Automatic Train Supervision for a CBTC Suburban Railway Line Using Multiobjective Optimization

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***Abstract*—Communication-based train control (CBTC) systems have been deployed on subway lines to increase capacities on existing infrastructures. For the same purpose, CBTC systems are to be deployed on suburban railway lines where operating principles and constraints are significantly different. In this paper, a regulation method for CBTC trains on a suburban line is presented. This method is designed to combine CBTC functionalities with suburban operating principles. It includes a traffic management method in station, and a rescheduling method in case of disturbances. The proposed regulation method is integrated into the railway system simulation tool SIMONE developed by SNCF. This simulation tool includes models the whole CBTC system, as well as the classic signaling system, train dynamics and railway infrastructures. Models of these different agents are described. The integration of the proposed regulation method into the tool SIMONE allows evaluating performances while taking into account the functional complexity of a CBTC railway system. The approach is illustrated with a realistic case: simulations of a CBTC traffic on the urban part of a railway line in the Paris region network are described. The proposed regulation method shows interesting results in disturbed situations according to the railway operating principles.**

Keywords—CBTC; railway; traffic management; suburban; rescheduling; optimization

I. INTRODUCTION

In peak times, subway and railway companies operate short headways in order to increase the capacity. As a result, the system reaches its maximal capacity and is very sensitive to disturbances, even small ones. The operational margins are limited or non-existent. More and more, operating companies turn to new intelligent signaling and control systems to increase the line capacity and the traffic robustness without expensive modification of infrastructures.

Communication-based-train-control (CBTC) systems are signaling and control systems that have been developed in the last decades. Currently, they are mainly deployed on subway lines to increase the capacity and improve performances in high-density areas. In such systems, CBTC trains are accurately localized by means of communication devices (regardless of infrastructure detection devices). Besides, CBTC trains are controlled by an automatic pilot system. Through localization and automatic pilot, CBTC systems operate a moving block system and achieve shorter headways than the fixed block signaling system.

In a near future, CBTC systems will be deployed on suburban railway lines which cross big cities. Suburban railway lines are generally characterized by a high-density traffic in the urban part of the line, and a low-density traffic in the suburban parts. The CBTC area can be limited to high density traffic areas where there is a need to gain capacity. Thus, in such a configuration, the driver is in charge of piloting the train in manual mode in the suburbs, while the automatic pilot runs the train in the high density area.

Most CBTC systems include automatic train supervision (ATS) module to manage the traffic and reschedule CBTC trains in real time according to traffic monitoring information.

Suburban railway lines have specific operation principles. In the general case, they differ from subway lines on four mains aspects: (1) on a suburban line, operation management generally seeks to combine two objectives: on one hand, like on subway lines, management aims to maintain a constant headway between trains in the high density area of the line. On the other hand, unlike subway lines, operation management seeks to respect the timetable in the suburbs where the traffic is not dense. In disturbed situations, a compromise can be necessary. (2) On a suburban line, the network is more complex. The ATS module can be charged with choosing itineraries to link remarkable nodes and with choosing platforms stations. These choices are made in real time and depend on the traffic state. (3) On a suburban line partially equipped with a CBTC system, it is unlikely that platform screen doors will be deployed, for technical and economic reasons. Thus the ATS will face more disturbances such as passengers blocking the doors or going to the tracks. (4) A suburban railway line is part of a large regional network. In nominal mode, tracks can be shared with trains which are not controlled by the ATS. They can either be non-equipped trains which use the same tracks or CBTC-trains in manual mode.

Supervision and rescheduling of a CBTC suburban line are challenging topics in the field of traffic management. In this paper, we present a regulation approach based a traffic management method in station, and on a multi-objective optimization method for rescheduling after disturbances. This approach has been integrated in the ATS module of a simulation tool called SIMONE. SIMONE is developed by SNCF, the French national railway operator. This tool models the whole CBTC system, as well as the classic signaling system, train dynamics and railway infrastructures. Section II briefly outlines some related work in literature. Section III introduces the simulation tool SIMONE. Section IV focuses on the traffic model in the ATS module of SIMONE. Section V presents the proposed regulation approach. Section VI presents some experimental optimization results. Section VII provides some discussion and points to future work.

