Innovative Decision Support System for Railway Traffic Control

Abstract — Traffic controllers monitor railway traffic in a wide control area and may actively set new targets to trains for smooth operations. A decision support system, ROMA (Railway traffic Optimization by Means of Alternative graphs), is developed to cope with real-time timetable disturbances (e.g., multiple train delays and blocked tracks) more effectively. This dynamic traffic control system co-ordinates the speed of successive trains on open track (re-timing), solves expected route conflicts (re-ordering) and provides dynamic use of platform tracks in a station or alternative paths in a corridor between stations (local re-routing). We adopt blocking time theory for modeling track occupation and signaling constraints and alternative graphs for solving dynamic traffic control problems with the aim of increasing punctuality through intelligent use of the rail infrastructure. An extensive computational study is carried out on two complicated and densely used areas of the Dutch railways.

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I. Introduction

Advanced train traffic control means to ensure safety, regularity, reliability of service and punctuality of operations. Railway business strongly needs to improve the quality of service and to accommodate growth while reducing the costs. The punctuality analysis represents an important measure of rail operation performance and is often used as standard performance indicator. In the autumn of 2001 the punctuality of the Dutch railway system decreased to below 80% (percentage of trains arriving at scheduled stops with a delay < 3 min). In 2003, a report by four major companies operating in The Netherlands [14] indicated a punctuality level of 95% as a target to reach within year 2015, despite the expectation of a significant increase of traffic intensity and the limited budget available to build new rail infrastructure. This paper addresses such challenging targets

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that can only be achieved through intelligent use of the existing rail infrastructure and efficient use of the available transport capacity. We describe traffic management strategies and dispatching support systems that can be used to improve punctuality of railway operations under disrupted traffic conditions.

Performance management is usually achieved by railway managers by carefully designing an off-line timetable and operating in real-time with strict adherence to it. However, train operations are intrinsically stochastic and traffic needs to be dynamically managed. When the scheduled railway traffic is seriously disturbed, decisions have to be taken in order to reduce delay propagation.

Railway Dynamic Traffic Management (RDTM) offers an interesting possibility to improve railway services by operating flexible timetables in which each train has to fit in a time window of arrival at a given set of feasible platforms/passing tracks. A specific platform and the exact arrival/departure times are then defined in real-time by the traffic controllers, which are therefore required to perform more actions with respect to non-flexible timetables. Traffic controllers have whence enhanced possibilities to react to unexpected events by adapting the timetable to the status of the railway network. Due to the strict time limits for computing a new timetable in case of disturbances, they usually perform manually a few modifications, such as local adjustments of train routes, orders and speeds, while the effects of the chosen measures at a network scale are often unknown.

Dispatchers should spend their time on preventing traffic disturbances instead of solving them when they have already

Decision support systems cope with real-time timetable disturbances more effectively.

happened [9]. To this end, dispatching systems support dispatchers to manage traffic flow (as shown in Figure 1). Existing support systems compute rescheduling solutions on the basis of local information. They operate only "on the spot" and "now" and may implement simple dispatching rules (see, e.g., [10]). More advanced traffic management systems consider the whole traffic in a larger area, detecting future conflicts affecting train movements, scheduling automatically trains in the whole area by using global information and suggesting possible changes of train orders or routes to the human dispatcher, as well as displaying advisory speeds to train drivers. However, most of the computerized decision support systems developed, so far, can provide fairly good solutions for small instances and simple perturbations. They cannot deal with heavy disturbances in larger networks as the actual train delay propagation is only roughly estimated and does insufficiently take into account interactions among trains in the whole network. Comprehensive review on the literature on models and algorithms for railway traffic control can be found in [3, 16].

This paper compares a simple dispatching procedure with an advanced traffic management system. The simple procedure is a first come first served rule, a common practice in railway real-time management (see, e.g., [15]). The advanced system is the recently developed software, ROMA (Railway traffic Optimization by Means of Alternative graphs), that makes use of an optimization tool based on precise information on the future evolution of the train traffic at a network level. This tool can be applied to various types of heavy disturbances (such as multiple delayed trains, dwell time perturbations, block sections unavailability, and others) within a short computation time. The mathematical models and algorithms are described in [1, 3, 4, 5, 6].

