban trains will have turnrounds as short as inner-suburban. The extra trains will have to be formed of rolling stock that can inter-work with the outer suburbs. In theory that gives us six more trains per hour, but let's not overdo things.

Work back from Charing Cross itself, and see what other constraints arise. Waterloo East comes next, where all trains stop. Again the Fast Lines could do what the Slow lines already do, in terms of frequency of service.

The problem comes at Metropolitan Junction, where the two-track section from London Bridge changes to four "paired by use". That means a diamond crossing, where the 18 trains up the Slow line have to cross the Down workings on the Fast line which, on the basis that what goes Up must come Down, now total 15. 33 trains per hour over a diamond crossing is a lot, even though the current Rules of the Plan allow 2 minutes separation, with 1½ minutes "not for successive moves". Exploiting that to the full with 33 trains would lead to the diamond being locked out for 58 minutes out of 60 – too high for a reliable service. But if overlaps short of junctions can be eliminated, and speed of trains controlled to keep them moving, maybe ERTMS brings enough to make it realistic.

But first the 33 trains have to use the one Up line from London Bridge, and we must assume the headway benefits of ERTMS will allow this.

Once the Thameslink Project is implemented, at London Bridge there will be two platforms for Up Charing Cross trains, needing to handle 16 or 17 each per hour. This is less than the current single Up Charing Cross platform does now off-peak when almost all trains call, albeit with off-peak dwell times. However, we can hope that peak dwell times will reduce - there will be 10% more trains to carry the passengers, and the project will improve station accesses, distributing passengers better. And as signal locations are currently heavily constrained on this complex layout, we can also hope that ERTMS will reduce platform reoccupation times.

Below London Bridge, headways effectively set capacity, as the intermediate station platforms are on the Cannon Street lines. We can reasonably hope for success, at least until we get to Parks Bridge Junction. Here trains are transferred between the Fast and Slow lines so as to sort them out for Cannon Street and Charing Cross. The numbers of trains making these crossing moves will increase, as the 10% increase we are aiming for should apply to Cannon Street as well, and much will depend upon how well the pattern of service exploits scope for parallel moves. This is a big unknown, especially as, to make the London terminal work, clockface patterns are jeopardised.

From Orpington to Parks Bridge, headway is again the main constraint on the Fast lines, although usage is lower as the network fans out into branches. But trouble starts again below Orpington, where the line via Sevenoaks is only double track, and capacity is limited by the speed differential between fast and stopping trains. The fast headway is already 2 minutes, and there are long tunnels

in which we may still want to limit the number of trains. The likelihood of being able to run three extra trains over this section in one hour is low.

But with the Thameslink Project to help at London Bridge, some doubts at Parks Bridge Junction, and some heroic assumptions about signal overlaps, a 10% increase in trains can be made to sound plausible - in the inner suburban area.

But our starting point was that the extra trains at Charing Cross would have to be capable of working round with outer suburban trains. So what limits the potential of ERTMS in this thought-experiment is a commercial desire to have trains that suit the passengers they carry, just the sort of trap in the realities of preparing a timetable that is overlooked by glib talk of “trains per hour”.

## 6 How to refine this analysis

First and foremost, some decisions need to be reached in respect of safety standards. Will elimination of signal overlaps be permitted given the Automatic Train Protection functionality of ERTMS? Will we feel able to place block boundaries in tunnels or on viaducts with the risk of trains being stopped in such places? Decisions in this respect have not yet been made.

Given these decisions, however, it is quite a simple application of a simulation package to derive new Rules of the Plan – line headways, junction margins, and (crucially) platform reoccupation times.

Then comes the essentially human task of timetable planning. It is all very well identifying a bit of capacity here and a bit there – but to put a train in a timetable, these bits have to link up into a conflict-free path, with platform slots at origin and destination, and a return path out of the terminus back to the origin or a stabling point. And unless such a path can actually be incorporated into a timetable, “capacity” cannot be said to exist.

The key role for simulation returns of course in analysis of the robustness of the resulting timetable. Additional trains will be operating over sections of the network that are fundamentally unchanged, eroding spare capacity. Even where ERTMS can influence the capacity, the fact that additional trains are running will exacerbate the effect of line blockages. Appropriate functionality will also capture the impact of system response times and probabilities of communication breakdown - “dropped calls”.

## 7 Conclusion

In the complex and intensively-worked area that was the subject of this “thought experiment”, an increase in operational terms of 10% in the number of trains run given ERTMS Level 2 is found to be plausible, albeit it at the upper extreme of plausibility.

However, this conclusion depends upon intensification of terminal workings to accommodate additional trains, requiring standardisation of the rolling stock fleet between inner and outer suburban trains, which may not be commercially



acceptable. Completion of planned infrastructure changes at London Bridge also needs to be assumed.

The conclusion also requires adjustment of standards, principally the effective elimination of signal overlaps, which has not yet been accepted.

Robustness of the intensified service is appropriately tested by simulation, once a timetable has been prepared.

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# Enhanced ETCS\_L2/L3 train control system

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## Abstract

The last decade has seen the development of the European Train Control System ERTMS/ETCS. This Automatic Train Protection system (ATP) was designed in three versions: ETCS\_Level 1, 2 and 3. ETCS\_Level\_3 uses moving blocks and provides short headways. However, ETCS\_Level 2 may also offer short headways provided suitable length of each block sections.

The proposed train control system could be seen as an enhancement of ETCS-Level 2 or Level 3. The main advantage of this new control system is to provide shorter headways than ETCS can. This offers the potential for capacity increases, particularly for busy High Speed Lines (HSL).

*Keywords: ATP, braking curves, capacity, ETCS, ERTMS, headway, high speed line (HSL), interlocking, moving block, Semi-Automatic Train Operation (SATO).*

## 1 Interoperability, safety and capacity with ETCS

### 1.1 ETCS for interoperability and safety

The European Train Control System was firstly developed to offer to the European Rail community a common Automatic Train Protection system in replacement of the existing ones. In theory, this is needed urgently as more than

Table 1: ETCS and some ATP spot transmission.

	Crocodile (France, Belgium)	KVB (France)	Indusi, PZB (Germany)	ETCS L1 and higher
Transmission system	Electric through mechanical contact	Transponder	Magnetic	Transponder

15 different and incompatible ATP systems equip the European main rail networks (cf. table 1) [1], which obviously precludes interoperability.

The Eurobalise is a local transponder providing trains with a lot of information on the downstream route attributes and speed limits. It could replace any kind of balises or contacts used today by ATP-systems on conventional lines. It makes it possible to implement a continuous speed control, in particular between the distant signal and its corresponding main signal. ETCS is thus able to offer safety levels that are higher than many of the ATP systems currently in service through Europe.

On high-speed lines, the cab-signalling is compulsory, and ATP-systems are logically coupled with cab-signalling. The cab-signalling that is part of ETCS is named Eurocab. Euroradio, a radio system using at this time a GSM-R layer, makes the transmission of signalling information from ground to Eurocab on high speed lines. The main advantage of using radio transmission is its ability to transfer high amount of data in both directions without installing equipments in the tracks (cf. table 2).

Table 2: ETCS and high speed line signalling systems [2].

	TVM 430 (France)	BACC (Italy)	LZB (Germany)	ETCS L2 and higher
Data transmission	coded track circuit		trackside cable	radio transmission
Data flow limitations	mono-directional		bi-directional	

## 1.2 ETCS and line capacity

The limitation of railway line capacity on conventional lines without cab-signalling is mainly due to the fact that the stop distance of a train must be shorter than the cumulative length of only a very few block sections.

If we consider a route at level gradient and a constant deceleration, the minimum headway between two similar trains succeeding at the same speed  $v$  is

$$h_{\min} = t_w + \frac{\left(1 + \frac{1}{n}\right) \cdot v}{2 \cdot d} + \frac{L_o + L_t}{v} + t_i \quad [\text{sec}] \quad (1)$$

with:  $t_w$ =watching time [sec],  $n$ =number of block sections needed by a train to stop from ceiling speed,  $d$ =safe mean deceleration [ $\text{m/s}^2$ ],  $v$ =speed [ $\text{m/s}$ ],  $L_o$ =overlap length [m],  $L_t$ =train length [m] and  $t_i$ =interlocking time [sec].

With cab-signalling, the number of block sections  $n$  can be raised substantially. For trains running at 300 kph, and if we consider standard values for trains and infrastructure, splitting the stopping distance into 6 instead of 5 blocks reduces the minimum headway by only 3 seconds!

As headways may already be significantly shortened, with the sole use of cab-signalling and short track sections, solutions like CIR-ELKE [3], LZB or ETCS\_L2 [4] offer already a high capacity level.

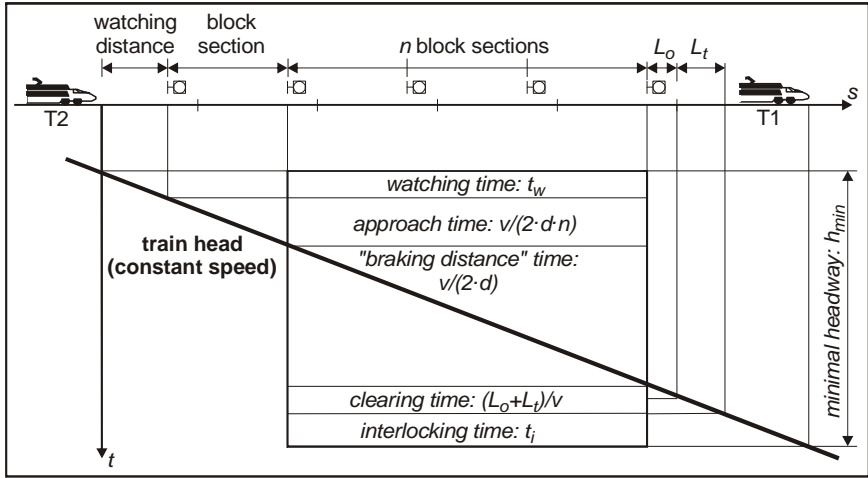


Figure 1: Minimal headway.

