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Improvement of real-time traffic management by using optimization tools

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Abstract

Railway operation management must cope with failures of the railway system or external disturbances that may cause initial delays or so-called primary delays. In heavy traffic areas of rail networks, primary delays can quickly propagate and lead to the so-called secondary or knock-on delays. This paper describes the results of experiments done to evaluate railway traffic optimization tools that enable to decrease the secondary delays by selecting appropriate route settings and sequence of the train movements. These experiments are part of a task of the European FP7 project ON-TIME. The project aims to develop a prototype for a new generation of railway traffic management systems which will increase capacity and decrease delays for railway customers' satisfaction. The results of the project will be validated through system simulation and real-life case studies proposed by railway undertakings which are partners of the project. This paper focuses on the results achieved in one of the case studies of the ON-TIME project, through an algorithm which we developed. It consists of the solution of a mixed-integer linear programming formulation for a limited computation time: the best feasible solution found within this limited computation time is the final solution returned by the algorithm. The case study tackled here represents traffic in the Gonesse junction, in France. We assess the impact of including the optimization in a rolling-horizon framework. The results show that the optimization is quite robust to different settings of the rolling-horizon framework.

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Keywords: railway traffic management; routing; scheduling; mixed integer linear programming; rolling-horizon

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1. Introduction

Railway timetables are often designed to fully exploit the infrastructure capacity at peak hours. When an unexpected event perturbs traffic, even slight delays may have a major impact on operations due to the knock-on effect. Delays that are directly caused by unexpected events, as a temporary speed limit reduction due to maintenance works, are named primary delays. The only possibility for reducing them is linked to the use of buffer times possibly present in the timetable. Primary delays, though, imply that trains reach specific locations along their route at times which are different from the scheduled ones. This may cause the emergence of conflicts: two trains claim the same track section concurrently and one of them has to stop to wait for the other train to clear the track section itself. These delays caused by traffic congestion are named knock-on or secondary delays. To minimize these secondary delays, it is necessary to wisely manage traffic, that is, to properly decide train routing and scheduling in real-time to tackle a specific perturbation.

In Europe, traffic management aiming to minimize secondary delay is mostly performed by dispatchers without decision support tools. However, the importance of developing such a tool is quite unanimously recognized. Different research projects have been funded in recent years for proposing possible tools and assessing their potential impact on the railway service quality. In particular, the European Commission funded a project named ON-TIME (Optimal Networks for Train Integration Management across Europe) within its Framework Programme 7 (FP7). The aim of this project is a step-change in railway capacity by reducing delays and improving traffic fluidity. This will be achieved by a partnership between railway industry experts, system integrators, small dynamic knowledge led companies and academic researchers. Within this project, a work package is focused on the development of a traffic management system able to deal with traffic perturbations in real time. This system is intended to implement the decision of an optimization algorithm for minimizing secondary delay.

In the academic literature, several algorithms have been proposed to this aim. These algorithms can be grouped in terms of: train rerouting possibility (exclusion of train rerouting in, e.g., D'Ariano et al. (2007a) and Dessouky et al. (2006), consideration of train rerouting in, e.g., D'Ariano et al. (2008) and Törnquist Krasemann (2012)), speed variation dynamics consideration (fixed-speed model in, e.g., Corman et al. (2010) and Mazzarello and Ottaviani (2007), variable-speed model in, e.g., D'Ariano et al. (2007b) and Lusby et al. (2013)) and interlocking system representation (route-lock sectional-release in, e.g., Pellegrini et al. (2014) and Rodriguez (2007), route-lock route-release in, e.g., Caimi et al. (2012) and Törnquist and Persson (2007)).

Within the ON-TIME project, different of these algorithms will be tested and, in particular, an algorithm based on the mixed-integer linear programming (MILP) formulation by Pellegrini et al. (2014). It is based on the solution of the MILP formulation for a limited computation time: the solution returned by the so obtained heuristic algorithm is the incumbent solution after this time. In the following, we will refer to this algorithm as to the RECIFE-MILP heuristic.