II. RELATED WORK

A. *Rescheduling methods*

In the literature of real-time traffic management, various methods have been proposed to solve the rescheduling problem in case of disturbances. Many approaches are based on multi-objective optimization and have shown interesting results on simulation tools. They tend to minimize delay as well as additional objectives such as travel time, energy cost, or passenger waiting time, depending on the application. There are four types of control actions: re-routing, modifying running times or dwell times (equivalent to modifying arrival and departure times), reordering at junctions, and re-servicing. Each rescheduling method generally uses one or two control actions, adapted to the kind of infrastructures and applications that are considered.

Most railway traffic studies apply re-ordering (or dispatching) as a traffic management action [1], [2], [3], [4], [5]. In complex networks, reordering is combined with rerouting [6], [7], [8], [9] to make use of the network alternatives. In [10], the rescheduling problem is adapted to complex central stations. The proposed approach assigns routes and running times to trains, in order to fully determine the block allocations. This corresponds to a microscopic regulation method adapted to high-density area.

Usually, subway traffic management method are designed for closed near-linear networks, and so focus on modifying running and dwell times (or departure and arrival times) [11], [12], [13]. Re-servicing is only considered to manage urban or multi-modal networks offering alternative routes to passengers [14]. Re-ordering and rerouting are not relevant for this kind of application.

Rescheduling methods are tested in simulation tools to evaluate their performances and their limits. Most of the times, simulation tools consist of a description of the tracks based on a node-link scheme, a description of train movements based on arrival and departure events, and a description of the signaling system based on a set of traffic constraints. These models allow describing traffic states with a flexible precision level and can be easily used for optimization process. The impact of the railway system components is not directly described; it appears through traffic constraints and delays.

To evaluate performances of a CBTC equipped line, it is not sufficient to model the CBTC system with constraints and delays. More precise models are needed to take into account its functional architecture, as well as some specific technical choices that can vary from a manufacturer to another. These features can have a strong impact on performances.

B. *CBTC System*

In the literature on CBTC systems, studies tend to focus on modeling the complex architecture of the system [15], on analyzing availability and performance of communication processes [16], or on designing speed profiles [17], [18].

CBTC systems are broadly deployed on closed near-linear networks. They generally operate simple but efficient regulation strategies based on maintaining a constant headway to handle high passenger volume [19]. Although usual CBTC traffic management strategies are efficient, they cannot be transposed to suburban railway context because the operation principles are not the same. Our work aims to develop a multi-objective optimization strategy for a suburban railway line, partially equipped with a CBTC system.

III. SIMULATION TOOL SIMONE

In previous work [20], the proposed method was firstly tested in a prototype traffic model to prove the viability of the approach on a reduced size and reduced complexity problem. This academic case study includes a description of the tracks based on a node-link scheme, a description of train movements based on arrival and departure events, and a description of the signaling system based on a set of traffic constraints. As described in section II, this kind of modelling is broadly used in literature to test traffic management strategy.

Our current work is supported by a new simulation tool SIMONE, developed by SNCF Reseau. This tool intends to simulate railway traffic including CBTC trains. In particular, this tool simulates the functional complexity of the different components of the railway system as well as their interactions. In this way, SIMONE takes into account the impact of functional complexity on performances.

The tool SIMONE is based on a multi agent simulation environment. A simulation core activates agents and assigns triggers such as messages, events or cycles. In this section, we describe some main agents and the models they embed. Due to space limitation, the models of tracks and vehicles are not described here.

A. *Signaling system*

In SIMONE, the classic signaling system is modeled with a set of state machines. The scope of the model consists of all the common components which have an impact on performances, and includes sensors (pedals, track circuits), interlocking, points, stop lights.

Each component is described by a state machine, and each state machine can be individually configured to include delays. On top of the component state machines, the main state machine models the software layer in charge of setting routes. It reproduces the functional sequences that lead to setting a route by activating the different components of the model.

The SIMONE signaling system model is currently based on the French main line signaling system. In particular, it described interlocking and sectional route releasing concepts.