Pushing  $n$  asymptotically towards infinity and using standard values for some fixed variables, eqn (1) tends to its simpler form (2):

$$h_{\min} = \frac{v}{2 \cdot d} + \frac{500}{v} + 10 \quad [\text{sec}] \quad (2)$$

with:  $d$ =safe mean deceleration [ $\text{m/s}^2$ ],  $v$ =speed [ $\text{m/s}$ ],  $L_o$ =100m,  $L_t$ =train length=400m, and  $t_w+t_i$ =watching, interlocking and system time=10sec.

Actually, additional capacity gains by the use of moving block, as proposed by ETCS\_L3, are relatively small compared to ETCS\_L2 [4, 5]: the maximum saving is about 10 seconds ( $n \gg 6$  versus  $n=6$ ) at 300 km/h.

At high speed, minimum headway is mainly determined by its component related to the braking distance (the initial part of eqn (2):  $v/(2 \cdot d)$ ). Thus, if deceleration could not be much increased, the only way to further reduce significantly the minimum headway is to accept operation based also on relative braking distances. The purpose of the following sections is to present a possible implementation of a concept combining absolute and relative braking distances.

## 2 REBAD: to get over the absolute service braking distance

### 2.1 Absolute and relative braking distance

Classic block systems or today moving block systems use absolute service brake distances to separate the trains (cf. fig.2-A-Case). Such systems ensure that in front of each running train there is a cleared distance at least equal to a full stopping distance.

On the other hand, a system of train separation based on relative braking distances considers that a part of the braking distance, needed by the following

train, could be occupied by the preceding one. This part is supposed to be released early enough, before the arrival of the second train (cf. fig.2-B-Case).

The main problem with relative braking distances is the risk that the second train collides with the rear end of the first train that has been brought to a sudden halt (accident) or decelerated with an unexpectedly rate. It should be noticed that some secondary risks on double track lines are nowadays already accepted. This may be the case of a derailing train that fouls the gauge of the opposite track. This is not a reason however to accept extra secondary accident risks, particularly if a first accident would immediately be followed by several consecutive accidents involving trains following each other on the same track.

The regulation distance  $R_d$  is a buffer distance depending on the rate of transmission of information from train T1 to train T2, of the speed, and of the performance of the traction-brake control system of train T2.

**2.2 Running and braking with REBAD**

The novelty of REBAD (“Running with Emergency Brake Absolute Distance”) is to combine absolute braking distance with relative braking distance in order to reduce the train separation time between trains following each other. Parameters adopted by REBAD must be chosen in a way that no secondary accidents could occur.

REBAD is not a new level of ETCS but could become a new mode of running under ETCS\_L2 or L3. As described below, running in REBAD mode is not easy (speed docking, speed regulation, short reaction time, etc.). Then, this mode should be considered as an SATO mode.

When two trains run at almost the same speed, two secure modes of running at minimal headway are possible (cf. fig. 3)

The adhesion conditions must be taken into great consideration, in particular to determine the minimal deceleration guaranteed by the emergency braking system. For evaluations made here, the Emergency Brake minimal Deceleration  $EBmd$  is considered to be slightly lower than the Service Brake Maximal Deceleration  $SBMD$  (cf. fig 4).

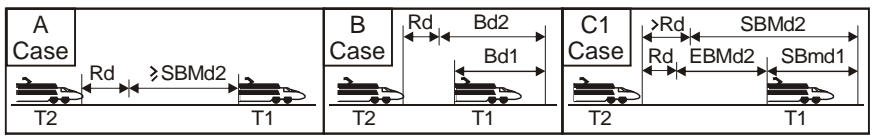


Figure 2: Running at absolute or relative braking distances. A Case: at service brake absolute distance. B Case: at service brake relative distance. C1 Case: at emergency brake absolute distance.  $R_d$ : regulation distance, 1: train T1, 2: train T2,  $SBMd$ : Service Brake Maximal distance,  $SBmd$ : Service Brake minimal distance,  $Bd$ : Braking distance and  $EBMd$ : Emergency Brake Maximal distance.

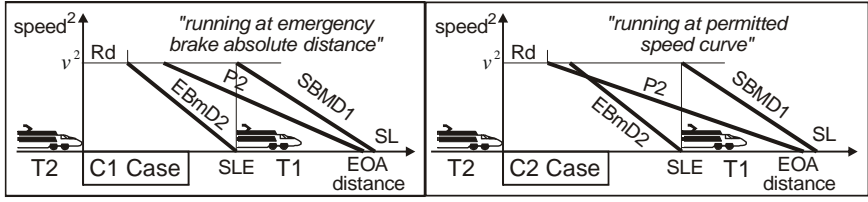


Figure 3: Two cases of very short successions of trains in REBAD (EOA: End of Authority, SL: Supervised Location, SL-EOA=L<sub>0</sub>=Overlap, SLE: Supervised Location in case of Emergency). Rd: regulation distance, 1: train T1, 2: train T2, EBmD: Emergency Brake minimal Deceleration, P: Permitted Speed Deceleration and SBmD: Service Brake Maximal Deceleration.

The condition to be in the C1-Case is:

$$\frac{P2 \cdot v^2}{2 \cdot L_0 \cdot P2 + v^2} - \frac{EBmD2 \cdot SBmD1}{EBmD2 + SBmD1} > 0 \quad (3)$$

In practice, this inequality may or not be true, so we have to keep on considering both C1 and C2 Cases.

The C2-Case providing longer headways than the C1-Case, C2-case is kept for comparison of headways between ETCS\_L3 and REBAD. At 300km/h minimal headway with REBAD could be shorter of about 45 sec [5].

In normal operation, the worst case to deal with is when train T1 has a Service Brake Maximum Deceleration SBmD1 better than the following train T2. One must be sure that the Service Brake minimum Deceleration SBmD2 of train T2 is high enough to always maintain the absolute emergency braking distance between the rear-end of T1 and the front-end of T2.

In the C1 Case, with  $v_1$  being the original speed,  $v_2$  the target speed,  $v_2 < v_1$ , and  $SBmD2 < SBmD1$ , the absolute emergency braking distance is respected if

$$\frac{v_1^2 - v_2^2}{2 \cdot EBmD2} \geq \frac{v_1^2 - v_2^2}{2 \cdot SBmD2} - \frac{v_1^2 - v_2^2}{2 \cdot SBmD1} - v_2 \cdot \left[ \frac{v_1 - v_2}{SBmD2} - \frac{v_1 - v_2}{SBmD1} \right] \quad (4)$$

with: Rd: regulation distance, 1: train T1, 2: train T2, SBmD: Service Brake Maximal Deceleration, SBmD: Service Brake minimal Deceleration, and EBmD: Emergency Brake minimal Deceleration.

This inequality is true for instance with  $v_2 = 0$  as long as SBmD2 is at least the half of EBmD2 and the half of SBmD1.

In the C2 Case, the inequality is given by:

$$v_2 \cdot (v_1 - v_2) \cdot \frac{SBmD1 - P2}{SBmD1 \cdot P2} \geq 0 \quad (5)$$

This inequality is true if SBmD1 is greater than P2.

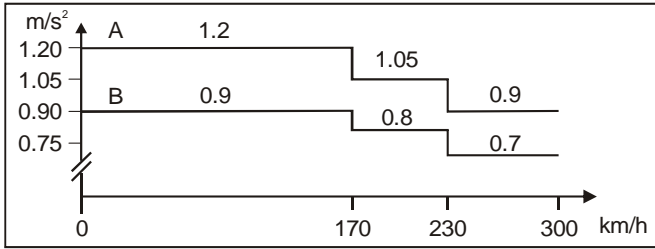


Figure 4: Emergency Brake minimal Decelerations EBmD [6]. A: with certain equipment isolated. B: as A plus unfavourable climatic conditions.

At this point we have to remember that decelerations are not constant but vary a lot according to the type of brakes, coordination of the braking systems, speed, gradients, and action of wheel-slide devices. So decelerations have to be calculated according to a braking model (cf. fig. 4) [6-8].

With the electro-pneumatic brake system EP for high speed train sets, the equivalent time of brake application is about 3 seconds.

The stopping distance from 300 km/h to 0 km/h following the B-curve is 4'690m, and the minimal mean deceleration for an emergency braking is 0.74 m/s². This value is impacted by gradient.

### 2.3 Regulation distance and emergency braking in REBAD

The regulation distance  $R_d$  is crucial to engage in time the braking of train T2 if needed. Information has to be transmitted every couple of seconds from train T1 to train T2 directly or through the RBC (cf. fig. 5). In a train sequence, the train that follows should permanently adapt its speed to the one that leads, in order to ensure that it is able to stop before reaching the rear of the preceding train. The status of the preceding train is also needed by the following one in order to start an emergency brake if necessary.

### 2.4 From ETCS\_L2/L3 to REBAD and reverse

The change from REBAD to ETCS\_L2/L3 is quite easy; the only thing to do is to fix the SL of the following train, till the previous rear end train passes this point. At contrary, the change from ETCS\_L2/L3 to REBAD needs speed docking procedures.

## 3 ETCS\_L2, ETCS\_L3 and REBAD

### 3.1 ETCS curve family, SBMD and EBmD

According to the most restrictive static speed profile of the track and of the train, and considering the braking performances of the train, the onboard ETCS computer calculates at least 6 braking curves (P, W, SBI, SBD, EBI, EBD) and

perhaps also the indication curve I, or the guidance curve GUI that may replace the P curve [9].

REBAD uses the same group of curves in order to supervise a usual stop at an EOA (End of Authority) or the required speed at a LOA (Limit of Authority).

However REBAD demands the computation of two new curves. The first one, using the service brake maximum deceleration SBMD, is needed for determining the minimum distance a train could run with full application of service brakes. This value will be used to determine the EOA of the following train.

The second one, using emergency braking minimum deceleration EBmD, is needed for determining the maximum distance the train runs with application of emergency brakes. This value will be used to determine how close a train could follow another one.

### 3.2 Main data exchanges with ETCS\_L2, ETCS\_L3 and REBAD

For migrating from ETCS\_L2 to ETCS\_L3, two challenges have to be dealt with:

- accurate acquisition and reliable transmission of train location;
- certainty of train integrity and reliable transmission of the information.

To achieve REBAD, we need:

- to gather not only the location but also the accurate speed of trains and to transmit them reliably;
- to additionally transmit train status parameters.

