Supervision and rescheduling of a mixed CBTC traffic on a suburban railway line

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***Abstract*— Railway companies need to achieve higher capacities on existing infrastructures such as high density suburban mainlines. Communication based train control (CBTC) systems have been widely deployed on dedicated subway lines. However, deployment on shared rail infrastructure, where CBTC and non-CBTC trains run, leads to a mixed positioning and controlling system with different precision levels and restrictions. New performance and complexity issues are to arise. In this paper, a method for rescheduling adapted to a CBTC system running in a mixed traffic, is introduced. The proposed method is based on a model predictive control (MPC) approach. In each step, a genetic algorithm solves the problem to optimize the cost function. It determines the dwell times and running times of CBTC trains, taking into account the non-CBTC trains planning and fixed-block localization. In addition, reordering can be allowed by modifying the problem constraints. The work is supported by a simulation tool developed by SNCF and adapted to mixed traffic study. The approach is illustrated with a case study based on a part of an East/West line in the Paris region network, proving the ability of the method to find good feasible solutions when delays occur in traffic.**

Keywords—CBTC; railway; traffic management; mixed traffic; optimization

I. INTRODUCTION

Urban and suburban transportation systems experience large passenger volumes. In peak times, railway companies operate short headways; the system reaches its maximum capacity. As a result, operational management margins are limited. The cost of any infrastructure modification being very high, operating companies seek to increase system capacity without such evolution, investigating ways to increase the capacity by relevant operating means.

In such a framework, communication-based train control (CBTC) systems consist of intelligent signaling and train control systems. They have been widely deployed on subway lines to manage the railway traffic in a more efficient way. CBTC trains are accurately localized by means of communication devices, and regardless of infrastructure detection devices. Besides, CBTC systems precisely control position, speed and acceleration of CBTC trains along their running phases. Thus, CBTC systems consist of a moving block signaling system operating shorter headways than the fixed block signaling system. They can achieve higher line capacities on existing rail infrastructures.

Besides, CBTC systems include automatic train supervision (ATS) modules to adjust services and performances in real time according to traffic monitoring information. The ATS is in charge of regulating the traffic, in case of short gaps with the objective schedule, and also in case of major disturbances.

However, deployment of CBTC systems on shared rail infrastructures, where CBTC and non CBTC trains are operated, leads to a mixed positioning and controlling system with different precision levels and restrictions: CBTC trains are operated precisely through the CBTC train tracking and the automatic train operation (ATO) system ("auto-pilot") on a moving block description, while non-CBTC trains are tracked using the track-circuits (discrete imprecise tracking), driven manually (with uncertainties), and obey a fixed block signaling system. Also both kinds of train respond to different degraded modes.

A CBTC system deployed in a suburban area operates midway between high-density operations and classic railway operations. This complex system requires a dedicated approach to ensure the robustness of its operation.

In this paper, we present an approach to enhance and evaluate the robustness of mixed systems. The proposed approach is based on an adapted regulation method and a dedicated simulation tool. Section III briefly outlines some related work. Section IV briefly described the modeled CBTC system. Section V introduces the railway traffic model used by the supervision module. In section VI, the proposed regulation approach is described. Section VII presents some experimental optimization results. Section VIII provides some discussion and points to future work.

II. RELATED WORK

Many approaches have been suggested to reschedule transportation traffic. Support systems for railway networks have been developed to help operational decisions on large and complex instances. Subway lines studies are generally based on closed systems, with less complex infrastructures and traffic constraints. Nonetheless, they address high density issues with limited operation margins. We also refer the interested reader to multi-modal network studies and air traffic studies, which are characterized by different constraints, but seek to answer similar questions.

Rescheduling approaches focus on 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. The chosen control actions highly depend on the kind of infrastructures and applications which are considered.

Railway traffic studies tend to propose re-ordering as a traffic management mechanism [1], [2], [3]. Some of them combine reordering with running time tuning [4], [20] or rerouting [5], [6], [7], [8]. In [9], the rescheduling problem is adapted to complex central stations. The resulting approach assigns blocking time stairways (combination of route and running time) to trains.