B. On-ground ATC module

On-ground ATC module is a wayside equipment. It localizes all trains (CBTC and non CBTC trains) on the map of the track. It also defines the movement authority of CBTC trains.

In the SIMONE framework, the on-ground ATC has a precise knowledge of the tracks, receives information regarding the tracks' state from the signaling system, and receives localization of trains from communication devices. The main functions of the on-ground ATC model include monitoring trains on a map of the tracks, computing the movement authority for each CBTC trains, sending the movement authorities to the on-board ATC modules, sending information regarding the tracks' state.

C. On-board ATC modules

The on-board ATC module is embedded into the CBTC train, it is responsible for respecting the safety area of the train called movement authority and computed by the on-ground ATC module. It drives the train and supervises it (w.r.t. safety). It computes its speed and localization and sends its localization report to the on-ground ATC module.

In the SIMONE tool, the main functions of the on-board ATC model include sending the localization of the train to the on-ground ATC, computing the target speed to respect the movement authority, computing traction or breaking command, operating turnarounds. The safe braking model, in compliance with IEEE Standards [21], consists of 5 phases: CBTC response time, traction disable response time, cruise time, emergency brake build-up, and emergency braking at guaranteed emergency brake rate.

D. Automatic Train Supervision (ATS)

ATS module supervises operations, adapts the CBTC trains flow and controls the signaling system, in order to reach the performance objectives.

In the SIMONE framework, the main functions of the ATS model include supervising trains through a traffic model, updating the traffic model with monitoring information, sending route commands to the signaling system, sending mission and schedule commands to the on-board ATC modules, rescheduling missions and schedule in case of disturbances. More details on the ATS module will be given in section IV and section V.

In the next section, we describe the ATS traffic model implemented in the SIMONE tool.

IV. ATS Traffic Model

In traffic management systems, regulation decisions are based on monitoring traffic information. Monitoring data are generally used to update a traffic model in case of disturbances. The traffic model helps to evaluate both the impact of disturbances and the impact of regulation decisions. Reference [22] compiles the state-of-the-art in infrastructure and operation modeling. This section describes the formulations of infrastructure configuration and railway operations used in the presented work.

The presented traffic model is designed to be part of a supervision module, like an ATS module. It is, to some extent, based on the model previously introduced in [20]. It has been adapted to be integrated in the ATS module of the SIMONE simulation tool. In this way, the traffic model is designed for traffic supervision and has been integrated into the ATS module of a modelling of a railway system. It is composed of of a description of the tracks based on a node-link scheme, a description of train movements based on arrival and departure events, and a description of the signaling system based on a set of traffic constraints.

A. Description of tracks

The description of tracks is the base structure of the traffic model; traffic events will be monitored and simulated according to this base structure. Tracks description is based on a node-link scheme, adapted to the data structure of the SIMONE tool. The density of nodes describing a track section depends on the required level of accuracy. Thus, it is possible to find a trade-off between the size of the model and the precision in critical areas.

The presented model considers two types of nodes. Stopping nodes are located on tracks, in a station or on a sidetrack. A stopping node is specific to a train and models its target functional stopping node. It is characterized by a station (or a trackside), a platform, and a position along the platform. As a result, a station hosts several stopping nodes. If stopping nodes are computed in real-time, to take into account the traffic state, the platform and position attributes can be modified in real-time.

On-line nodes are located on tracks, outside of stopping areas. On-line nodes can be used in a timetable to model a milestone where the reference schedule should be respected. On-line nodes can also be used in a timetable to force a route else than the nominal route.

B. Timetables

To supervise traffic in real time, the ATS module uses timetables based on the structure of the link-node scheme. A timetable is composed of a collection of triplets: node identifier, arrival time and departure time, for each train.

The supervision functions use three types of timetable: the reference, the monitoring and the evaluation ones. The reference timetable consists of the objective schedule followed in nominal operations. The monitoring timetable reflects how the traffic actually evolves during operations. The ATS updates the monitoring schedule with arrival and departure data coming from the on-ground ATC for CBTC-trains, and with track circuit states coming from the signaling system for all trains (CBTC and non-CBTC trains). Then the future steps of train missions are shifted in consequence. The evaluation timetable is used to evaluate solutions to the rescheduling problem.