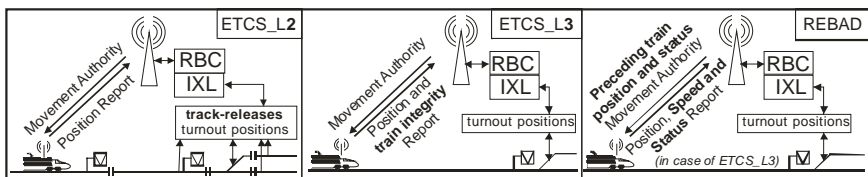


Figure 5: Main exchanges between ground and trains for ETCS\_Level 2, ETCS\_Level 3 and REBAD.

### 3.3 The needs for new ETCS messages for REBAD

The Train Position Report provided by ETCS\_L2 and ETCS\_L3 contains already data about position, speed and train integrity (Packet 0 or 1 - Message 136 - [9]). However, speed is not accurate (given in 5 km/h steps).

For REBAD, some new parameters should be added to the train position report:

- the minimum distance to stop with full use of service brakes;
- the status of the train. This information may be given by either the Yes/No value coming out from the emergency onboard unit, or by transmitting all the input data of this unit (cf. table 3).

The status of a preceding train must be regularly built up and transmitted to the following train. The interruption of the transmission to the following train should trigger a service braking and eventually, if the transmission is not restored, an emergency stop.



Table 3: Inputs and outputs of some onboard units.

Units	ETCS_L2	ETCS_L3	REBAD
<b>ODO</b> (ODOMetry) <u>Outputs:</u> Position, Speed Acceleration	<u>Inputs:</u> Wheel sensors, Radars, Accelerometers, Balises, etc.	<u>Input:</u> same as for L2	<u>Input:</u> same as for ETCS_L2 and L3
<b>TIN</b> (Train Integrity) <u>Output:</u> Yes/No	---	<u>Inputs:</u> Braking pipes pressure sensors, Train loops, etc.	<u>Input:</u> if necessary: same as for ETCS_L3
<b>EME</b> (EMERgency) <u>Output:</u> Yes/No	---	---	<u>Inputs:</u> Acceleration TIN output, Braking pipes pressure sensors, Derailment sensors, Emergency brake interventions

The movement authorities and the train status of the preceding train must be transmitted to the following train very often and in a safe way. One has to pay attention to the safety and capacity of the GSM-R transmission. Perhaps the transmission of a train status to its following train could also bypass the RBC.

## 4 Application case: facing points on a high speed line

Considering two trains running with REBAD with a minimal headway and a facing point on a high speed line, three cases are possible.

### 4.1 Both trains stay on the same track

In this case, the two trains locked the turnout during a certain time. When the first train clears it, the turnout must continue to be locked by the second train.

### 4.2 First train takes the diverging route

In this case, the position of the turnout has to be changed after the first train clears the turnout. The second train will lose a minimum of time if its speed is regulated some time before. The advantage of REBAD versus ETCS is also visible in this case: as soon as train T1 clears the turnout, the second train could be at full speed at location P1 (cf. fig. 6-a).

### 4.3 Second train takes the diverging route

In this case, the position of the turnout has also to be changed after the first train clears the turnout. The need of a specific speed regulation is depending not only on all parameters visible in figure 3 but on the speed difference between ceiling speed  $v_c$  and diverging speed  $v_d$  as well. The greater is the difference, the smaller

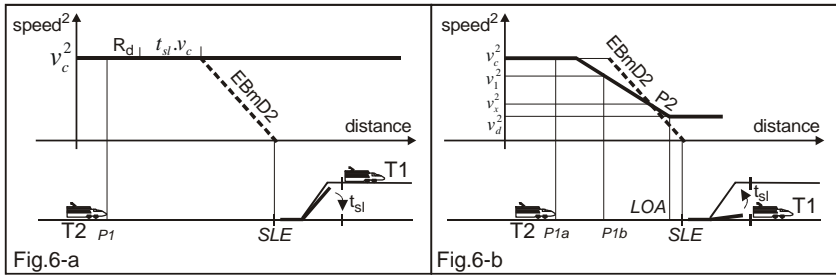


Figure 6: Change of position of a turnout under the protection of an emergency brake curve.  $t_{sl}$ : maximal time needed to switch and lock the turnout.

is the probability to need a specific speed regulation. Figure 6-b shows a case in which  $v_x$  is between  $v_c$  and  $v_d$ . For a low  $v_d$ , a short diverging speed, a brief  $t_{sl}$ , and a large difference between EBmD2 and P2, train T2 must not overrun location P1b when T1 leaves the turnout. In other cases, it is the location P1a that has to be considered.

## 5 Conclusion

With the combination of service brake relative distances and emergency brake absolute distances, REBAD provides a performing mode of running. This new mode, using an SATO system, allows not only schedulers to introduce shorter buffer times during timetable construction, but offers also significant savings of time in case of operational disturbance, in particular for high speed lines.

This enhanced mode, however, should be turned off in some peculiar circumstances, such as under very bad adhesion conditions.

## 6 Acronyms

ATP	Automatic Train Protection
BACC	Blocco Automatico di Corrente Codificato
CIR-ELKE	Computer Integrated Railroading – Erhöhung der Leistungsfähigkeit im Kernnetz
EOA	End of Authority
EBmD	Emergency Brake minimal Deceleration
EBMd	Emergency Brake Maximal distance
ERTMS	European Railway Train Management System
EP	Electro-Pneumatic
ETCS	European Train Control System
ETML	European Train Management Layer
GSM-R	Global System for Mobile communications - Railways
GUI	Guidance Curve
HSL	High Speed Lines

I	Indication Curve or Indication point
INDUSI	INDUktive ZugSIcherung
IXL	Interlocking
KVB	Contrôle de Vitesse par Balises
LOA	Limit of Authority
LZB	LinienZugBeeinflussung
P	Permitted Deceleration
PZB	Punktförmige ZugBeeinflussung
RBC	Radio Block Centre
REBAD	Running with Emergency Brake Absolute Distance
SATO	Semi-Automatic Train Operation
SBmD	System Brake minimal Deceleration
SBMD	System Brake Maximal Deceleration
SBmd	System Brake minimal distance
SBMd	System Brake Maximal distance
SL	Supervised Location
SLE	Supervised Location in case of Emergency
TSI	Technical Specification for Interoperability
TVM	Transmission Voie-Machine

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# European experiences with ERTMS implementation: the case of the high-speed railway Amsterdam-Antwerp

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## Abstract

The high-speed railway Amsterdam (The Netherlands)-Antwerp (Belgium) is nearly completed. As part of a TEN-T priority project it will connect to major metropolitan areas in Northwest Europe. High-speed railways have been built in many (European) countries. So, at first sight, the development of this particular high-speed railway should be relatively straightforward, but the situation seems to be more complicated. Full interoperability is necessary in order to run direct international services. However, there turned out to be compatibility problems that are mainly caused by the way decision making has taken place, in particular with respect to the choice and implementation of ERTMS, the new European railway signalling system. In this contribution major technical and institutional choices, as well as the choice of system borders, that have all been made by decision makers involved in the development of the high-speed railway Amsterdam-Antwerp will be analyzed. This will make it possible to draw some lessons that might be used for future railway projects in Europe and other parts of the world.

*Keywords: high-speed railway, interoperability, signalling, metropolitan areas.*

## 1 Introduction

Two major new railway projects were initiated in the past decade in The Netherlands, the Betuweroute dedicated freight railway between Rotterdam seaport and the Dutch-German border and the high-speed railway between Amsterdam Airport Schiphol and the Dutch-Belgian border to Antwerp (Belgium). Both projects were severely delayed. The Betuweroute railway was opened in the summer of 2007. Since December 2008 regular daily services have

been running. Regular passenger services started on the Amsterdam-Rotterdam and Antwerpen-Noorderkempen sections of the high-speed line in September and June 2009, respectively. Cross-border services wait for the arrival and testing of new and upgraded train sets. Serious problems with respect to the installation of the European Rail Traffic Management System (ERTMS) are responsible for the delayed introduction of new services.

The anchor point of our contribution is the question whether the technical, institutional and organisational setting of the project was to a certain, maybe even a considerable, extent responsible for the delays. The Dutch parliament had the impression that the Ministry of Transport, Water Management and Public Works in The Netherlands, the project supervisor in The Netherlands, did not do its work well enough. Our study for them [1] dealt in particular with the following questions:

- How did the project delays occur?
- Could these delays have been prevented and if so, how?
- What lessons can be learned from this project for new, large-scale infrastructure projects in the future?

This contribution deals with the high-speed line connecting Amsterdam Airport Schiphol and Antwerp. Building a high-speed railway may be a new phenomenon for The Netherlands, but this is not the case in other (European) countries. In these countries high-speed passenger trains have already been operating for several decades. Until now high-speed trains in The Netherlands have used conventional tracks only for services to France (Thalys trains) and to Germany (ICE trains). The maximum speed is limited to 140-160 km/h only instead of 200-300 km/h. As a consequence, passengers do not (fully) benefit from the main benefit of these trains: fast and comfortable transport of passengers over long distances [2].

This contribution consists of the following sections. An overview of the project is given in section 2. In section 3 ERTMS technology is compared with proven technology, while in section 4 the institutional choice of PPP is compared with traditional contracts and in section 5 the choice of the national boundary as the project boundary is compared with system boundaries as project boundaries. Finally, in section 6 the main conclusions of this contribution can be found.

## **2 The high-speed railway Amsterdam-Antwerp and ERTMS**

The sub- and superstructure of this railway was built between the years 2000 and 2006 [3]. It consists of conventional (Amsterdam-Schiphol, Rotterdam station, Breda station and Antwerp-Brussels) and high-speed sections (see Figure 1). The railway is part of the 'Priority Project No. 2' of the Trans-European Transport Networks (TEN-T), also known as the 'high-speed railway Paris-Brussels-Köln (Cologne)-Amsterdam-London (PBKAL)' (see Figure 2).