Usually, subway traffic management method are designed for closed near-linear networks, they use running and dwell time tuning (or departure and arrival time), as management mechanism [10], [11], [12]. Re-servicing is only considered to manage urban or multi-modal networks offering high frequency departures or alternative routes to passengers [13], [14], [15].

Most approaches tend to minimize delays. Depending on the application context, common additional objectives consist of minimizing travel time, energy cost, missed correspondences, passenger waiting time.

Regarding CBTC systems, they have been studied through different focuses; the following publications and their references provide an overview of key topics. CBTC traffic simulation and performance analysis are introduced in [16]. In [17], a speed profile optimization is presented. Speed profile tracking have been developed in [18]. In [19] the authors propose a prediction method to adjust train arrival time relatively to the previous departing train.

III. CBTC SYSTEM

CBTC systems [23] were developed according to several distinct architectures. The CBTC system that has been modeled in this work is briefly described in this section. Each CBTC train carries an on-board automatic train control (ATC) module.

A. On-board ATC module

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

B. Zone Controller ATC module

The Zone Controller (ZC) is a trackside 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.

C. Signaling system

The signaling system (not including CBTC) consists in a large set of control mechanisms ensuring interlocking, safe distances and routing. We refer to [22] for detailed information on railway signaling systems, interlocking and automation.

D. Automatic Train Supervision (ATS)

ATS module supervises operations; it decides how to adapt the CBTC trains flow and controls the signaling system in order to reach the performance objectives.

IV. TRAFFIC MODEL FOR SUPERVISION

A supervision module bases its decisions on relevant information on the traffic state. Reference [21] 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.

A. Network graph

The proposed supervision module comprises a common traffic model based on network graphs. This kind of model allows to alternate between microscopic and macroscopic views of the system easily, in order to find a trade-off between the size of the problem and the necessary precision in critical areas.

The network is defined as a set of particular point, linked by segments. A point can represent a junction or any point of interest in the network. A point has a certain capacity representing the number of trains that can be handled; this attribute is useful to model stations on a macroscopic level.

B. Schedule

A schedule consists of a collection of triplets: point identifier, arrival time and departure time, for each train. A pre-defined route is considered for all trains.

The supervision functions are based on two types of schedule. The reference schedule consists of the objective schedule followed in nominal operations. The monitoring schedule reflects how the traffic actually evolves during operations.

The supervision module monitors the traffic through discrete events: arrivals and departures of trains at particular points. As CBTC-trains are localized accurately, their schedule could be described and monitored over a high number of points. To limit the size of the model, they should be described and monitored with a reduced number of key points (in the supervision module only). Non-CBTC train schedules may be described with fewer points than CBTC-train schedules.

Every time a train reaches or leaves a particular point, the monitoring schedule integrates the time measurement of the event. From this event integration, the expected arrival and departure times at the points ahead of the related train are calculated in order to evaluate traffic evolution and constraints and to determine whether adjustments are necessary.

C. Traffic constraints

The proposed ATS is in charge of satisfying traffic constraints and meeting the objective schedule on the particular points of the network. As the signaling system is not defined explicitly in the ATS, the supervision checks five types of constraints on arrival and departure times in the monitoring schedule, to ensure safety requirements:

- Order constraints
- Capacity constraints
- Arrival interval constraints
- Departure interval constraints
- Running time and dwell time constraints

These constraints are checked at particular points belonging to both CBTC trains and non-CBTC trains schedules (at least stations and junctions).

As described in [20], all constraints have the same structure:

$$e_i > e_j + p_{ij} \tag{1}$$

where e_i, $e_j \in R$ are events times and $p_{ij} \in$ R is the minimum process time. The ATS checks the constraints step by step, i.e. point by point (from the origin to the destination) and train by train (in arrival order).

- Order Constraints

The order constraints are checked only if the ATS is allowed to modify arrival orders at junctions, for example using a First Come First Served (FCFS) strategy. In this case, for each train *t* arriving to a point, the ATS considers the following arriving train *f*. If *t* and *f* arrive from different segments, the constraint is satisfied. If *t* and *f* arrive from the same segment, and if *t* enters this segment before *f* (i.e. *t* departs from the previous point before *f)*, the constraint is satisfied. Otherwise, the constraint is broken. If the order is considered to be fixed, the ATS is not allowed to modify it. The reference order sequences are then used to check the three other types of constraints, while the order constraints are ignored.