Moreover, the ATS checks, through the evaluation timetable, that solutions do not break traffic constraints.

C. *Traffic constraints*

The simulation environment comprises precise models of the signaling system and the CBTC equipment that are in charge of ensuring safety. These models reproduce the real architecture and functional sequence. To evaluate solutions to the rescheduling problem, the ATS needs to simulate the traffic and to take into account safety requirements. In order to limit the computational time, the ATS module includes a more abstract, and less complex, model of safety based on a set of constraints. The signaling system and the CBTC functions are not explicitly described in the supervision traffic model (it is modeled in the SIMONE simulation environment). When the ATS needs to evaluate the feasibility of a solution, it checks traffic constraints at the nodes of the node-link scheme, using the evaluation timetable.

1) Order Constraint

In the presented model, the ATS uses a First Come First Served (FCFS) strategy. The order constraint is checked at every node. It confirms that arriving order is compliant with departing order at previous nodes.

2) Capacity Constraint

The capacity constraint is checked at every station. For each station, and for each train, it confirms that the arrival time is compliant with the station capacity and the departure times of previous trains.

3) Headway constraint

The headway constraint is checked at every on-line node. For each train crossing the considered on-line node, it confirms that the arrival time is compliant with the departure time of the previous train according to the minimum headway.

The minimum headway between two trains depends on their communication mode (communicating mode / non-communicating mode) and their driving mode (automatic pilot mode / manual driving mode). Non CBTC-trains are considered to be in non-communicating mode and in manual-driving mode, at any time.

4) Running time constraint

The running time and dwell time constraints define the minimum values for running times and dwell times [22].

The running time constraint is not explicitly defined in the ATS model. Instead, the functions that are able to modify running times select the corresponding values in a dictionary of possible values. The possible values of running times correspond to the different running types available in the on-board ATC. A running type consists in a coefficient which multiplies the maximum speed of a train on a link of the node-link scheme. For example, we consider that the nominal running type correspond to a multiplying coefficient of 0.9. The running times dictionary is computed off-line, for each train according to its features, and for each link of the node-link scheme crossed by the considered train.

Based on the presented traffic model, the ATS can evaluate traffic indicators, simulate solutions to disturbances and take decisions. Regulation will be discussed in section V.

V. ATS Regulation Method

The presented work aims to develop a regulation method for a suburban railway line, partially equipped with a CBTC system. This method is designed to be part of the ATS module of a CBTC system. It is expected to supervise all trains in the CBTC area and to reschedule CBTC trains, while taking into account the specific principles of suburban operations. Thus, the proposed method is based on the state-of-the-art of railway traffic management as well as on the state-of-the-art of CBTC systems. Problem formulation and solution are adapted to the specific features of CBTC mixed traffic management on a suburban railway. The presented regulation method includes two main modules: a train management method in multi-platform stations, and a rescheduling method for CBTC trains using a multi-objective optimization. A first version of the rescheduling method was presented in [20].

A. *Train management method in multi-platform stations*

In order to make full use of platforms in stations, the proposed regulation method includes a train management method in multi-platform stations. This method is composed of three sub-functions that can be independently activated.

1) Platform choice according to expected occupation

When the ATS module defines its timetables and its node-link scheme based on the reference data, the platform attributes of stopping nodes of trains are not computed. The ATS computes the platform choice only when the considered CBTC train is in the previous station. This computation takes into account a set of weights that are predefined in the reference timetable, as well as the expected occupation of platforms on the ATS monitoring schedule.

2) Delay of route command in stations

After computing a platform choice for a CBTC train, the ATS computes the best route to reach the platform. Then, the command is sent to the signaling system as soon as the trigger area corresponding to the route is occupied. Generally this trigger area consists of the platform area. Once a route is commanded to the signaling system and set, it is quite long and complex to undo this decision in favor of another train with another route. It is due to the approach locking [23]. In order to allow flexible departure order at station, the ATS delays the sending of commands to the signaling system. It sends command just before departure. The time of sending before departure is defined by an ATS parameter.