Harmonisation and standardisation of national railway networks is a critical precondition for efficient cross-border (high-speed) railway traffic. In reality, each railway network in Europe has its own dedicated systems. In this

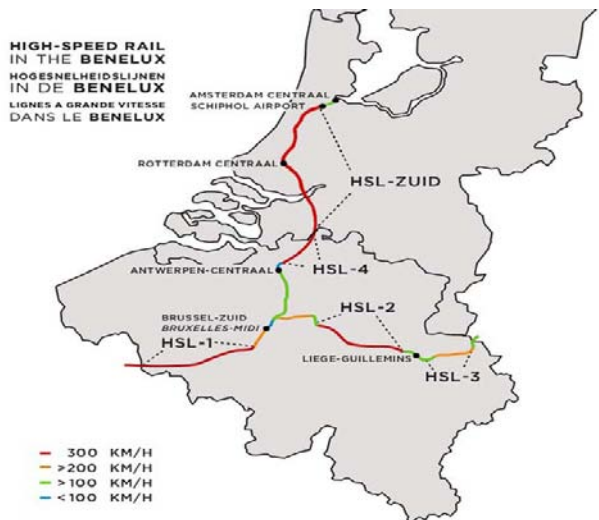


Figure 1: HSL-Zuid/HSL 4 [4].

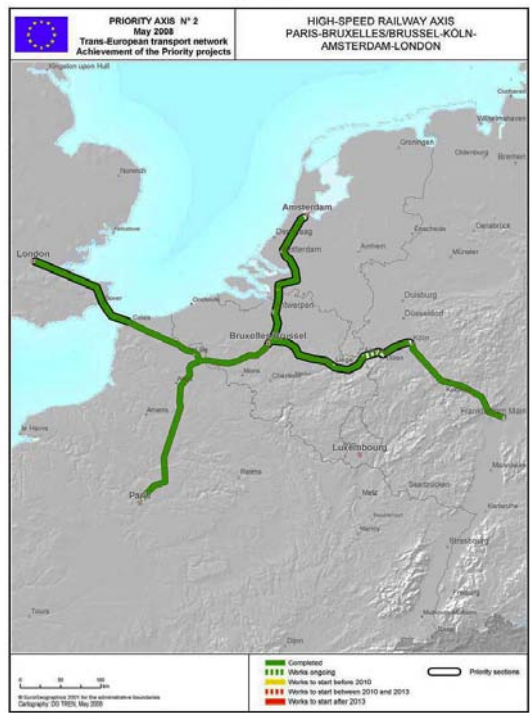


Figure 2: High-speed railway Paris-Brussels-Cologne-Amsterdam-London [5]. Note: the Liège-Köln section was put in operation in 2009.

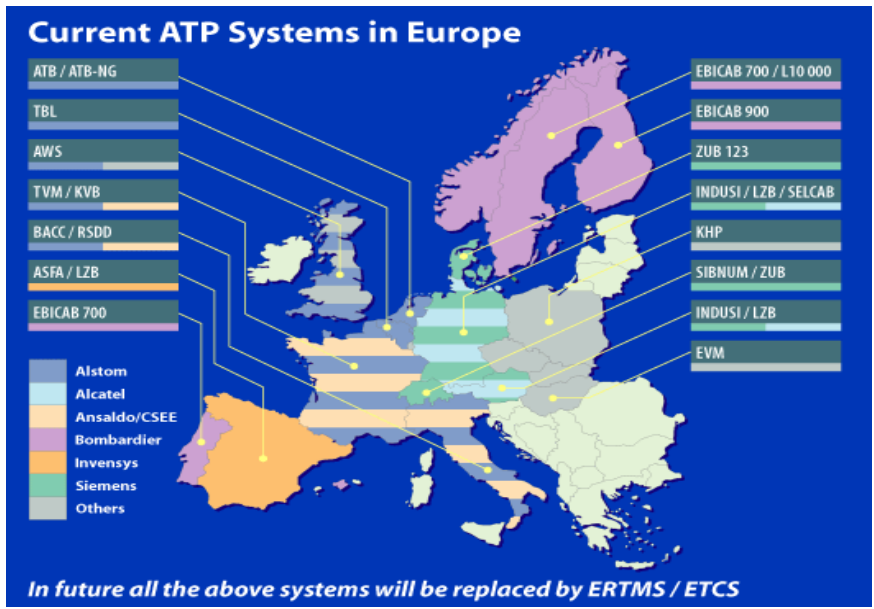


Figure 3: Signalling systems in Europe [6].

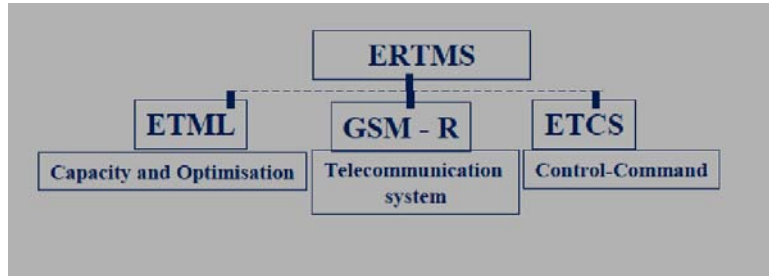


Figure 4: ERTMS layers [8].

contribution we will concentrate on one of the key problems: the existence of more than 20 different signalling and speed control systems ([6]; Figure 3).

Because of this, the engine of a direct international train service has to be equipped with all the national or regional systems attached to the tracks in the countries it passes. For instance, a Thalys trainset has seven different signalling systems on board: TVM (France), TBL (Belgium), LZB (Germany), ATB (The Netherlands), Crocodile/Krokodil (Belgium), KVB (France) and PZB/Indusi (Germany) [7]. TVM, TBL and LZB have been developed for use on high-speed railways and the other four systems are for use on conventional railways. This lack of standardization unnecessarily complicates train protection (with a potentially negative impact on safety) and it strongly increases the purchase and maintenance costs of rolling stock and infrastructure [7].

Table 1: ETCS levels and their function [4].

	Protection	Detection
Level 1	infrastructure	infrastructure
Level 2	train	infrastructure
Level 3	train	train

The introduction of ERTMS is financially supported by the European Commission.

ETCS currently exists in two major levels. Each level has different technical requirements and applications. To complicate matters, local variants and intermediate levels are allowed as well. A higher level involves less track side equipment, but more on-board equipment. This shifts the (high) costs of the signalling system from the infrastructure providers to the train operators. Table 1 gives an overview.

The migration to ERTMS is a long-term process in the case of existing lines. Suppliers of railway equipment are now introducing Levels 1 and 2. Level 2 is mainly introduced on new tracks and Level 1 on existing tracks [9]. Level 3 is regarded as an option for the future. Research into technical specifications is underway, but implementation is not foreseen before 2011 or even 2020 [10].

### 3 Railway signalling: ERTMS or proven technology?

The decision to deploy ERTMS on the HSL-Zuid was taken at a moment in time when only a (global) functional specification existed. The technical details were still under discussion, so there was no practical experience with the new technology and no de facto standardization. Hence, the Dutch choice added a major risk (and costs) to an already complicated project. On other (international) high-speed railways already proven signalling systems were deployed. The French TGV signalling system TVM, for instance, had been installed on Paris-Brussels, on the Channel Tunnel Rail Link to London and the LGV Est (as dual standard TVM430 and ERTMS Level 2 configuration for the Paris-Ost Frankreich-Süddeutschland (POS) corridor).

The Netherlands and Belgium contracted different suppliers for the development and installation of ERTMS on their respective railway sections. The functional specification of ERTMS left some margin for interpretation by the engineers of the supplying companies. As a result, the interpretations by Alcatel (for the Dutch part of the railway) and Alstom (for the Belgian part of the railway) turned out to be incompatible (next to this there is also incompatibility between certain train-side implementation and track-side implementations, which is not discussed in this contribution). To solve this serious problem, a ‘dedicated’ and costly solution has been found. It consists of a localized version of ERTMS (referred to as ‘Version 2.3.0 Corridor’) and a ‘gateway’ (computer) translating messages from one ERTMS system into the other. This dedicated solution shows that ERTMS standardization has not reached its final stage.



Table 2: Considered fall-back options for HSL-Zuid/HSL 4 and current other systems on the PBKAL corridor in 2005 [11, 12].

Route:	Contracted on HSL-Zuid and HSL 4:	Option: TBL2 on HSL-Zuid and HSL 4	Option: ATB-NG on HSL-Zuid TBL2 on HSL 4	Option: ERTMS L1 Overlay on existing tracks
Amsterdam-Schiphol Schiphol-Rotterdam CS Rotterdam Rotterdam south-border <i>Border NL-B</i> border-Antwerp	ATB-EG ERTMS L1+L2 ATB-EG ERTMS L1+L2  ERTMS L1+L2	ATB-EG ERTMS L1+L2/TBL2 ATB-EG ERTMS L1+L2/TBL2  ERTMS L1+L2/TBL2	ATB-EG ERTMS L1+L2/ATB-NG ATB-EG ERTMS L1+L2/ATB-NG  ERTMS L1+L2/TBL2	ATB-EG/ERTMS L1 ERTMS L1+L2 ATB-EG/ERTMS L1 ERTMS L1+L2  ERTMS L1+L2
Antwerp/Leuven-Brussels Brussels-Halle Halle-border <i>Border B-F</i> border-Lille-Paris	Crocodile-Krokodil (in Brussels: also TBL1) TBL2 TVM430  TVM430 (near Paris-Gare du Nord: KVB)			
Leuven-Liège Liège-border <i>Border B-D</i> border-Aachen Aachen-Cologne	TBL2 ERTMS L1+L2  ERTMS L1 PZB/LZB80			
Lille-Chunnel <i>Border (Chunnel) F-GB</i> Chunnel-London	TVM430 TVM430 TVM430 (near London-St. Pancras: KVB)			

In The Netherlands many alternatives have been studied. The initial idea was to temporarily use an existing system until ERTMS would become available. However, there was a high level of optimism among suppliers that ERTMS would be available soon. Then, intermediate solutions would only introduce additional risks and costs, hence the choice to directly implement ERTMS. Interestingly, when the Dutch contract was signed, it was still unclear whether Belgium would choose ERTMS on HSL 4 and, if so, from which supplier.