FIG 1 A dispatcher at the traffic control center (Source: ProRail).

The innovative scientific contribution of ROMA is characterized by a combination of blocking time theory (see, e.g., [7]) for the recognition of timetable conflicts in case of disturbances and a general discrete optimization model, based on the alternative graph formulation of [12], for the real-time evaluation of train retiming, reordering and rerouting in railway networks, while the costs of the different options are measured in terms of delay minimization.

Computational experiments are based on two complex and densely occupied dispatching areas of the Dutch railway network, namely the Schiphol bottleneck area [8] and the Utrecht station area. The former is a dispatching area subject to high frequency passenger traffic, while the latter consists of a complex set of routes, heterogeneous traffic and less dense traffic conditions. A large set of disturbances are proposed for increasing values of train delays, multiple track blockage and different time horizons of traffic prediction. For each perturbed situation we generate several feasible schedules by using different configurations of the ROMA system. This allows us to quantify the effects of different railway dynamic traffic management strategies.

II. Decision Support System

The ROMA system is a laboratory version of dispatching support tool that is designed to assist traffic controllers in the computation and evaluation of real-time dispatching solutions. ROMA is implemented in C++ language and uses the AGLibrary developed by the "Aut.Or.I." Research Group of Roma Tre University. The proposed dispatching system does not include coupling to actual train monitoring data. A discussion of its real-time applicability and the necessary communication links between the running trains and the traffic control centers can be found in [6].

A human dispatcher should interact with the system by adding/removing constraints or changing the existing timetable. Figure 2 presents the overall ROMA dispatching support system architecture, which is composed by interrelated modules. We next describe the function of each module.

Automatic Data Loading

The **automatic data loading** module is in charge to gather all the information, which is required by the other modules. This module loads static data (off-line data such as infrastructure and timetable information) and dynamic data (train detection and other real-time information that varies in time) from the field. The operational timetable contains a list of arrival/departure times for a set of relevant points in the network, including all the station platforms visited by each train. The infrastructure consists of a set of available block sections delimited by signals. Infrastructure data includes the status and length of each block section and other characteristics, such as speed limitations and the traversing direction. The data associated with each train includes speed and position at its entrance of the network, acceleration and braking curves (calculated on the basis of traction force/speed diagrams and maximum speeds) and a prioritized list of routing options (the most evident and frequently used alternative routes are selected by the human dispatcher and given to the dispatching support system). At any time a route, i.e., a sequence of block sections, is feasible if none of its block sections is blocked. Finally, the blocking time for each pair (train, block section) is computed by this module on the basis of current rolling stock characteristics and infrastructure data.

A human dispatcher interacts with the system by adding or removing constraints or assitedly changing the existing timetable.

The off-line data is stored in a format compatible with RAILML specifications that are a standard interface for railway data in Europe. Regarding the on-line data, we suppose there are GPS sensors on board of trains such that information flows over a GSM-R channel to the traffic control center. A more comprehensive approach could be to combine GSM-R for actual train speed data and an automatic data mining tool, such as TNV-Conflict [2], for track occupancy and clearance data.

Disruption Recovery

The **disruption recovery** module checks if there are unavailable block sections in the network, which make some train route unpassable. For each train, this procedure discards disrupted routes, sorts the passable routing options on the basis of a priority list (given by traffic controllers) and then assigns the one with the highest priority, called the default route. The default route of each train and the set of remaining passable routes are then given to the railway traffic optimization module.

Since the ROMA system is only allowed to select the route of each train from a given set, when no passable route is available for a train, the system requires external support by the human dispatcher. In case of a heavy disruption, the human dispatcher authorizes ROMA to use an emergency timetable in which train routes are strongly modified, e.g., enabling a specific train to reverse its running direction according to a specific movement authority given by the traffic controllers.