- Capacity Constraints

The capacity constraints are checked at every particular point. For every train *t*, in arrival order, the train *l* limiting the arrival of *t* for capacity reasons is the first train to depart among the *c* trains that arrive before *t*, where *c* is the point capacity. The capacity constraint defines a minimum time between the departure of the limiting train and the arrival of train *t*:

$$a_t > d_l + s_{tl} \tag{2}$$

where a_t is the arrival time of *t*, d_l is the departure time of *l*, and s_{tl} is the technical separation time between *t* and *l*.

- Arrival / Departure Constraints

The arrival and departure interval constraints are checked at every particular point. They define a minimum headway between two arrival events, respectively two departure events. For every train *t* in arrival order, respectively in departure order, the following train *f* to arrive, respectively to leave, is constrained by (3), respectively (4):

$$a_f > a_t + s_{aft} \tag{3}$$

$$d_f > d_t + s_{dft} \tag{4}$$

where a_t is the arrival time of *t*, a_f is the arrival time of *f*, s_{aft} is the technical separation time between arrivals of *t* and *f*, respectively d_t is the departure time of *t*, d_f is the departure time of *f*, and s_{dft} is the technical separation time between departures of *t* and *f*.

- Running Time / Dwell Time Constraints

The running time and dwell time constraints define the minimum values for running times and dwell times [20].

If any constraint is broken the ATS adjust the running time or the dwell time of the concerned train to solve the conflict. The trains depart and arrive as soon as all constraints are satisfied.

The presented model makes no difference between CBTC and non CBTC trains. In any case, a train must be operated in safe conditions, respecting traffic constraints. However, CBTC and non-CBTC trains are not constrained with the same time interval and headway values as they are not operated under the same signaling systems. Also they are characterized by different performances; as a consequence their running time and dwell time constraints may vary.

Based on the presented traffic model, the ATS can adjust the schedule by executing regulation functions responsible for optimizing some traffic indicators. Regulation will be discussed in section V.

V. REGULATION METHOD

The purpose of this work is to provide a regulation method for CBTC mixed traffic based on the state-of-the-art of railway and subway traffic management. Formulation and optimization are adapted to the specific features of CBTC mixed traffic management on a suburban railway.

The proposed regulation is based on a model predictive control (MPC) approach. It determines the control inputs of the CBTC-trains. The control inputs are the running times (or dwell times) of CBTC trains. The non-CBTC trains are not controlled by the ATS, but are taken into account in the traffic constraints.

The optimization of control inputs is based on centralized genetic algorithms (GA) and Pareto ranking. The solutions are evaluated according to 3 objectives: distance to traffic constraints satisfaction, distance to objective headway, and punctuality at critical points. The considered traffic constraints were presented in section IV. In each step, the schedule is optimized over a spatiotemporal horizon: for each train, the following stages to the next critical point, where punctuality should be satisfied, compose the horizon. The corresponding running times are the control inputs to optimize. Then, in the proposed genetic algorithm, a chromosome is a list of running time (or dwell time) modification rates (Fig.1), restricted to maximum decreasing and increasing rates of the nominal values, for example [-20%, +30%].

The presented genetic algorithm includes widely known evolution mechanisms such as two-point crossover, random mutation or Pareto selection. It also includes specific mutation mechanisms adapted to the traffic rescheduling issue: a conflict-fixing mutation mechanism adjusts chromosomes to satisfy traffic constraints; it consists in decoding the chromosome, fixing the constraints in the schedule and recoding the schedule into chromosome. A headway-fixing mutation mechanism (HFMM) brings the chromosome closer to the objective headway; it consists of decoding the chromosome, modifying the schedule by regulating the headway point by point and train by train, and recoding the chromosome. Likewise, a delay-recovering mutation mechanism (DRMM) reduces running times of delayed trains (Fig.2).