3) Delay of platform choice

When a CBTC train is stopped in a station, it may be blocked for various reasons (for example change of departure order or disturbances). As a result, its departure time is delayed; it will be shifted in the ATS monitoring timetable. In order to take into account the latest occupation prediction at the next station, the platform choice is computed just before departure. The time of computation before departure is defined by an ATS parameter.

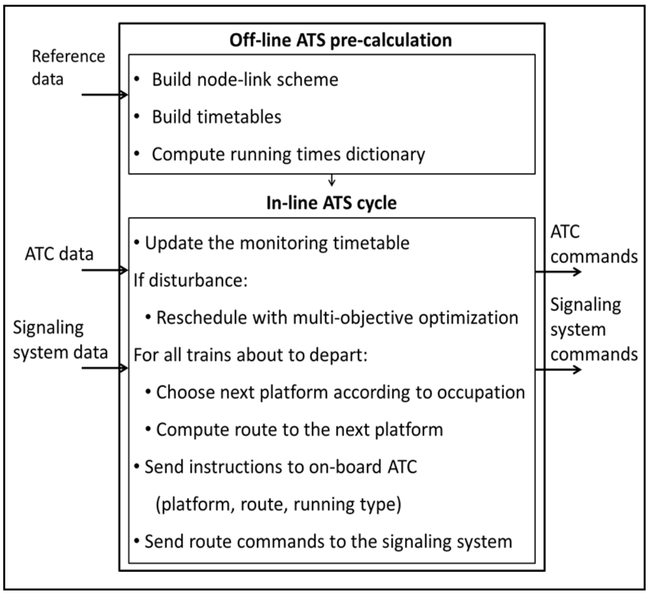

Fig. 1. Simplified functional sequence of the ATS module.

B. Rescheduling through multi-objective optimization

In case of disturbances, the ATS module executes a rescheduling method to adapt train runs in the aim of improving some traffic indicators. In the presented work, the rescheduling method is based on a model predictive control approach (MPC) and its receding horizon principle. It adapts the running types of CBTC trains; Non-CBTC trains are not controlled by the ATS, but are taken into account in the supervision functions, and in the evaluation functions.

The rescheduling method uses a multi-objective centralized genetic algorithm to compute the control inputs. This algorithm is partly based on the one presented and tested in [20]. The solutions are evaluated according to 2 objectives: distance to objective headway and punctuality at the end of the CBTC area. We also consider distance to traffic constraints satisfaction as a third traffic indicator. It is used as a strong penalty applied to both objective values. The considered traffic constraints were presented in section IV.

In the genetic algorithm, a chromosome is a list of running types. It is built on the basis of the monitoring timetable. For each train, according to its position on the node-link scheme, the first link on which the running type can be modified is computed. From this first link to the end of the optimization horizon, each running type corresponding to a step of the node-link scheme is part of the chromosome.

The selection process uses a Pareto ranking process. The random mutation process uses values generated from the running times dictionary mentioned in section IV. The crossover process uses a 2-points-crossover operator.

The proposed regulation method is designed to combine CBTC functionalities with suburban operating principle. It includes a train management method in multi-platform stations to make use of available capacity in a flexible way. It also includes a rescheduling method which is executed in case of disturbances (Fig. 1) and provides a global response to disturbances, for CBTC trains in the CBTC area and according to the suburban operation objectives.

VI. Experiments

The regulation method, described in section V, has been tested in the SIMONE simulation tool described in section III.

In the tool SIMONE, a scenario is composed of: a precise description of tracks, the corresponding signaling system model (described in section III), vehicles parameters, CBTC parameters, reference operation data and a set of predefined disturbances. Reference operation data consist of a reference timetable and reference weights for platform choice computation.

In the presented experiments, the scenarios take place on the future extended version of the suburban line "RER E" in Paris region. The description of tracks exactly corresponds to the real track map, from the sidetracks of station "Nanterre-La-Folie" (Fig. 2) to the sidetracks of station "Rosa Parks". This 18km-long area corresponds to the CBTC control area and includes 6 stations. The signaling system model is also based on the real system configuration. The vehicle parameters are based on validated vehicle description data. CBTC parameters are based on the state-of-the-art of existing CBTC systems.