Railway Traffic Optimization

The **railway traffic optimization** module is the ROMA decisional kernel that is responsible for detecting and solving train conflicts (unintended slow-down or stop in front of signals) while minimizing train delay propagation. Given all the necessary information by the automatic data loading module and (at least) a passable route for each train by the disruption recovery module, a conflict detection and resolution problem is addressed as follows (similar approaches can be envisaged in air traffic control [11]). A conflict detection procedure checks whether the timetable is deadlock-free and detects potential conflicting train paths in a given period of traffic prediction (e.g., 15 minutes ahead). A conflict resolution procedure computes a new feasible schedule compatible with the status of the network, by proactively defining routes, orders and times for all trains.

The conflict detection and resolution problem can be formulated as a job shop scheduling problem with additional real-world constraints [12]. The main value of the alternative graph is the detailed but flexible representation of the network topology at the level of railway signal aspects and operational rules. In case of fixed block signaling each block signal corresponds to a node in the alternative graph and the arcs between nodes represent blocking times or time headways.

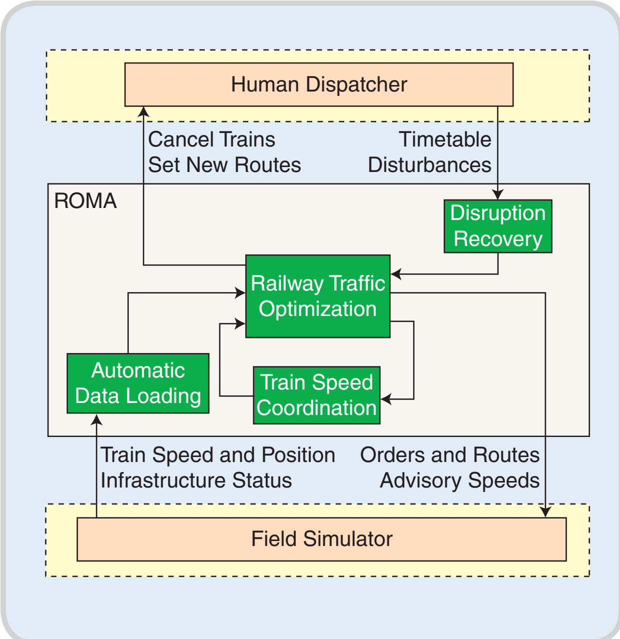

FIG 2 ROMA dispatching support system architecture.

Since the resolution of train conflicts has direct impact on the level of punctuality, delay minimization at relevant points (e.g., station platforms) can be achieved introducing suitable scheduled times. Let α_{yu} be the scheduled arrival time of a train y at a block section u in the timetable, which can be infeasible in case of real-time disturbances. Let τ_{yu} be the earliest possible arrival time of y at u computed according to its initial position, initial speed, assigned route and following a maximum speed profile (allowed by the train characteristics and infrastructure) in the empty network (i.e., by disregarding the presence of other trains). We define the total delay of y at u as the difference between its actual arrival time t_i and α_{yu}. We divide the total delay into two parts as follows. If $\tau_{yu} > \alpha_{yu}$, then the quantity $\tau_{yu} - \alpha_{yu}$ is an unavoidable delay that cannot be recovered by real-time rescheduling of train operations. We call $\max\{0, \tau_{yu} - \alpha_{yu}\}$ the initial delay of y at u. The quantity $\max\{0, t_i - \max\{\tau_{yu}, \alpha_{yu}\}\}$ is called consecutive delay of y at u, which is the additional delay due to the solution of conflicts between y and the other trains circulating in the network.

This paper compares the following two scheduling algorithms in terms of total, unavoidable and consecutive delays. The Branch and Bound (BB) is an exhaustive algorithm that explores all the reordering alternatives and chooses the one minimizing the maximum consecutive delay. Here we consider a truncated branch and bound [5] that returns near-optimal schedules for practical size problems within a short computation time. The First Come First Served (FCFS) is also evaluated. This rule gives precedence to the train arriving first at a block section, and therefore requires no dispatching action since trains pass at merging or crossing points on the basis of their actual order of arrival and not necessarily as in the timetable.