Fig. 1. Chromosome coding.

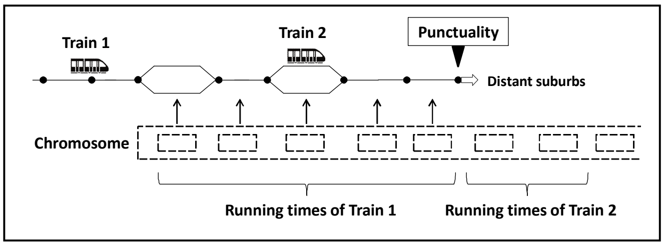
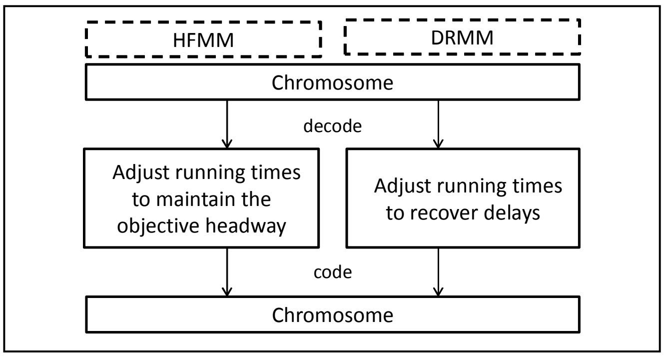


Fig. 2. Specific mutation mechanisms for suburban high-density traffic management.



In addition, reordering can be allowed by modifying the problem constraints. In this case, reordering is an implicit consequence of the optimization process. If reordering is not allowed, the reference schedule order is maintained: the order constraint is ignored and the reference schedule sequence is used to check capacity constraints, arrival interval constraints, and departure interval constraints. Whereas when implicit reordering is allowed, the reference order sequence is ignored and the order constraints are checked instead. The actual order sequence is then used to check capacity constraints, arrival interval constraints, and departure interval constraints.

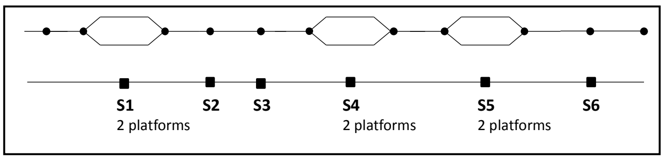
The proposed regulation method is intended to manage a mixed CBTC traffic on a suburban railway. Inside Paris, many passengers take suburban trains as they would take a subway line. A regular short headway is needed to meet the demand. However in the distant suburbs, passengers taking suburban trains expect punctuality. The regulation objectives must fit these expectations. In the proposed regulation method, regularity is measured at every station inside the high density area while punctuality is measured at critical points representing the transition between the high density area and the suburban area.

VI. EXPERIMENTS

The presented work aims to develop an approach to enhance the robustness and the performance of CBTC systems, more specifically in mixed CBTC traffic conditions. A dedicated regulation method has been introduced. The formulation and the proposed regulation method have been applied on mixed traffic scenarios and only-CBTC traffic scenarios where trains are subject to delays. Scenarios consist of a set of delays which occurs in the traffic. When a delay occurs, the regulation method optimizes the running times of trains over their respective horizon.

In all scenarios, the network is a simplified view of the central part of a suburban mainline of the Paris region (RER E). This area is characterized by high density traffic. The one-direction model (Fig.3) is composed of 14 single track segments and 11 nodes. 6 stations are modeled, 3 of them are composed of 2 platforms. The scenarios include 5 trains. The problem is composed of 55 optimization variables. In the presented scenarios, the size of the problem decreases as the time goes. The objective headway between trains is 110 seconds. The platforms to deserve are predefined for each train. This parameter cannot be modified by the optimization process. However double platforms allow change of order at their junctions.

Fig. 3. Network model of ecperimental scenarios.



In future work, the regulation method will be integrated into a microscopic simulation tool which is dedicated to CBTC and mixed traffic simulation, and includes a detailed model of the signaling system. This tool will allow testing more complex scenarios, with regard to infrastructures, schedule and disturbances.