In this paper, we propose an experimental analysis based on RECIFE-MILP applied to traffic perturbations in the infrastructure representing one of the case-studies considered in the ON-TIME project: the Gonesse junction in France. A junction is a portion of infrastructure in which multiple lines cross and in which the emergence of conflicts is quite frequent in case of traffic perturbation. The Gonesse junction is characterized by an intense traffic including conventional passenger, high-speed passenger and freight trains. In the experiments proposed in this paper, we include the optimization in a rolling horizon framework: several optimizations are performed sequentially considering the time evolution. For example, a first optimization is performed on the traffic which is present in the infrastructure between 7:00 am and 7:30 am. Then, a second optimization is performed on the traffic which is present in the infrastructure between 7:05 am and 7:35 am. In this second optimization, the initial traffic condition at 7:05 am takes into account the decisions made in the previous optimization. The rolling-horizon framework simulates what happens in real-time traffic management. In this framework, the routing and scheduling decisions are re-assessed periodically and they are possibly modified if the actual traffic conditions changed from one assessment to the other. These assessments can be made through an optimization algorithm: it must be run repeatedly based on the current traffic state prediction concerning the time instant in which the new decisions will be implemented. The computation time available to the optimization must be coherent with the frequency of decision re-assessments, five minutes in the above example. In particular, it must be slightly shorter for taking into account the time necessary for actually implementing the decisions. The fact of tackling instances representing traffic in a possibly short time interval allows computation time to be in line with the real-time purposes, but may bring to sub-optimal decisions due to the myopic view of their consequences.

We propose an experimental analysis for assessing the robustness of the inclusion of RECIFE-MILP in a rolling-horizon framework, with respect to the settings of the framework itself. These settings correspond to the definition of the duration of the time interval tackled at each optimization and of the frequency with which the optimization is repeated. This frequency corresponds to the computation time available for each optimization. Thus, it may have a major impact on the quality of the results.

The rest of the paper is organized as follows. In Section 2, we shortly describe the ON-TIME project. In Section 3, we detail the experimental analysis. Finally, in Section 4, we draw conclusions.

2. The ON-TIME Project

The ON-TIME project (http://www.ontime-project.eu/) is supported by the European Commission FP7 and it commenced in November 2011. The overall aim of the project is to improve railway customer satisfaction through increased capacity and decreased delays for passenger and freight. To do so, it develops new methods, processes and algorithms that will enable railway undertakings to significantly increase the available capacity.

More in detail, the ON-TIME project has nine stated objectives:

- Objective 1: Improved management of the flow of traffic through bottlenecks to minimize track occupancy times. This will be addressed through improved timetabling techniques and real-time traffic management.
- Objective 2: To reduce overall delays through improved planning techniques that provide robust and resilient timetables capable of coping with normal statistical variations in operations and minor perturbations.
- Objective 3: To reduce overall delays and thus service dependability through improved traffic management techniques that can recover operations following minor perturbations as well as major disturbances.
- Objective 4: To improve the traffic flow throughout the entire system by providing effective, real-time information to traffic controllers and drivers, thus enhancing system performance.
- Objective 5: To provide customers of passenger and freight services with reliable and accurate information that is updated as new traffic management decisions are taken, particularly in the event of disruptions.
- Objective 6: To improve and move towards the standardization of the information provided to drivers to allow improved real-time train management on international corridors and system interoperability; whilst also increasing the energy efficiency of railway operations.

- Objective 7: To better understand, manage and optimize the dependencies between train paths by considering connections, turn-around, passenger transit, shunting, etc. to allocate more appropriate recovery allowances, at the locations they are needed, during timetable generation.
- Objective 8: To provide a means of updating and notifying actors of changes to the timetable in a manner and to timescales which allow them to use the information effectively.
- Objective 9: To increase overall transport capacity by demonstrating the benefits of integrating planning and real-time operations, as detailed in Objectives 1-8.

The project is organized into ten work packages:

- WP1 – User and technical requirement elicitation and validation;
- WP2 – Examination of existing approaches and specification of innovations;
- WP3 – Development of robust and resilient timetables;
- WP4 – Methods for real-time traffic management;
- WP5 – Operations management of large scale disruptions;
- WP6 – Driver advisory systems;
- WP7 – Process and information architecture;
- WP8 – Demonstration;
- WP9 – Dissemination, training and exploitation of knowledge ;
- WP10 – Project management.

The study reported in this paper has been developed within the WP4. This work package focuses on the analysis, the development and the benchmarking of a traffic management system. Such a system's aim is the effective handling of traffic perturbations through the implementation of the decisions made by optimization algorithms. The perturbations tackled here (differently from what is done within the WP5) are of small entity: the decisions are to be taken by the infrastructure manager, with no need to coordinate with the railway undertakings. In particular, neither train cancelation nor stop suppressions and additions are considered. The implementation of the train ordering is done thanks to a driving advisory system which instructs the driver on the optimal speed profile to be held for ensuring the train ordering itself, while minimizing delay and capacity consumption.