We also use rerouting algorithms based on advanced heuristics [4] that analyze the alternative routes of each train, searching for a train route potentially leading to a better schedule. Whenever a better schedule is found, the new route is set as default route and the search is repeated. Here we address the minimization of the maximum and average consecutive delays in lexicographic order. To be precise, we denote the lexicographic comparison as $[a; b] < [c; d]$ if $a < c$ or if $a = c$ and $b < d$. Since the combinatorial structure of the conflict detection and resolution problem is similar to that of the job shop scheduling problem with routing flexibility, this paper focuses on the tabu search approach that achieved very good results with the latter problem [1].

If the railway traffic optimization module is unable to find deadlock-free and conflict-free schedules, the human dispatcher has to carry out other types of timetable modifications such as introduction of new train routes, application of short-turning of trains in case of track blockage or even cancelation of train services at some stations (e.g., connections between passenger trains).

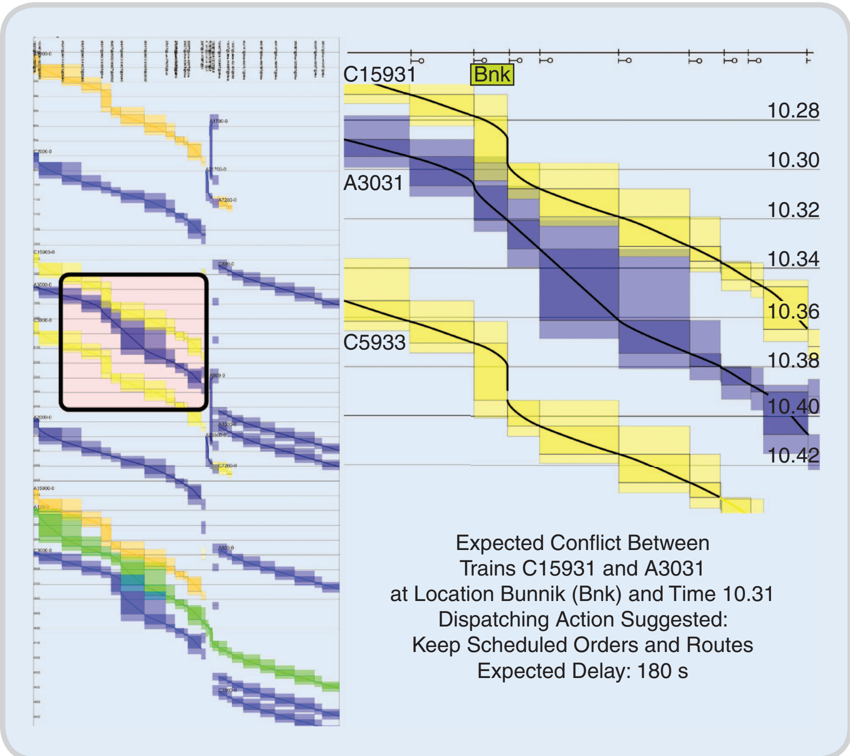

FIG 3 An interface based on the blocking time plot of the proposed control actions.

Train Speed Coordination

Given the schedule computed by the previous module, the train speed coordination module is needed to ascertain whether safe space headway between consecutive trains is respected and to update train speed profiles according to typical driver behaviors and to the dynamics of the rolling stock. In fact, the alternative graph model assumes deterministic blocking and waiting times, and train trajectories are only feasible in case of small timetable deviations.

In case of overlappings of blocking times, this module performs an iterative procedure to compute acceptable train speed profiles [6]. Speed coordination among consecutive trains is achieved by iteratively adapting the trajectories of the trains facing changes in signal aspects and by updating the blocking and waiting times in the corresponding alternative graph, such that the resulting train schedules comply with the constraints of the signaling and safety system in use, as for ETCS [13].

Interaction Between Human Dispatcher and System

Before the implementation of the predicted dispatching actions proposed by ROMA, the human dispatcher receives a detailed forecast of the future traffic flow and train delays, and has to recognize and acknowledge the changes in the timetable. In case of small perturbations, a dispatching solution could be presented in terms of the only relevant actions that differ from the scheduled ones, avoiding unnecessary corrections of the paths of on-time trains. In other more disturbed traffic conditions with multiple delayed trains, several timetable modifications may be needed to recover from delays and infeasible traffic situations. In this case, the dispatcher needs to be informed of the reasons for a particular modification of advisory speeds, arrival/departure times, and train routes and sequences.