Since ERTMS was not a mature product, the discussion about the necessity and benefits of fall-back/overlay options continued. In 2003 TVM had been considered as such, just like the present implementation on the LGV Est [13]. It was rejected by the Minister of Transport then and again in his discussion with the future operator HSA in 2005. He considered the additionally installed ERTMS Level 1 (by Siemens) as a fall-back option. In November 2005 it also did not seem possible to install and certify one of three most promising fall-back options (TBL2, ATB-NG and ERTMS Level 1 Overlay) before the initially proposed opening date of April 1, 2007 [14]. Table 2 gives an overview.

In retrospect, a choice for the French dual standard approach, using TVM430 and ERTMS [13], would have been wise, because this would have allowed direct high-speed services from Amsterdam to Brussels, Paris, the Mediterranean and London (via Lille) (see Table 2). In addition, the delay in introducing services due to the upgrading of the existing Thalys trainsets would have been prevented. Later, a (mature) ERTMS Level 2 could have been added. Instead of ERTMS Level 2/Level 1, ERTMS Level 2/TVM could have been installed. Level 1 only allows operating speeds up to 160 km/h, while TVM allows 300 km/h. So, a different fall-back would not have introduced a speed penalty.

#### **4 Institutional arrangements: PPP or traditional contracts?**

In The Netherlands the HSL-Zuid project was developed by a public private partnership (PPP). This created a complex contract structure with three infrastructure projects and one transport project/concession [3]:

- separate infrastructure projects for sub- and superstructures and for the connections with existing track by different building conglomerates;
- an agreement between the Dutch government and the Infrasppeed consortium (including Siemens Nederland) to build the infrastructure. Another consortium was responsible for the connection with the existing network. Finally, the substructure project was divided into six agreements between the government and building consortia;
- a transport concession given by the government of The Netherlands to the High Speed Alliance consortium (HSA, consisting of Dutch railways NS (90%) and KLM Royal Dutch Airlines (10%)) for a period of 15 years.

The Belgian HSL 4 project has a totally different main structure of agreements:

- an infrastructure agreement (excluding signalling) between the national railway operator SNCB/NMBS and TUC RAIL [15, 16];
- an agreement about signalling between SNCB/NMBS and AILS (a consortium of Alstom and Siemens);

- a transport service contract, in which SNCB/NMBS is the service provider.

Infraspeed partner Siemens contracted Alcatel to develop ERTMS Level 2. In Belgium, ERTMS Level 2 has been installed by AILS partner Alstom. Siemens installed ERTMS Level 1 in The Netherlands (via Infraspeed) and Belgium (via AILS). The infrastructure provider in The Netherlands is ProRail, while Infraspeed is responsible for maintenance, renewal and development. In Belgium Infrabel takes care of the infrastructure. HSA has an exclusive concession as the only supplier of domestic rail services on HSL-Zuid. For cross border services, HSA has to co-operate with the Belgian SNCB/NMBS and the French SNCF. There is no direct connection between the Dutch infrastructure and transport agreements, which means that Infraspeed and HSA do not have contractual liability against each other. However, they have a legal obligation to match their agreements.

In the realm of liberalization, the Dutch government considered PPP as a goal, as such [17] using ERTMS as an opportunity to apply the concept. The Dutch choice did not match the Belgian preference for traditional contracts. The complex contractual situation in The Netherlands contributed to the problematic deployment of ERTMS in The Netherlands.

## 5 Project boundaries: national or system boundaries?

Another technical choice that increased complexity was the choice to connect the Dutch and Belgian projects at the national border instead of the system border. The latter is a point where the high-speed tracks connect with the existing tracks of the conventional railway system. If the system border would have been chosen instead, it would have been much easier to connect the signalling systems. This would have meant a connection of signalling systems in Rotterdam and Antwerp. This would also have saved a Radio Block Centre.

The division of the project into two parts could have been avoided by The Netherlands in the 1996 treaty with Belgium. The Netherlands asked for a route that uses the Belgian territory over a much longer distance than initially intended by Belgium, in order to make Breda an additional high-speed train stop. Belgium accepted this only after The Netherlands agreed to pay the additional costs of NLG 823m (about EUR 373m) [17]. So, The Netherlands have paid a substantial share of the cost of the Belgian HSL 4 without using this favourable position to demand one integrated project with technical standardization where possible. Belgium, on the contrary, used the opportunity to ask even more from The Netherlands by linking the negotiations about this project with several other 'open' infrastructure cases. It also may have missed the opportunity to achieve economies of scale and reduction of costs due to shared tendering.

## 6 Conclusions and recommendations

The problems that arose when ERTMS was implemented on HSL-Zuid/HSL 4 result from specific choices regarding technology and institutional arrangements.

Our retrospective analysis has shown that alternative choices could have been made, enabling mitigation or prevention of such problems.

A first important option would have been a joint project by The Netherlands and Belgium instead of two completely separate projects. A joint tender could have produced economies of scale, hence lower costs. The Netherlands have paid a substantial part of the HSL 4, but did not use this as leverage in the negotiations with Belgium. A positive example is the joint Austrian-Italian project for the Brenner Base Tunnel (BBT), a 55 km long railway tunnel beneath the Brenner Pass, for which a so-called European Economic Interest Group was established [18].

A second option could have been to choose a proven signalling system as an intermediate system. TVM would have been the best option, as HSL-Zuid/HSL 4 connects with France and the Thalys trains are also of French origin. As soon as ERTMS would have become fully available, it could have replaced TVM as the primary signalling system. What happened instead is that the risk of major parts of the product development of ERTMS became concentrated in the HSL-Zuid/HSL 4 project.

A third option is the choice in favour of traditional contracts instead of PPP. The institutional settings of the project in The Netherlands and Belgium were completely different. The separation between the infrastructure and transport contracts by The Netherlands did not really make sense, because it became much more difficult to implement a reliable signalling system. By putting the project mainly in the hands of private partners, The Netherlands have created an unnecessary contractual complexity, which in turn made co-operation with Belgium much more difficult. One of the results of this situation is that there are now two different interpretations of the ERTMS 'standard' (by Alcatel and Alstom) that will be connected in a rather synthetic way by an additional computer system.

Related with the third option is the option of using the system borders instead of the national borders as the project boundary. The choice of the national boundary as the system boundary is one of the main reasons why the whole project has been delayed for several years. If the project would have been developed as one international cross-border project, most, if not all, technical problems could have been prevented or at least mitigated substantially.

Finally, the Dutch government should improve its contracts with private companies. In this project the risks of development and implementation risks were mainly taken by the government, which is not a healthy situation. Balanced risk-sharing by means of what may be called technology-development contracts, approved by independent experts in the field, could ensure mitigation of many of the discussed problems.

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## **Analysis of braking performance for the definition of emergency braking intervention in ATP systems**

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### **Abstract**

A traffic management system is generally based on a set of supervision curves relating the permitted velocity of the train to the running distance, in order to ensure the respect of speed restrictions on the line by intervention of an emergency braking in case of train velocity exceeding the permitted one. The basic braking model defines a deceleration profile, which represents the train nominal braking performance, used to determine the stopping distance and to compare it with the available distance. This deceleration profile value has to be reduced using properly defined safety coefficients.

The paper describes the method that allows one to calculate the safety coefficient as a function of the safety target (in terms of probability of failure). The method is based on the braking performance probability distribution estimation, expressed as the ratio between the real and the nominal deceleration. This study permits one to evaluate the probability that the real deceleration is smaller than the one used in the basic braking model and then that the real stopping distance is longer than the one calculated by the braking model. This model can then be used to tune the value of the safety margin in order to obtain a certain probability of system failure.

The numerical procedure used to simulate the braking performance is based on the Monte Carlo method, which is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs. This method is often used when the model is complex, nonlinear, or involves several parameters.

*Keywords: deceleration distribution, Monte Carlo, safety margins.*

## 1 Introduction

The operation of traffic on a railway network necessitates a good control of the stopping behaviour of the trains using a signalling system. For the majority of train operations today, the main information the driver is given is via signals placed at regular intervals along the track ordering the train to stop before the danger point, for example: another train or switch. The necessity of optimising the traffic density and the new possibilities of technology have led to the design of on-board automatic train control systems that calculate, with data transmitted from the ground, the exact distance to prevent passing the danger point. The on-board automatic train control system computes a “safe” distance, represented by a “safe” curve function of the train speed, beyond which the train is not allowed to run. In case of a predicted overrun, emergency braking is initiated.

A new approach using modern probabilistic methods to determine unified safety margins on emergency braking [6,7] has been developed by the authors in collaboration with the UICb126-15 C group.

The braking curves are calculated on the basis of a braking model, that calculates train deceleration on the basis of some parameters (time, braking weight percentage, speed etc.). The deceleration used for the definition of the braking curves has to be ‘safe’, in other terms it has to assure that the actual braking performance of the train will be sufficient to guarantee the respect of the objective speed.

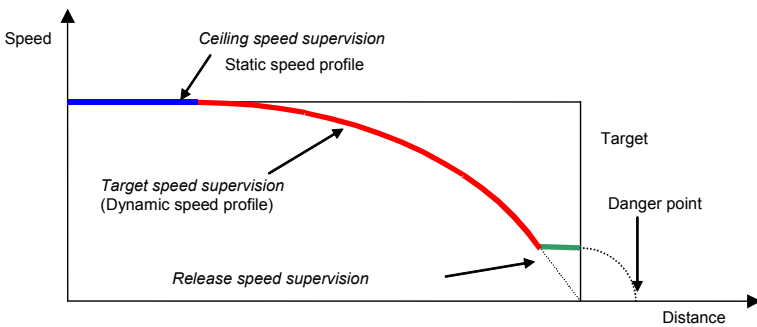


Figure 1: Example of a braking curve.

In general the deceleration profile during a braking can be represented as shown in Figure 2:

- an initial delay,
- a linear or step transient,
- a series of constant deceleration steps within established speed ranges.

As a particular case of that general representation, a braking model with a step transient is shown in Figure 2 b).

The basic parameters of this model are the following:

- $t_e$  braking equivalent time,
- $d_s$  deceleration of fully developed braking.