A basic regulation method was implemented in order to be compared with the proposed regulation method based on GA. This basic regulation consists in reducing the running time on the following stages of delayed trains, as much as possible and until the delay is recovered. Its action is equivalent to the delay-recovering-mechanism that has been integrated to the GA.

TABLE I describes scenarios and cases that illustrate the presented work. A reference schedule may be built such as punctuality and regularity are consonant. Improving one indicator would contribute to improve the other one. However, punctuality and regularity may also be conflicting; improving one of these indicators would generally degrade the other one. A compromise is necessary. This situation may occur for some network configuration, or when a large deviation modifies the schedule. If a deviation induces a change of order between trains, the conflict between the two indicators might be accentuated.

TABLE II summarizes the results for each regulation strategy with respect to the improvement of regularity and punctuality indicators relatively to the initial situation (without any regulation). In these experiments, the conflict-fixing mutation mechanism and the delay-recovering mutation mechanism were activated in the GA. The delay-recovering mutation mechanism is consistently applied on one chromosome of the first generation of the GA. Hence, the GA is expected to improve the solution corresponding to the basic regulation strategy.

In TABLE II, “R” stands for regularity indicator, and “P” stands for punctuality indicator. As all solutions are conflict-free, the conflict indicator is not shown. Punctuality is measured only at the last station of train missions, as a train should leave the high density area on time. A regulation strategy may be able to completely recover a delay before this last station. Thus, relative improvement may reach 100%. Regularity is measured at each node. In case of delay or disturbance, this event impacts the regularity measurement. Thus a regulation strategy may improve the regularity indicator by modifying the following stages of train missions, but it cannot reach a relative improvement of 100% as it cannot change the past. Eventually, relative improvement of regularity and relative improvement punctuality are not comparable. An improvement of 50% for the punctuality indicator means that 50% of the delay is recovered at the last station. An improvement of 50% for the regularity indicator means that the total distance to the objective headway for all trains at all nodes has been divided by two in spite of disturbances that occurred at these same nodes. A negative improvement means that the indicator is degraded instead of improved.

Results from TABLE II show a potential in building a multi-objective optimization for CBTC mixed traffic management. The proposed regulation is not able to improve the solution of the basic regulation for scenario A in case 2, i.e. when disturbances induce no change of order and when regularity and punctuality are consonant in the reference schedule. In this case recovering the delays, as does the basic regulation, is a very good solution. In all other cases, when the situation is more complex to solve, the proposed regulation outperforms the basic regulation and provides good feasible solutions.

TABLE III presents the average improvements of indicators reached by GA with and without activating the delay-recovering mutation mechanism (DRMM) or the headway-fixing mutation mechanism (HFMM). DRMM tends to stimulate the evolution in the direction of improving the punctuality indicator, while HFMM tends to stimulate the evolution in the direction of improving the regularity indicator.

TABLE I. DESCRIPTION OF SCENARIOS AND CASES

Experiments	Scenarios and cases
Scenario A.	Set of short delays (<100seconds) No change of order Total delay applied : 200 seconds
Scenario B	Set of longer delays (<180seconds) Induced change of order Total delay apllied 260 s
Case a	CBTC trains only
Case b	4 CBTC trains and 1 non CBTC train
Case 1	Punctuality and regularity : conflicting
Case 2	Punctuality and regularity : consonant

TABLE II. RELATIVE IMPROVEMENTS OF GA AND BASIC STRATEGIES

Experimental results	**Relative improvement of regulation strategies**	
	Basic regulation	***Regulation with GA***
Scenario A.a.1	R: 9%, P:100%	R: 19%, P: 100%
Scenario A.b.1	R: 22%, R: 65%	R: 31%, P: 65%
Scenario A.a.2	R: 75%, P: 100%	R: 75%, P: 100%
Scenario A.b.2	R: 35%, P: 78%	R: 35%, P: 78%
Scenario B.a.1	R: -12%, P: 52%	R: 4%, P: 48%
Scenario B.b.1	R: -7% P: 95%	R: 20%, P: 88%
Scenario B.a.2	R: 18%, P: 58%	R: 48%, P: 60%
Scenario B.b.2	R: 7%, P: 47%	R: 7%, P: 63%