> Dynamic traffic control systems co-ordinate the speed of successive trains on open track, solve expected route conflicts and provide dynamic use of platform tracks in a station or alternative paths in a corridor between stations.

Figure 3 depicts an interface between ROMA and the human dispatcher. Blocking time graphs are useful to represent, visually, the future evolution of the train traffic. The main limitation is that only one corridor at a time can be investigated in sufficient level of detail (e.g., Figure 3 shows four virtual overlaps of blocking times for trains C15931 and A3031 that are running on the same line) while the visualization of route conflicts and route booking actions is quite complex in station areas. So, specific points of interest, where a specific train would experience consecutive delays, and the suggested rescheduling solutions are highlighted with a sufficient amount of detailed information (e.g., location of potential conflicts, suggested orders and routes, expected delay) to let the dispatcher understand the proposed dispatching actions and their actual impact on operations.

III. Computational Experiments

The aim of the study is to assess to which extent train delays could be minimized by choosing suitable dispatching actions and dynamic traffic management strategies. We show experiments performed to evaluate the ROMA system over a large sample of real-life instances. ROMA runs on a PC equipped with a processor Intel Pentium D (3 Ghz), 1 GB RAM and Linux operating system. Each run of the BB algorithm is truncated after 10 seconds of computation (the best-known solution is often found during the first few seconds of computation), while the FCFS algorithm takes less than 1 second of computation. The whole time allowed to the railway traffic optimization procedure to compute a solution is limited to 60 seconds in order to be timely reactive to disturbed traffic situations.

Schiphol Dispatching Area

The dispatching area around Schiphol tunnel is shown in Figure 4. The network consists of 86 block sections, 16 platforms and two traffic directions. The rail infrastructure is around 20 km long and consists mainly of four tracks, divided into two pairs for each traffic direction. Trains enter/leave the network from/to ten access points: the High Speed Line (HSL), the station of Nieuw Vennep, the shunting yard of Hoofddorp station, and two stations in Amsterdam, namely Amsterdam Lelylaan and Amsterdam Zuid WTC. The two traffic directions are largely independent except around Amsterdam Lelylaan station and at the border of Hoofddorp shunting yard. There are two intermediate stations: Hoofddorp and Schiphol.

We use an experimental timetable for passenger trains, designed to face the expected increase in traffic through this bottleneck area in the next years. This challenging timetable is very close to capacity saturation of this area, thus making it an interesting test case for our study. The timetable is cyclic with a period length of one hour and contains 27 trains per direction, for a total of 54 trains running each hour. This is a timetable with a limited amount of time reserves to recover

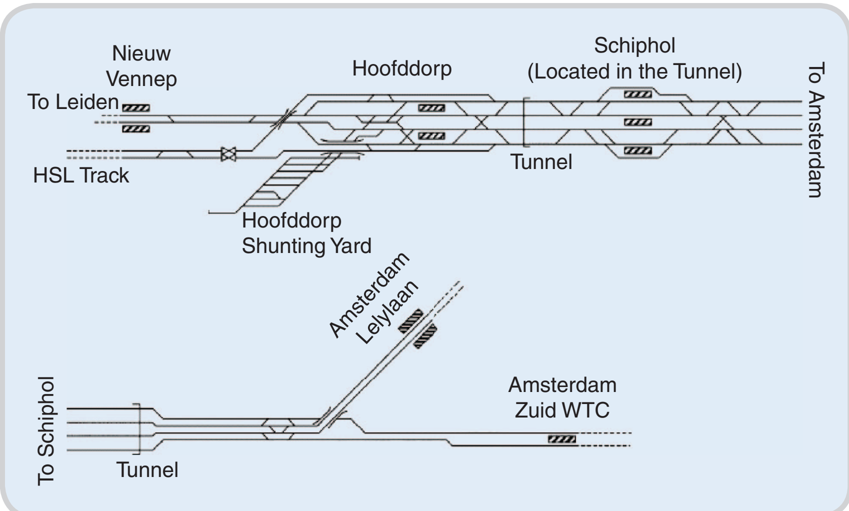

FIG 4 Schiphol dispatching area (Source: [8]).