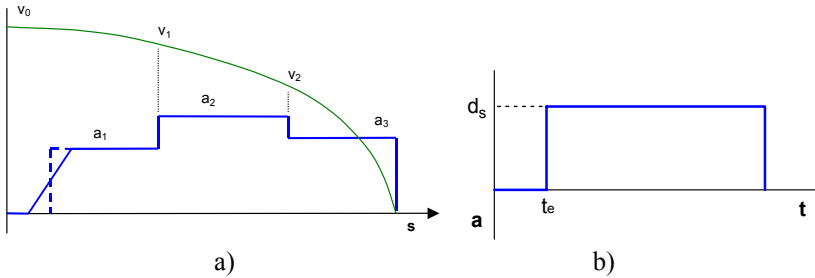


Figure 2: Deceleration profile during a braking, a) deceleration steps during a braking, b) single step profile, equivalent time and *safe* deceleration.

For reasons of simplicity this representation refers to the situation on level track. The complete model must obviously take into account the effect of the gradient on the deceleration. The fully developed deceleration is calculated reducing the nominal deceleration  $d_0$  (that depends on train braking properties) by a proper safety factor  $k_s < 1$ .

The model described in this paper calculates the statistical distribution  $p(k)$  of the ratio between the actual and the nominal deceleration  $k$ . Then, if a safety coefficient  $k_s = k$  is chosen for the braking intervention curve, the probability that the actual deceleration is lower than those used to calculate the curve (in other terms the probability that the train is not able to follow the braking curve) is  $p(k_s)$ . In other terms the model allows one to relate the safety coefficient to the probability of failure and thus can be used in two ways:

- given a certain safety coefficient, it allows to calculate the associated safety level (expressed in terms of failure probability):

$$p = p(k_s);$$

- given a certain safety target (expressed as an acceptable failure rate) the corresponding safety factor can be calculated:

$$k_s = k(p).$$

## 2 Model description

### 2.1 Parameters that influence braking performance

The actual braking performance of a train is different from the nominal one due to a number of causes. For example, the features of the braking evaluation method used to define the braked weight do not provide an absolute definition of the braking performance. The braked weight percentage corresponds to the mean stopping distance and is evaluated from a series of stopping distances that, even in nominal testing conditions (no gradient, normal efficiency of the braking system, good wheel-rail adhesion, etc.) present a certain statistical distribution. For a sufficiently high number of tests, the distribution of stopping distance can be approximated with a normal distribution.



Even if the actual braking performance corresponds to the nominal one at the characteristic speed used for the evaluation of the braked weight, often the braked weight percentage relative to different speeds differs from the nominal one. In the case of disc brakes, usually the stopping distances for speeds higher than the nominal one are lower than those resulting from the UIC diagrams. Conversely for speeds lower than the nominal one the opposite effect can happen, however this result is not taken into account in the UIC leaflet because these stopping distances result in an additional margin with respect to the signalling distances. However, for a speed control system the actual behaviour of the braking performance, even for low speed values, has to be taken into account.

On the vehicles, in particular those equipped with disc brakes, different friction components are generally used. Their friction coefficients have to be included in the tolerance range set by the UIC leaflet. The braked weight percentage is calculated on the basis of the nominal friction coefficient and then verified by tests. However different friction elements, with a friction coefficient different than the nominal one (within the UIC tolerance), could be used in future without varying the vehicles' nominal characteristics. Moreover, the composite brake elements are sensitive to temperature. For low temperature, in particular in winter, brake performance generally decreases, but also the temperature increase of the brake elements, due to repeated braking applications, can have a negative effect on the braking performance. The composite brake elements are also sensitive to humidity, and in case of rain or snow, the friction coefficient may decrease significantly.

The functional parameters of the braking, such as the brake pressure, brake rigging efficiency, braking intervention times, may have certain variability. Furthermore, in case of disc brakes, the variability of wheel diameters due to the wear of the wheels has an effect on braking performance [9,10].

The braked weight percentage of a passenger train is calculated for nominal load conditions. Therefore, the actual variability of the load has an effect on the braking performance of the train.

Wheel/rail adhesion coefficient has a sensitive effect on braking performance. Trains with a good braking performance, that requires an adhesion coefficient higher than those available on the line in wet conditions, are equipped with WSP devices that are designed to avoid the wheel locking up and to optimize braking performance [11,12].

The safety level of a UIC braking system is usually quite high; however the failure of a component has a given probability. For example, the failure of a distributor causes the loss of the braking force of the correspondent unit (vehicle or bogie). The effect of brake component failures on braking performance depends on train composition (its effect decreases as the length of the train increases).

In order to have a complete overview of braking performance the effects of all the above mentioned parameters have to be combined. The following section describes a numerical model that, given the probability distribution of the main parameters affecting braking performance, allows the calculation of the probability distribution of train deceleration.

## 2.2 Numerical procedure

The numerical procedure used to simulate the braking performance is based on the Monte Carlo method that is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs. This method is often used when the model is complex, nonlinear, or involves several parameters. The method can be summarized in the following steps:

- **Step 1:** Create a parametric model,  $y = f(x_1, x_2, \dots, x_q)$ .
- **Step 2:** Generate a set of random inputs,  $x_{i1}, x_{i2}, \dots, x_{iq}$ .
- **Step 3:** Evaluate the model and store the results as  $y_i$ .
- **Step 4:** Repeat steps 2 and 3 for  $i$  varying from 1 to  $n$  (number of samples).
- **Step 5:** Analyze the results.

The parametric (deterministic) model has a certain number of inputs and a few equations that use those inputs to give a set of outputs (or *response* variables).

The inputs for the deterministic mathematical model are randomly generated from *probability distributions*, previously defined, to simulate the process of sampling from an actual population, the randomly generated inputs are used to evaluate the outputs of the mathematical model and the data generated from the simulation are elaborated in order to be represented as probability distributions.

In the numerical approach the distribution of each parameter can have any arbitrary distribution that can be simulated by means of Monte Carlo techniques, “logic” parameters, like failure of a vehicle braking system can be easily inserted, and complex and highly non linear models can be easily reproduced. On the other hand the minimum value of probability that can be obtained depends on the number of samples used for the simulation, and the computation burden increases as the number of samples increases.

## 2.3 Parametric model description

This section shows the application of the model to a passenger train, only the pneumatic brake is considered in this example, however the model can be modified to take into account different types of braking (magnetic, electrodynamic etc.).

The ratio between actual and nominal deceleration can be expressed as:

$$k = \frac{d}{d_0} = \frac{\frac{F_b}{F_{b0}}}{\frac{M}{M_0}}, \quad (1)$$

where  $F_b / F_{b0}$  is the ratio between the actual and the nominal braking force, relative to the entire train, while  $M / M_0$  is the ratio between the actual and the nominal train mass. The ratio between the actual and the nominal value of the

braking force, relative to a train composed of  $n_v$  homogeneous vehicles is given by:

$$\frac{F_b}{F_{b0}} = \frac{1}{n_v} \sum_{i=1}^{n_v} \frac{F_{bi}}{F_{bi0}}; \quad (2)$$

while the ratio between the actual and the nominal value of the mass, relative to a train composed of  $n_v$  homogeneous vehicles is given by:

$$\frac{M}{M_0} = \frac{1}{n_v} \sum_{i=1}^{n_v} \frac{M_i}{M_{i0}}. \quad (3)$$

The ratio between the actual and the nominal value of the braking force, relative to a single vehicle, can be expressed as function of the ratios between the actual and the nominal value of the parameters whose variability have been considered in the study, for example, for a passenger train:

$$\frac{F_{bi}}{F_{bi0}} = \frac{\frac{p_i}{p_{i0}} \frac{\eta_i}{\eta_{i0}} \frac{\mu_i}{\mu_{med}} \frac{\mu_{med}}{\mu_0}}{\frac{D_i}{D_0}} \cdot B_{fail,i} \cdot A_i \quad (4)$$

where  $p_i / p_0$  is the ratio between the actual and the nominal value of the pressure on the brake cylinders,  $\mu_i / \mu_{med}$  is the ratio between the actual and the mean value of the brake friction coefficient,  $\mu_{med} / \mu_0$  is the ratio between the mean and the nominal value of the brake friction coefficient,  $\eta_i / \eta_0$  is the ratio between the actual and the nominal value of the brake efficiency,  $D_i / D_0$  is the ratio between the actual and the nominal value of the wheel diameter,  $B_{fail,i}$  is a coefficient that takes into account the failure of a brake component, and  $A_i$  is a coefficient that takes into account wheel/rail adhesion conditions, defined as:

$$A_i = \min \left( \frac{\rho_i}{\rho_{r,i}}, 1 \right). \quad (5)$$

in which  $\rho_i / \rho_{r,i}$  represents the ratio between the actual adhesion coefficient and the value required by the braking system. The “actual” adhesion coefficient  $\rho_i$  is defined as a function of the adhesion value relative to the first vehicle, randomly extracted from a normal distribution (Figure 3), and the position of the vehicle in the train: the adhesion increasing, due to the “cleaning effect” of the wheel on the rail, is described in the model by a parabolic law defined on the basis of experimental data, as shown in Figure 4.

The adhesion required by the braking system is given by:

$$\rho_{r,i} = \frac{d_i}{g} = \frac{1}{g} \left( \frac{d_{r,i}}{d_0} \right) d_0 = \left( \frac{\frac{p_i}{p_0} \frac{\eta_i}{\eta_0} \frac{\mu_i}{\mu_{med,i}} \frac{\mu_{med,i}}{\mu_0}}{\frac{M}{M_0} \frac{D}{D_0}} \right) d_0 \quad (6)$$

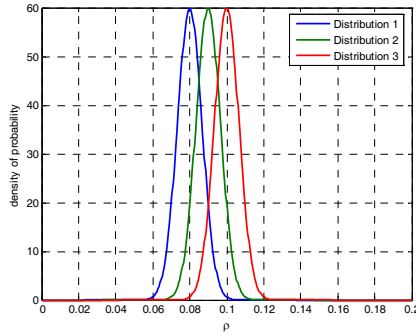


Figure 3: Available adhesion coefficient: probability density functions for the chosen distributions.