The improvement in the capacity exploitation allowed by the new traffic management system is assessed in simulation on five case-studies. These case-studies cover different railway administrations across Europe and represent specific challenges in railway operations:

1. High-capacity mixed-traffic lines: the East Coast Main Line in the UK;
2. Cross-border traffic: the Iron Ore line in Sweden and Norway;
3. Management of large complex nodes: the Gonesse junction in France;
4. Allocation of resources in significantly disturbed traffic scenario: the area around Utrecht station in the Netherlands;
5. Incorporation of improved traffic management techniques in real-world scenarios: the station of Bologna in Italy.

The simulation of the traffic management system in these five case-studies is performed thanks to a microscopic railway system simulator named HERMES.

3. Experimental analysis

The RECIFE-MILP heuristic used within the ON-TIME project is based on the formulation proposed by Pellegrini et al. (2014). The algorithm consists of solving this formulation for a fixed computation time and of considering the incumbent solution after this time as the final solution.

For the experimental analysis, we use an implementation of RECIFE-MILP based on the IBM ILOG CPLEX Concert Technology for C++ (IBM ILOG CPLEX version 12) (IBM Corporation, 2012).

We run the experiments on Intel Xeon 2.67GHz processor with 24 GB RAM, under Linux Ubuntu distribution version 12.06, and we execute CPLEX excluding parallel computation. For each run, we impose a limit of one hour and a half of CPU time.

We tackle instances representing perturbations of the timetable of a weekday in the control area including the Gonesse junction. In particular, we consider three random perturbations of this timetable, in which we randomly assign a delay between 5 and 15 minutes to 20% of trains. We focus on the interval between midnight and 11 am. This portion of the timetable includes 131 or 132 trains.

The junction, which is shown in Figure 1, includes 39 routes, 174 block sections and 89 track-circuits. For each block section, formation and release times are 15 and 5 seconds, respectively.

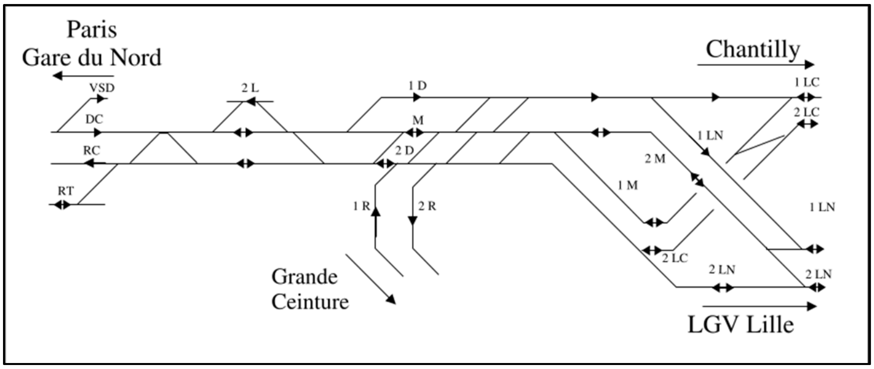

Fig. 1. Representation of the infrastructure of the Gonesse junction.

As mentioned in the introduction, we assess the robustness of the application of RECIFE-MILP in a rolling-horizon framework. In this framework, several optimizations are performed subsequently for scheduling and routing trains during a long time horizon, e.g., one day, and the decisions resulting from each optimization are implemented as they are produced. In this case, the time interval for a single optimization advances throughout the day. Hence, we must ensure the compatibility of the decisions made in the time interval being tackled and the previously made ones. Previously made decisions can be either modifiable or not. Here, the modification of previous decisions is possible. Pellegrini et al. (2014) details how to include the suitable constraints in the MILP formulation.

Figure 2 represents an example of a train sequence to be considered in a rolling-horizon framework. For sake of simplicity, it shows five block sections along a mono-directional line. The current time interval is included between the dashed lines. The trains whose track-circuit utilization is represented in white are excluded from the current optimization: either they were part of a previous optimization, or they will be part of a subsequent one. The trains whose track-circuit utilization is represented in dark-grey are those entering the control area within the current time interval. The train for which we use the light-grey color is the only one which has entered the control area before the beginning of the current time interval but it has not exited it yet. For this train, coherent constraints concerning the last track-circuit of the third block section traversed must be imposed: it is the last one that the train has started utilizing before the beginning of the current time interval. In this case, the partial route highlighted through the thick contour is part of the optimization.