> Experimental evaluation has been carried out at the dispatching area around Schiphol tunnel is shown in and at the railway network around Utrecht Central station.

delays, due to the high number of trains which is not far from the network capacity saturation. It is worthwhile observing that the actual number of trains per hour scheduled at Schiphol during year 2007 was 20 trains per direction [8]. In 2009, the hourly timetable of Schiphol is expected to include 24 trains per direction [15]. We chose the more challenging timetable with 27 trains per direction in order to assess the effectiveness of ROMA under even more dense traffic conditions. We consider alternative platform stops at Schiphol station. This flexibility is only applied to nearby platforms in order to limit passengers' discomfort. In total, there are 111 routes available for train rerouting.

Utrecht Dispatching Area

The railway network around Utrecht Central station is shown in Figure 5. Five main lines converge to Utrecht, connecting the North and South regions of The Netherlands to the lines to the West and the East. The network considered is delimited by the following stations: Utrecht Overvecht on the line to Amersfoort, Driebergen-Zeist on the line to Arnhem, Culemborg on the line towards Den Bosch, Vleuten on the line to Rotterdam and the Hague plus Maarssen on the line towards Amsterdam. In total, the diameter of the dispatching area is around 20 km long.

Utrecht Central station is one of the most complex Dutch railway areas, including more than 600 block sections and a very complicated and densely occupied interlocking area, defining a large amount of inbound and outbound routes. Most of the trains have a scheduled stop at one of the 20 platform tracks. The total amount of travelers at Utrecht Central Station is around 150.000 per day.

We use a provisional 2008 timetable that is cyclic with a cycle length of one hour. The trains are mostly for passenger services, operated by NS (Nederlandse Spoorwegen), except for a few freight trains. The timetable schedules up to 80 trains in a peak hour and provides connections between passenger services, coupling and splitting of rolling stock for intercity and local services coming from/going to Rotterdam, the Hague or Amersfoort, as well as rolling stock re-use for