The proposed method is tested on a set of 4 train paths in each direction. The purpose of these tests is to evaluate how much a disturbed situation can be solved or at least mitigated. In order to analyze the results, the method is compared with a common basic strategy (denoted individual delay strategy) which consists in individually adapting the running types of trains according to their own delays. The individual delay strategy was implemented into the ATS module of the CBTC system in the SIMONE tool. Both compared methods include the traffic management method in stations; they only differ on their rescheduling approach.

The disturbances in scenarios represent the second train being blocked in a station, up to 60 seconds over the expected dwell time. Regulation methods are evaluated according to two indicators: the total delay and the total distance to the objective headway. For scenarios with a blocking time less than 40 seconds, the proposed method shows equivalent results to the individual delay strategy. It proposes a compromise between the two objectives. The individual delay strategy is able to partly recover the primary delay. The latter is faintly spread.

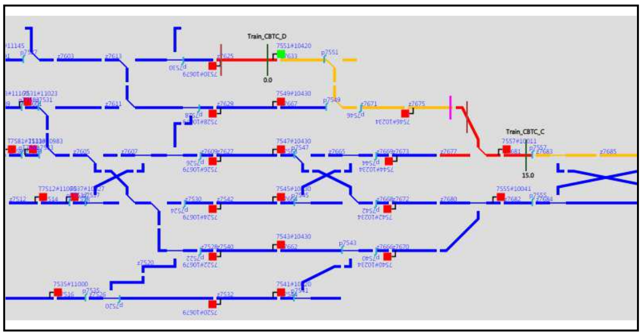

Fig. 2. Sidetracks and platforms of station "Nanterre-La-Folie" in SIMONE

TABLE I. EXPERIMENTAL RESULTS

Scenario	**Regulation method**	***Punctuality***	***Headway***
Blocking time = 40s, in “Saint-Lazare” station	Individual strategy	21%	4%
	Proposed method	11%	16%
Blocking time = 60s, in “Saint-Lazare” station	Individual strategy	-2%	4%
	Proposed method	33%	23%
Blocking time = 60s, in “La Defense” station	Individual strategy	1%	-2%
	Proposed method	37%	26%

For scenarios with a blocking time over 40 seconds, the proposed method has the ability to outperform the individual delay strategy. Table I. presents experimental results of two scenarios. It shows the average improvement of each regulation method, for both indicators, in comparison with the same scenario without speed regulation. The proposed rescheduling method provides a global response to disturbances and takes both indicators in consideration.

These experiments points to the usefulness of multi-objective optimization in the traffic management functions for CBTC railway lines. Multi-objective optimization is able to provide good solutions to disturbed situations. In the case of complex situations, where delays spread across the line, it outperforms the individual delay strategy by better taking into account the system features. In future work, it would be interesting to adapt the regulation method to the monitored situation. The ATS could host several regulation methods and use the more relevant one, depending on the extent of disturbances.

VII. CONCLUSION

This paper has presented the design of automatic train supervision functions for a railway line equipped with a CBTC system. Our work is supported by a new simulation tool SIMONE, developed by SNCF Reseau. This tool precisely describes the main agents of the railway system and the CBTC system. By means of the SIMONE simulation tool, we developed an ATS module, including a traffic management method in multi-platform stations and a rescheduling method based on a multi-objective optimization algorithm. The proposed rescheduling method was tested in SIMONE. Experiments showed an interest in designing CBTC regulation method using a multi-objective optimization, according to suburban railway principle.

REFERENCES

[1] Ho T.K., Yeung T.H., “Railway Junction Traffic Control by Heuristic Methods”, in *IEE Proc. Electric Power Applications* vol. 148(1), pp. 77-84, IET, 2001.

[2] Wegele S., Slovák R., Schnieder E., “Automatic Dispatching of Train Operations Using a Hybrid Optimisation Method”, in *8th World Congress on Railway Research*, Seoul, 2008.

[3] Fan B., Railway “Traffic Rescheduling Approaches to Minimise Delays in Disturbed Conditions”, Ph.D Dissertation, University of Birmingham, 2012.