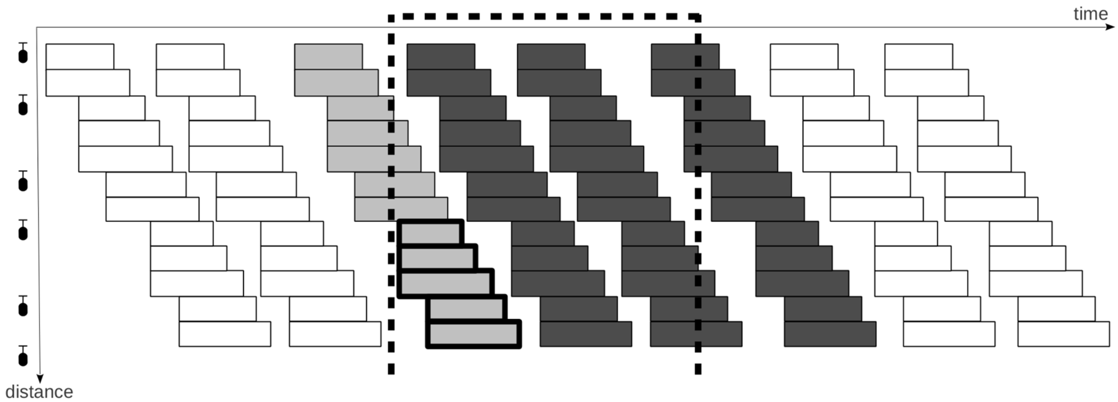

Fig. 2. Space-time diagram representing a sequence of trains traveling along a mono-directional line, considered in a rolling-horizon framework. The white trains are not part of the current optimization (dashed lines).

To perform the experiments which we analyse in this paper, we take a comprehensive horizon of 11 hours for each of the perturbed instances considered and we vary the settings of the rolling-horizon framework. In particular, we consider:

- time intervals of 15, 30, 45 and 60 minutes;
- re-optimization frequency of 5, 10 and 15 minutes.

In this analysis, we set the computation time available for each optimization equal to the re-optimization frequency.

In principle, the fact of considering subsequent short time intervals may imply myopic decisions. In fact, it is possible that a decision on the assignment of a route to a train, for example, appears very advantageous when neglecting the subsequent arrival of other trains in the infrastructure, trains with which the first one might be in conflict along the novel route. However, a short time interval should correspond to an instance which can be solved to optimality even in a short computation time, that is, even in case of very frequent re-optimization.

The impact of the frequency is quite difficult to predict. On the one hand, a frequent re-optimization implies that myopic decisions may be recognized and corrected very quickly, before strongly impacting traffic. On the other hand, the same frequent re-optimization requires a coherently quick optimization, which may result in the impossibility for the algorithm to find a very high quality solution.

The objective of RECIFE-MILP is minimizing the total delay suffered by trains within the infrastructure considered. The timetable for the Gonesse junction does not include buffer times within the junction itself: the primary delay cannot be reduced and minimizing the total delay corresponds to minimizing the total secondary delay. Then, in this analysis we assess the performance of RECIFE- MILP in terms of total secondary delay suffered by trains when they exit the infrastructure.

Figures 3-5 show the total secondary delay for each of the three perturbation instances representing 11 hour-traffic in the Gonesse junction. The plots show how this total secondary delay varies for each setting considered for the rolling-horizon framework. In each of the figures, the solid line represents the result of the rolling-horizon framework and the dashed line the optimal result which we obtained by solving the 11-hour time intervals in one shot without computation time limit.

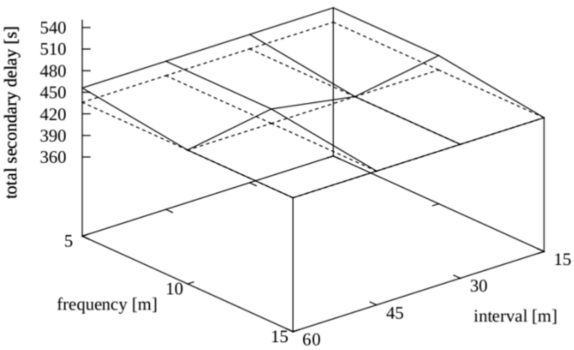

Fig. 3. Total secondary delay with different settings of the rolling-horizon framework: first perturbation instance.