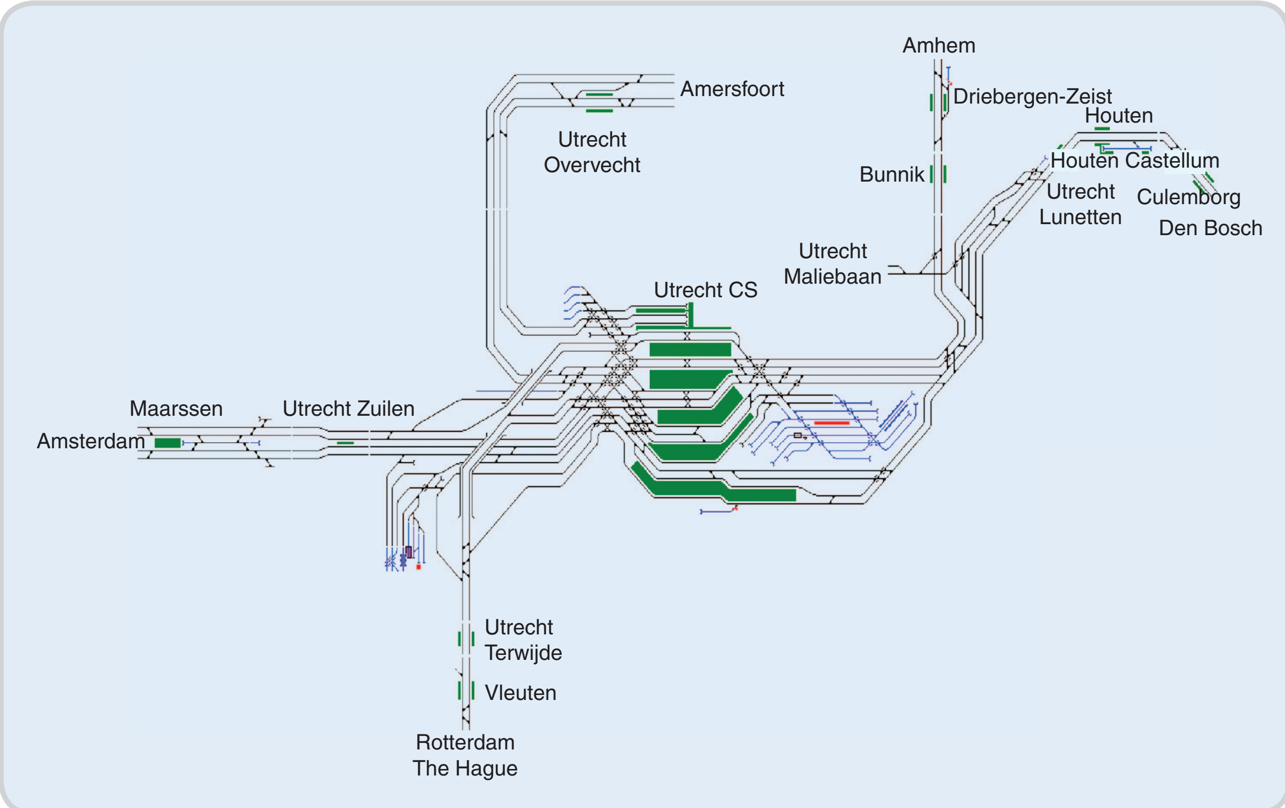

FIG 5 Utrecht dispatching area (Source: ProRail).

commuter services towards Utrecht Overvecht and Culemborg. We consider the possibility of rerouting trains to nearby platforms. This flexibility results in a total amount of 228 alternative train routes.

Various improvements are achieved and up to 50% reduction in maximum consecutive delay is possible.

Railway Dynamic Traffic Management Strategies

The effectiveness of implementing various RDTM strategies in the ROMA system is now discussed. For each railway area, we consider 81 delay instances by varying the number of delayed trains (between 1 and 5), the number of available tracks (between 67% and 100%), the maximum entrance delay (between 100 sec and 900 sec) and the time horizon length (between 15 min and 60 min). In Figure 6, we report the average results on the 81 instances for all the combinations of the following RDTM strategies: two scheduling algorithms ("FCFS" and "BB"), two types of departure times (the case "Flexibility" means one minute of flexible departure time for all trains at their scheduled stops, otherwise all the departure times are fixed) and two types of routing (the case "Rerouting" means the routes can be chosen by the tabu search of [1], otherwise only the default routes are selected).

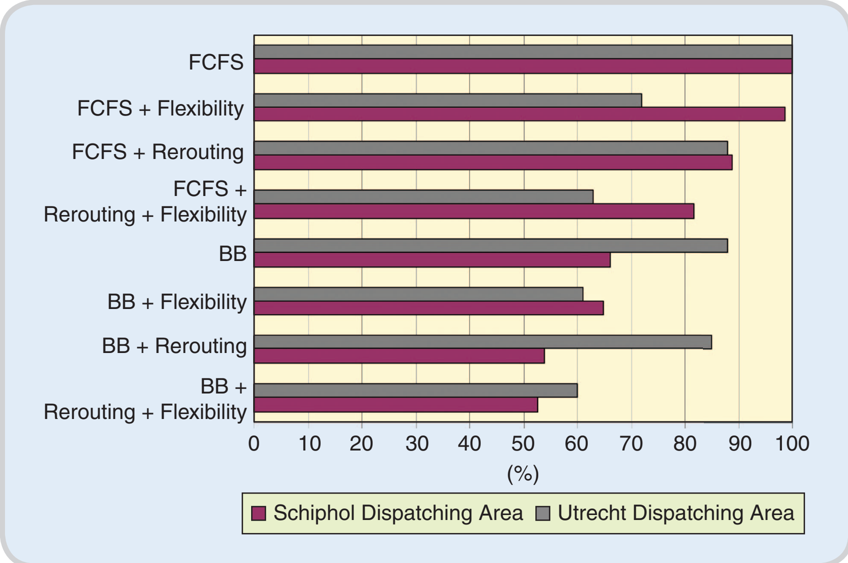

FIG 6 Maximum consecutive delay with various ROMA configurations.