[4] Tornquist J., “Train Traffic Deviation Handling Using Tabu Search and Simulated Annealing”, in *Proc. 38th Annual Hawaii International Conference on System Sciences*, pp. 73a, 2005.

[5] Kersbergen B., van der Boom T., De Schutter B., “Distributed model predictive control for rescheduling of railway traffic”, IEEE 17th Inter. Conf. on Intell. Transp. Syst., Qingdao, China, 2014., pp. 2732-2737.

[6] D’Ariano A., “Improving Real-Time Train Dispatching: Models, Algorithms and Applications”, Ph.D Dissertation, Delf University of Technology, 2008.

[7] Corman F., “Real-time Railway Traffic Management: Dispatching in Complex, Large and Busy Railway Networks”, Ph.D Dissertation, Delf University of Technology, 2012.

[8] Flamini M., “Job-Shop Scheduling Algorithms with Applications to Railway Traffic Control”, Ph.D Dissertation, University Roma Tre, 2005.

[9] Tornquist J., Persson J., “A.: N-tracked Railway Traffic Re-scheduling during Disturbances” in *Transportation Research Part B: Methodological* (Elsevier), vol. 41, pp. 342-362, 2006.

[10] Fuchsberger M., “Algorithms for Railway Traffic Management in Complex Central Station Areas”, Ph.D Dissertation, ETH Zurich, 2012

[11] Ven Breusegem V., Campion G., Bastin G., “Traffic Modeling and State Feedback Control for Metro Lines”, *IEEE Trans. Autom. Control*, vol. 36, pp. 770-784, Jul, 1991.

[12] Fernandez A., de Cuadra F., Garcia A., “SIRO: An Optimal Regulation System in an Integrated Control Centre for Metro Lines”, *WIT Trans. on the Built Environment*, vol. 21, pp. 10, 1996.

[13] Assis W.O., Milani B.E.A., “Generation of Optimal Schedules for Metro Lines Using Model Predictive Control”, in *Automatica* , Issue 8. Philadelphia: Elsevier, 2002, vol. 40, pp. 1397-1404.

[14] Zidi S., “SARR: Support System for Regulation and Reconfiguration of Multimodal Transportation Networks” (in French). Ph.D Dissertation, University of Lille, 2007.

[15] Chen R., Guo J., “Development of the New CBTC System Simulation and Performance Analysis”, *WIT Transactions on the Built Environment*, vol. 114, pp. 11, 2010.

[16] Sun W., Richard Yu F., Tang T., “Performance improvement in Communication-Based Train Control (CBTC) Systems using cognitive control”, *IEEE 17th Intelligent Transportation Systems Confreence (ITSC),* Oct, 2014

[17] Fernandez-Rodriguez A., Fernandez-Cardador A., Cucala A.P., Dominguez M., Gonsalves T., “Design of Robust and Energy-Efficient ATO Speed Profiles of Metropolitan Lines Considering Train Load Variations and Delays”, *IEEE Trans. Intell. Transp. Syst.*, vol. 16, pp. 2061-2071, Aug, 2015.

[18] Bu B., Yang J., Wen S., Li Z., “Predictive Function Control for Communication-Based Train Control (CBTC) Systems”, *Int. J. of Advanced Robotic Syst.*, vol. 10, 2012.

[19] Ning B., Xun J., Gao S., Zhang L., “An Integrated Control Model for Head-way Regulation and Energy Saving in Urban Rail Transit”, *IEEE Trans. Intell. Transp. Syst.*, vol. 16, pp. 1469-1478, Jun, 2014.

[20] Pochet J., Baro S., Sandou G., “Supervision and rescheduling of a mixed CBTC traffic on a suburban railway line”, *IEEE Intelligent Rail Transportation Conference*, Aug, 2016

[21] IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements, IEEE Standard 1474.1, 2004.

[22] Hansen I.A., Pachl J., “Railway Timetable and Traffic”. Eurailpress, 2008.

[23] Schoen W., Larraufie G., Moens G., Pore J., “Railway Signaling and automation”, *La vie du Rail* , vol. 1, pp.300, 2013.