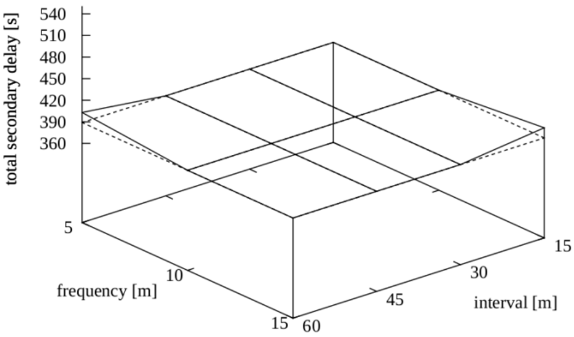

Fig. 4. Total secondary delay with different settings of the rolling-horizon framework: second perturbation instance.

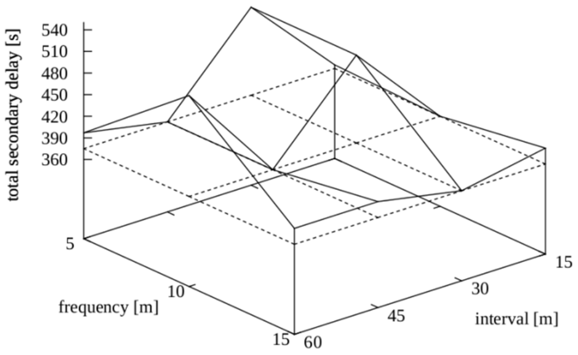

Fig. 5. Total secondary delay with different settings of the rolling-horizon framework: third perturbation instance.

In the first perturbed instance, the results achieved are extremely similar in all rolling-horizon settings. The difference with respect to the optimal solution is never higher than 20 seconds (5%) and with 6 out of 12 settings RECIFE-MILP applied in the rolling-horizon framework achieves the overall optimal solution. A trend in the solution quality can be detected in Figure 3: the frequency is the most important factor and infrequent re-optimizations appear more appropriate.

In the second perturbed instance (Figure 4), RECIFE- MILP applied in the rolling-horizon framework is even better performing: it finds the optimal solution with 10 out of 12 settings. In the two cases in which this is not the case, the error is of 14 seconds (4%). Interestingly, these two cases are the extreme ones: the performance is the worst when either a short time interval is seldom re-optimized (interval=15 m, frequency=15 m) or a long time interval is frequently re-optimized, hence with a short computation time available to RECIFE-MILP (interval=60 m, frequency=5 m).

Finally, in the third perturbed instance, the results appear more sensitive to the setting of the rolling-horizon framework. Only in 4 cases the optimal solution is achieved. Three of these four cases correspond to a time interval of 45 minutes. The error made gets to 140 seconds (37%), with a mean of 40 seconds (11%). More in detail, it gets above two minutes in three cases and it is equal to 22 seconds in the five other sub-optimal cases. The identification of a trend linking the settings of the rolling-horizon framework and the performance is not evident in Figure 5.

In summary, the quality of the results achieved changes from one instance to another. However, in the great majority of the cases the settings of the rolling-horizon framework have very slight or no impact on the quality of the solutions, with the optimal one found in 56% of the experiments on an overall horizon of 11 hours.

4. Conclusions

In this paper, we propose an experimental analysis performed in the context of a European Commission FP7 project named ON-TIME. We tackle railway traffic perturbations in a French complex junction: the Gonesse junction, where conventional passenger, high-speed passenger and freight trains cross. For managing traffic, we use a heuristic algorithm based on a MILP formulation tackled with a commercial solver which is stopped after a limited computation time. We include RECIFE-MILP in a rolling-horizon framework in which the optimization is periodically re-run for managing traffic throughout a long time horizon. We consider a horizon of 11 hours and we test the robustness of the results with respect to different settings of the rolling-horizon framework, namely in terms of re-optimization frequency and of duration of the time interval considered at each re-optimization. The results appear very robust, with the rolling-horizon framework finding the overall optimal solution in 56% of the cases and deviating of about 20 seconds in the great majority of the others.

In future research, we will extend this analysis to the other infrastructures which are considered in the ON-TIME project and we will include the optimization in a closed-loop framework involving a microscopic railway simulation tool.

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