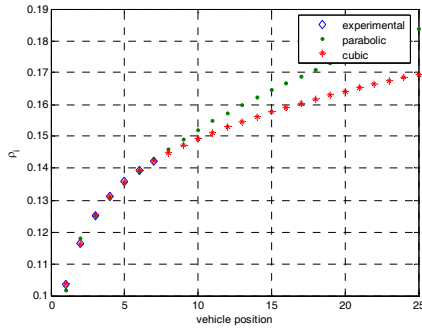


Figure 4: Reference adhesion increase along the train (relative to SNCF tests), extrapolation obtained with a parabolic and a cubic law.

where  $d_{r,i}$  represents the deceleration that the train would have in case of good adhesion conditions, that depends on the values assumed by the other parameters.

## 2.4 Numerical procedure

Given the probability distributions of the parameters affecting braking performances, the developed algorithm extracts from them random numbers and combines them, according to the mathematical model described in the preceding section, in order to obtain the deceleration value of a “simulated” train. This computation is repeated, for each train type and each train length, for a very high number of samples, up to  $10^9$ . At the end of the simulation then, for each test a set composed by  $10^9$  “virtual” trains is generated. The obtained results are then analyzed and the probability distribution of the ratio between the actual and the nominal deceleration can be found.

3 Applications and result discussion

As an example the results obtained simulating a high speed train composed of 8 vehicles are described in this section. Table 1 summarizes the parameters selected for the simulation. Table 2 and Figures 7 and 8 summarizes the results obtained in terms of *k* values. The results can be used to relate the safety coefficient to the failure probability, as it can be seen, for low probabilities

Table 1: Parameters for the simulation.

Variable	Distribution	Mean	Standard deviation or range	Notes
<i>Track properties</i>				
<i>gradient</i>	Not taken into account			
<i>First vehicle adhesion</i>	Normal	0.09	0.005	
<i>Adhesion increasing</i>	(derived from experimental data- parabolic law)			
<i>Degraded/good adhesion conditions</i>	20-80%			
<i>Number of vehicles</i>	Deterministic	8		
<i>Nominal deceleration</i>	Deterministic	1.3 m/s <sup>2</sup> (high pressure)		
<i>Mass</i>	Normal	1	0.013	<i>The same value for the whole train</i>
<i>Pressure</i>	Normal	1	0.02	<i>One value for each bogie</i>
<i>Efficiency</i>	Uniform	0.975	- 0.025 + 0.025	<i>The same value for the whole train</i>
<i>Friction</i>	Normal	1	0.015	<i>One value for each bogie</i>
<i>Mean friction</i>	Normal	0.95	0.045	<i>The same value for the whole train</i>
<i>Wheel diameter</i>	Uniform	0.97	-0.03 + 0.03	<i>The same value for the whole train</i>
<i>Failure probability</i>	10 <sup>-6</sup>			The failure is applied to a single bogie
<i>Partial brake failure</i>	10 <sup>-5</sup> for the high pressure stage			

Table 2: *k* ratio and deceleration as a function of probability.

probability	1.0E-08	1.0E-07	1.0E-06	1.0E-05	1.0E-04	1.0E-03	1.0E-02	1.0E-01
k	0.5873	0.6023	0.6230	0.6465	0.6728	0.7029	0.7411	0.8083
deceleration (m/s <sup>2</sup> )	0.7634 9	0.7829 9	0.8099	0.8404 5	0.8746 4	0.9137 7	0.9634 3	1.0507 9

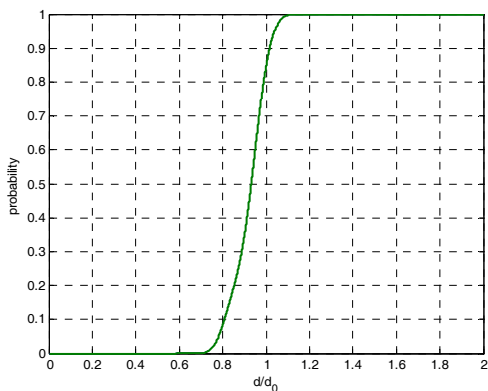


Figure 5: Simulated train, probability distribution of the ratio  $d/d_0$ .

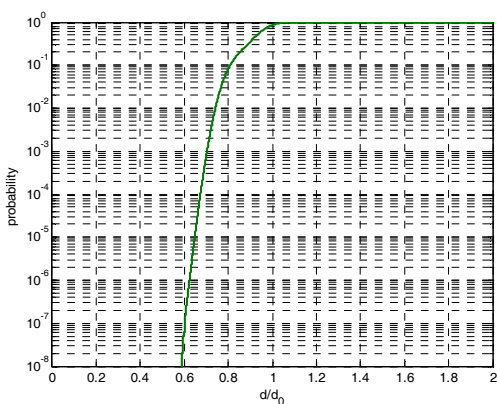


Figure 6: Probability distribution of the ratio  $d/d_0$  on a logarithmic diagram.

## 4 Conclusions

The method briefly presented above gives an overview of the possibilities of the probabilistic way to evaluate safety margins in order to guarantee an emergency braking performance or deceleration. This approach can offer a large number of advantages. First of all it gives the possibility to quantify the margins depending on the respect of a safety target (that is the probability to stop before the danger point). Furthermore the results are linked with the physical train brake characteristics, the reliability of its brake system and the precision of its brake performances. Thus, a train whose brake system is classified as high quality (in terms of reliability and efficiency) can benefit from narrower safety margins and a better emergency curve in the signalling system. Finally, the results can be compared with statistical on line data.

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# The impact of GSM-R on railway capacity

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## Abstract

The operation of railway systems strongly depends on the underlying train control system. ERTMS (European Rail Traffic Management System) is a project launched by the European Union in order to increase the interoperability of the national railway systems in Europe. One of the two main components of ERTMS is GSM-R, a wireless communication standard based on GSM.

In this paper, we focus on the stochastic nature of GSM-R communication failures and their possible impact on railway capacity. Firstly, we will compare the results of our newly introduced model to the results obtained with a standard blocking time model, applied by a couple of European railway infrastructure managers. After this validation of our model, we will then use the stochastic approach in order to evaluate the impact of GSM-R communication on the railway operation and railway capacity with ETCS level 3. We can show that ETCS level 3 indeed leads to a capacity increase in our setting. So, while a single GSM-R message may be more error-prone than traditional communication, the framework of ETCS can cope well with this imperfection.

*Keywords: ERTMS, GSM-R, ETCS level 3, railway capacity.*

## 1 Introduction

Railway systems know a long history of train protection and control, as to reduce the risk of train accidents. Many systems include some automated communication between train and trackside equipment. Several different, mostly national systems



emerged [1]. The different train control systems are still a major obstacle for cross-border rail traffic. Today, trains for cross-border traffic need to be equipped with all train control systems installed on the tracks that the train utilises during its journey. The European Rail Transport Management System (ERTMS) shall lead to a harmonisation of the European train control systems. It is one of the backbone projects to achieve higher interoperability between the different train control systems used in European countries in the hope to increase the share of rail transport on the overall transport in Europe.

ERTMS consists of two standards: the European Train Control System ETCS and the Global System for Mobile communication for Railway applications GSM-R [2]. Today ETCS is foreseen to have three levels (1, 2 and 3). Level 1 defines a standard for discontinuous train control with standardised hardware. Level 2 replaces traditional line side signals by transmission of movement authorities via GSM-R communication. It still operates on an infrastructure that is segmented into fixed blocks. Wendler [3] and Geiß [4] show that adapting the size of these fixed blocks increases the capacity of a line. ETCS level 3 further requires that trains report to the train control centre via GSM-R which infrastructure they have safely left. This provides the possibility to create a virtual block around a train. If GSM-R communication fails, the train control centre cannot reassign the infrastructure to another train and line capacity decreases.

As with many new developments, it is still difficult to estimate the impact of ERTMS. Will it achieve at least the same level of safety as traditional train control? Will it allow at least the same performance (speed, headway)?

### 1.1 Formal methods for early evaluation

Formal modelling, simulation and verification is a method to evaluate the safety and performance of (a model of) a system before its full deployment. Already in an early stage of the development process, one may be able to generate a formal model of the system to be constructed, which then can be fed into several simulation tools. Formal modelling is an accepted method for the evaluation of communication protocols. A formal model also captures unforeseen interference between the parts and exposes weaknesses of the protocol.

However, the results from simulation only carry over to the real system if the modelling process did not introduce some distortion into the model. One of the authors has previously worked on simulation of the GSM-R communication between train and (trackside) block centre in ETCS. To test whether the model is faithful, though, requires expertise from railway engineering. Therefore, we undertook to compare a model based on Jansen and Hermanns [5] (called “Model B”) with an equivalent model (“Model A”) constructed in the approved railway modelling tool RUT [6]. Model A is used by a couple of European railway managers. This comparison has given us confidence that the earlier model is realistic enough. With a correct model of the communication, one is able to estimate the impact of communication failures on the capacity.

## 1.2 Examining the impact of GSM-R communication

In order to examine the impact of GSM-R on railway operation, it is necessary to model the communication together with the relevant environment. Our current model thus covers the radio communication, the train behaviour and the track properties.

Wireless GSM-R communication is relatively unreliable, so transmission errors and short blackouts are current. Cell hand-overs (switching from one GSM radio cell to another) are another source of short connection interruptions. Cell sizes are also distributed probabilistically. A realistic model of ERTMS, therefore, has to include a probabilistic model of the radio communication.

The ERTMS specification contains requirements on the minimum quality that GSM-R has to offer [7, 8], mostly through bounds on the probability of failure or delay. We assumed that the GSM-R communication quality reaches the prescribed level. (This can be achieved by installing enough base transceiver stations along the track that have enough transmission power.)

In our earlier work [5, 9], we checked whether these requirements on the quality of a single transmission ensure an acceptable long-term behaviour. We could show that the small probabilities of failure of single transmissions do not sum up too much during a typical train trip.

The relevant environment of GSM-R, for our purposes, consists of train behaviour and track properties. From the train behaviour, the main elements are the acceleration and braking characteristics. We have chosen characteristics for a high-speed train that reacts quickly to commands of the driver. The track also influences (positive and negative) accelerations that can be achieved; therefore, a choice of track model is necessary.