Figure 6 shows the percentage reduction of the maximum consecutive delay from the worst configuration of the railway traffic optimization module, obtained with the only FCFS algorithm, up to the best ROMA configuration, obtained with the combination of BB, flexible departure times and rerouting. For both ares, consecutive delays are computed for all trains at their scheduled stops and at their exit from the network. In the Schiphol case, the overall reduction is close to 50% (224 sec), more than 30% of which is due to the BB algorithm that chooses train orders on the basis of global information on the delay propagation. The routing optimization procedure contributes to most of the remaining reduction even if rerouting is only allowed as alternative platforming of trains at their scheduled stops. In this case, flexible departure times are not very relevant. This is likely due to the fact that the Schiphol timetable is dense of trains that run with short time headways. In the Utrecht case, the overall reduction is around 40% (101 sec) and is largely due to the combined effect of using BB and departure flexibility. The different performance is probably due to the longer dwell times at Utrecht Central Station, leading to more possibilities to improve train punctuality by means of flexible departure times. In general, the different RDTM strategies have a considerable impact in terms of limiting the propagation of train delays but their effect depends on the infrastructure topology, density of traffic and time headways between consecutive trains.

Table 1 presents other three performance indicators (i.e., the maximum total delay, the average total delay and the number of trains with a positive total delay) in order to quantify the system impact in a global measure. Each row reports the average improvement obtained on the 81 instances for a dispatching area by comparing the best ROMA configuration against the FCFS algorithm.

Table 1. Total delay reduction of the best ROMA configuration versus FCFS.

Dispatching Area	Max Total Delay (s)	Avg Total Delay (s)	Number of Trains With Delay > 0
Schiphol	408	86	3
Utrecht	128	21	14

When dealing with total delays, the average improvement offered by the best ROMA configuration is relevant since the train speed coordination module needs to perform less speed adjustment iterations (12 less iterations for the Schiphol case and 5 less iterations for the Utrecht case). The total delay reduction is more evident for the Schiphol case since the train speed coordination module causes a larger domino effect of increasing train delays. However, the number of delayed trains is better reduced for the Utrecht case that has significantly larger time reserves to recover from delays.

IV. Conclusions

This paper presents the performance of different ROMA configurations and various RDTM strategies. The results show the effectiveness of using advanced optimization tools compared to a simple and local dispatching procedure. ROMA can be applied to compute precise and efficient dispatching solutions for any given infrastructure and timetable. This fact enables its usage when managing dense traffic in complex railway networks and under severe traffic disruptions, such as when emergency timetables are required and traffic controllers need support to solve conflicts and deadlocks.

As for the impact of railway dynamic traffic management (flexible departure times at scheduled stops, train retiming, reordering and rerouting), our computational results demonstrate that all the discussed strategies may lead to interesting improvements. These benefits are the largest when the strategies are used in combination with advanced traffic management algorithms.

Future research should address the integration of the proposed system into a larger framework, enabling to cope with several dispatching areas. To this end, it is important to address the decomposition of large problems into smaller problems to be solved by local dispatching systems, and their coordination may ensure globally viable and effective solutions for the whole railway network.

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Author Biography

Andrea D'Ariano was born in 1979. He received the B.S. and M.S. degrees in Computer Science and Automation Engineering from Università degli Studi Roma Tre, Rome, Italy. In November 2003, he joined the TRAIL Research School and the Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology. In April 2008, he successfully concluded his Ph.D. studies under the supervision of Prof. I.A. Hansen. He is now working as Post-doc Researcher at Università degli Studi Roma Tre, Department of Computer Science and Automation Engineering, under the supervision of Prof. D. Pacciarelli. His research publications were acknowledged by TRAIL Congresses, International Association of Railway Operations Research Seminars and INFORMS Railway Applications Section Meetings as best papers, and by IEEE ITSS as best PhD thesis. A large number of articles (by him and co-authors) are published in peer reviewed international scientific journals and conference proceedings. He also served as reviewer for international journals and as expert for European Commission.

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