TABLE III. RELATIVE IMPROVEMENTS OF GA WITH AND WITHOUT DRMM

Experimental results	Relative improvement of GA		
	GA	***With HFMM***	***With DRMM***
Scenario A.a.1	R 32%, P 95%	R 48%, P 92%	R 19%, P 100%
Scenario A.b.1	R 37%, P 59%	R 47%, P 69%	R 31%, P 65%
Scenario A.a.2	R 58 %, P 100%	R 76%, P 100%	R 75%, P 100%
Scenario A.b.2	R 34 %, P 73%	R 40%, P 76%	R 35%, P 78%
Scenario B.a.1	R 14%, P 24%	R 19%, P 23%	R 4%, P 48%
Scenario B.b.1	R 30%, P 44%	R 43%, P 40%	R 20%, P 88%
Scenario B.a.2	R 43%, P 54%	R 46%, P 44%	R 38%, P 60%
Scenario B.b.2	R 12%, P 2%	R 16%, P 4%	R 7%, P 63%

As the experiments show, the proposed regulation significantly improves punctuality and regularity when disturbances occur in CBTC traffic and mixed CBTC traffic, in particular when these indicators are conflicting, or in case of large disturbances. Dedicated mutation mechanisms, which represent usual regulation actions, were developed in order to bring information to the GA and stimulate the evolution. It would be interesting to develop more mechanisms inspired from regulator expertise.

VII. DISCUSSION AND FUTURE WORK

Most existing research tends to develop traffic management methods for CBTC subway lines on the one hand, and for complex railway networks on the other hand. In order to increase capacity on high density areas, suburban lines are to be equipped with CBTC systems. It results in specificities that should impact traffic management: the line is partially equipped (high density area only), and the traffic is possibly mixed (CBTC and non CBTC trains). Also regulation objectives depend on the problem configuration; punctuality and regularity are key indicators of suburban railway lines.

The proposed regulation method consists of an adaptation of the well-known genetic algorithms to CBTC suburban line management, in particular in mixed traffic conditions. Experiments showed the method is able to enhance traffic indicators when disturbances occur.

Future work should address several opportunities of improvement:

- The proposed regulation was compared to a basic delay recovering strategy. Further comparison should be done in future work, with more realistic regulation methods.
- Optimization performance was not the main focus of this work. GA construction and parameters could probably be optimized. Other optimization algorithms could also be implemented.
- This work has not tried to solve optimality. GA solutions were not compared to optimal solutions.
- In future work, more mechanisms could be developed to bring regulator expertise in the optimization algorithm. It would be interesting to consider specific management solutions currently used in operational entities and to translate them in terms of mathematical optimization.

In future work, the proposed regulation will be integrated into a simulation tool which is dedicated to CBTC and mixed traffic simulation, and includes a detailed model of the signaling system. This tool will allow a more accurate evaluation of solution, taking into account the signaling system, and CBTC train specifies (such as shorter headways and higher speeds). It will also allow using more types of regulation action such as rerouting. Besides, more complex and realistic scenarios could be modeled, with regard to infrastructures, schedule and types of disturbance. For example, signaling equipment failures, train breakdown or platform unavailability could be modeled.

This work presented an adaptation of traffic management for mixed CBTC traffic on suburban lines. This new type of railway system faces complex issues related to its specificities. There is a potential in building a multi-objective optimization to enhance its performances; further steps forward are necessary in this direction.

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

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

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

[8] 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.

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

[10] 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.

[11] 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.

[12] 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.

[13] Fayech B., “Regulation of Multimodal Transportation Network: Multi-Agent Systems and Evolution Algorithms” (in French), Ph.D Dissertation, University of Lille, 2003.

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

[15] Song W., "Real Time Dispatching Control in Transit Systems", M.Sc Thesis, MIT, 1998.

[16] 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.

[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] 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.

[21] Hansen I.A., Pachl J., "Railway Timetable and Traffic". Eurailpress, 2008.

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

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