Unfortunately, the current railway modelling tools like RUT do not allow for probabilistic modelling of communication failures. Due to the different modelling paradigms merging the deterministic Model A and the stochastic communication model is impossible. Therefore the existing probabilistic model of communication [5] was extended by components that simulate the train behaviour and track properties, similarly to Model A. This enabled us to compare the results of both models and to examine the impact of GSM-R communication failures on railway operation.

In particular, the impact of communication failures on the minimum headway time of two similar trains will be discussed.

## 2 Simulation approaches

In this section, we introduce two modelling approaches: a new, stochastic modelling approach and the deterministic model that is used by a couple of European railway infrastructure managers. We examine an example railway system by means of these two approaches and illustrate the obtained results.

## 2.1 Common setup

In both models, we assumed a single track between two stations 250 km apart from each other. The track is flat and straight, so the same forces apply to the train everywhere. Start and end stations have two tracks each, connected with a switch. We assumed that two trains run from the start station to the end station in short succession. The trains run at limited speed in the stations and on the switches (80 km/h) and are allowed full speed on the track (250 km/h). The acceleration and braking characteristics are similar to that of a modern high-speed train. Trains measure their position with an error bound of 50 m. The safe distance between trains is maintained by ETCS level 3 with moving blocks.

## 2.2 Deterministic simulation (Model A)

The deterministic simulations are conducted using Model A. They base on the running time estimation documented by Brünger and Dahlhaus [10] and operate on a microscopic railway model, the so-called *Spurplan* model. It contains all those components that influence the speed profile of the train and thus its running time. The speed profile is determined by two groups of parameters. One group determines the characteristics of the train (accelerating and braking characteristic). The other group enfolds the track side components and limitations induced by the track: distances, gradients, signal positions, speed limits, etc.

The software tool RUT has been designed with the fixed block operation principle in mind. As described by Wendler [3], the moving block operation principle can be emulated by applying the fixed block operation principle with an infinitesimal length of track segments. Similarly, we simulate moving block operation by positioning a huge number of signals along the track.

Model A supposes a deterministic behaviour of the railway system's components. Trains will run exactly on schedule. This is a useful assumption and deterministic simulations are widely applied in the field of operations research for railway systems. Nevertheless, the assumption of deterministic behaviour is rather strong, since various influences on railway operation can not be modelled this way. One of these influences with uncertain effect is the communication delay when using ETCS level 2 or 3. Therefore, we introduce a stochastic model.

## 2.3 Stochastic simulation (Model B)

We modelled the communication protocol of GSM-R at a high level using the StoCharts modelling language [11], an extension of UML state-charts that includes probabilistic choice and stochastic delays. In particular, we were able to include stochastic communication delays and connection interruptions in accordance with the specification documents. For example, it is prescribed [7] that a message arrives within at most 0.5 sec with probability 0.95, and within at most 1.2 sec with probability 0.99. More stochastic requirements can be found in Jansen and Hermanns [5]. We translated the communication model using a prototype translator

to the MoDeST language [12] and analysed it earlier [5, 9]. To make this model more realistic, one has to extend it with a track model. We added the track model mentioned in section 2.1 directly in MoDeST. We chose a very simple track model because the general stochastic language MoDeST does not offer basic operators for track-specific features.

All MoDeST models are analysed by the tool set MoTor / Möbius [13], a discrete event simulator tool that generates statistical overviews from its simulation runs.

## 2.4 Comparing the models

Model A is deterministic. The pre-calculated average communication delay is taken as the communication time. The strength of model B lies with the communication model: the failures are modelled in detail and with realistic random distributions.

The tool RUT (used for model A) allows a detailed track description, with several types of track, points etc. Model B only includes a simple track and train model. To reduce the differences between the models to what we want to compare, we restricted ourselves to an equivalent track and train model in model A, not using all the possibilities of RUT. As mentioned earlier, we can emulate moving block operation by making blocks smaller than the (assumed) measurement error.

As we restricted ourselves to a track and train characteristics that could be described in both models, the only real difference lies in the communication model.

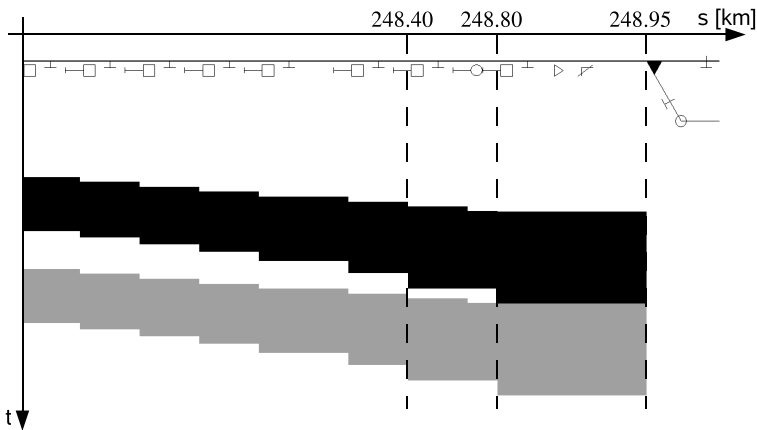


Figure 1: Diagram showing a segment of the track model and the blocking time stairway of two trains following each other with minimum headway time (diagram not to scale).

### 3 Experiment: outcomes and interpretation

#### 3.1 Model A: simulation results

The deterministic simulation conducted with model A calculates the mean running times of both trains on the infrastructure of our example. Moreover, it estimates the blocking times of each train on the sections of the regarded infrastructure under the assumption that the train is not hindered in its run by other trains (green wave). This way the user obtains a blocking time stairway for each train. With this stairway at hand it is possible to evaluate the minimum headway time between the trains by shifting them to the closest possible position without blocking time overlaps. Figure 1 illustrates the blocking time stairways for two trains following each other by a time difference equal to the minimum headway: the stairways touch each other at the last section of the open track. The resulting minimum headway time of the two trains is 110 sec for the deterministic simulation.

#### 3.2 Model B: single run analysis

Model B follows a different scheduling principle: the following time, the time between the departures of the two trains, can be chosen freely by the experimenter. Whenever the leading train communicates its new position to the train control system, the freed track is reserved for the second train at once. The train departs after its following time has passed, but if it is too short, the train adapts dynamically by braking somewhere on the track. If the following time is large, the track reserved ahead of the second train is longer than strictly necessary, giving it a buffer against temporary GSM-R failures. Möbius generates a similar blocking time stairway to that in Figure 1 for the two trains including the dynamic adaptation of the following train. We can see that the stairway of the second train is not deformed whenever the following time chosen is at least 111 sec.

Using smaller following times, we made an interesting observation: actually, shorter headways upon arrival in the final station are possible. As long as the following time is not much smaller than 111 sec, the braking phase is still critical. Before braking starts, the trains can typically achieve a headway around 70 sec, and during braking, the headway increases further, but not to 111 sec. The reason is that the braking distance (which is the largest part of the distance between the two trains) diminishes quadratically as the following train brakes, but the headway increases less. This effect becomes visible in moving block operation because here, very small (infinitesimal) blocks are possible.

#### 3.3 Validation of Model B by means of Model A

In model B, the minimal headway where the following train is unhindered is almost the same as in model A. The blocking time stairways are similar throughout the track. If we start the second train early, it will have to brake on the open track. We could mimic this behaviour in model A, by adding extra speed limitations to the

Table 1: Positions of the speed limits.

Position [km]	Speed [km/h]
244.178	240
245.771	211
247.824	136

Table 2: Simulation results.

Following time	70 sec	80 sec	100 sec	111 sec
Mean headway	78.45 sec	84.62 sec	101.28 sec	111.41 sec
90% confidence interval	0.007 sec	0.003 sec	0.002 sec	0.0008 sec
Early breaking	2390 m	1162 m	447 m	0 m
	28 sec	21 sec	10 sec	0 sec

following train that let it brake early, similarly to the early braking phase in model B. We added three extra speed limiting points, as shown in table 1. The positions and speeds are chosen from a typical simulation run for model A with a small following time ( $\leq 80$  sec) between the trains. By imposing this speed profile on the following train, the minimum headway time is reduced to 92.5 sec (1.54 min). This minimum headway time does compare to the result obtained by applying Model B. It thus validates Model B.

### 3.4 Model B: statistics over runs

In a second simulation setup, we let MoTor/Möbius collect data from 5.000 simulation runs each for several initial headways to estimate the distribution over the final headway. We found that in almost all cases, the final headway is in a very slim interval, the distribution is almost deterministic, with variances between 0.6 and  $0.13 \text{ sec}^2$ . Table 2 shows the mean and confidence interval for some values, together with an indication how long the early braking phase in an example run is. (Following times below 70 sec are not interesting, because they lead to braking just after departure.) As discussed by Wendler [3] and verified by simulation, the braking phase determines the final minimum headway time. (The braking phase in this case is more restricting than the accelerating phase). But at low speeds, the communicated train position is a good estimate of its current position – at 80 km/h, the train tries to report its position once every 111 m –, so that intermittent communication errors do not lead to much delay for the following train.

## 4 Conclusion

In order to estimate the impact of GSM-R communication on the line capacity we introduced a stochastic communication model. We extended this model in order to

emulate track and train behaviour and conducted simulations of a railway system with a simple track layout by means of two modelling approaches, and compared the results. We found that the results of this newly introduced stochastic model are comparable to those obtained by applying a sophisticated modelling tool. As the tool RUT is being used in practice, we are confident that the models we produced are also close to reality.

The simulation of ETCS level 3 indicates that GSM-R communication failures do not have a severe impact on the capacity of a line. Thus, the deterministic modelling approach of model A (which does not take into account GSM-R communication errors) may be appropriate. These results can even be extended for railway systems equipped with GSM-R communication as it occurs in ETCS level 2, as long as the braking phase on the track determines the minimum headway time; this holds for traditional, same-size blocks and for the case where blocks are smaller near stations (but not if one also enlarges blocks maximally on open track). We could verify the appropriateness of the deterministic modelling approach with regards to the GSM-R communication by comparing it to a stochastic modelling approach.

We propose, as future work, to evaluate similarly other aspects of railway operation which are represented deterministically for simplicity: are those simplifications also close enough to the (stochastic) real behaviour?

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