Intelligent Network Traffic Management in Emergency Situations

Francesco Corman (1), Andrea D’Ariano (2), Ingo A. Hansen (1)

(1) Department of Transport and Planning, Delft University of Technology, Stevinweg, 1 - 2628 CN Delft, The Netherlands (f.corman@tudelft.nl, i.a.hansen@tudelft.nl)

(2) Dipartimento di Informatica e Automazione, Università degli Studi Roma Tre, via della Vasca Navale 79 - 00146 Roma, Italy (a.dariano@dia.uniroma3.it)

Abstract

The railway system is vulnerable to disruptions that require careful management of available infrastructure capacity in order to keep operations feasible and attractive for passengers and for the environment. Dispatchers manage traffic with a limited view on the network impact of their actions. Effective large scale dispatching solutions are required to better forecast the delay propagation in multiple dispatching areas.

This paper describes a dispatching support system for the real-time management of disrupted traffic in large networks. We use an advanced (multi-area) version of the ROMA (Railway traffic Optimization by Means of Alternative graphs) tool that is composed by a coordinator and several local decision support systems, one for each dispatching area. This tool manages disrupted traffic on a large Dutch network including 10 areas. We consider serious disturbances on double track lines where some block sections of one track are unavailable for traffic. We start from a set of disruption resolution scenarios and compute a feasible plan of operations for each of them. For each scenario, we apply the multi-area ROMA tool in order to compute a feasible schedule of operations at the level of signal control. The traffic controllers will choose one train schedule for implementation with least delays and cancelled services. A test case is evaluated on a large part of the Dutch railway network (300 km long) with hourly heavy traffic (150 trains). We solve a set of disruption resolution scenarios and evaluate them in terms of travel times, train delays and track occupation.

Introduction

Operational traffic management is mainly directed towards recovering from disruptive events as quickly as possible. Technical failures, delays and other unscheduled events (longer dwell times due to passengers, reduced operating speeds, bad weather and temporary unavailability of some routes) are considered as serious disturbances or even disruptions since these may influence seriously the running times, dwelling and departing events of trains. In fact, some trains may be required to stop in front of crossings or junctions, causing non-scheduled waiting times and longer running times due to slowing down and subsequent re-acceleration. Due to the interaction between trains, such disturbances can propagate to other trains in the network. The railway system is vulnerable to changed traffic conditions and railway traffic has quite often to be rescheduled.

During disruptions train operating companies adjust, in short time, the personnel and rolling stock plan in order to be compliant with the actual traffic situation, avoiding unbalances that may result in unavailability of train units or crews. Traffic controllers then manage traffic under shortage of spare capacity and several delayed trains. Experienced infrastructure managers have developed strategies allowing them simply to foresee disruptions well in advance and to take compensatory control actions based on local information. In the Netherlands, so called emergency timetables are used as a response to disruptions, covering every possible infrastructure malfunction. However, dispatchers control local areas and have a limited view on the broader network impact (costs and benefits) of their actions. Also, existing dispatching systems are only used to monitor disrupted situations rather than to control railway traffic. So far, train dispatching is still limited to simple timetable updating, changing orders and routes according to predetermined rules or personal experience. Most of the dispatching approaches existing in literature limit the analysis to simple networks or simple perturbation patterns. The analyzed delay patterns are often quite specific, e.g., only one train is delayed or the problem is limited to a single junction or to a simple line. Moreover, the assessment of disturbed traffic conditions is often simplified and does not capture entirely the consequences of delays and other disturbances, such as limited capacity, potential conflicts and deadlocks.

The main contribution of this paper is the evaluation of advanced dispatching approaches for the management of train traffic flow in a large railway network during exceptional traffic situations such as network disruptions. We consider serious disturbances on double track lines where some block sections of one track are unavailable for traffic. We start from a given set of disruption resolution scenarios: disrupted train services are either cancelled, rerouted in the disrupted area or rerouted in other areas while still with the
same origin and destination. For each scenario, a large scale dispatching system is used in order to compute a feasible schedule of operations at the level of signal control, as for ETCS (see e.g. Hansen & Pachl, 2008 and Winter, 2008). A coordination procedure takes care of harmonizing the dispatching solutions over multiple dispatching areas, ensuring feasibility from a global point of view. The output of the system is a series of feasible plans of operations at microscopic level that might be evaluated according to a variety of performance indicators. The dispatcher of each local area has to choose one schedule for implementation, with least travel times, train delays and cancelled services.

Discussion on the current railway practice and ambition

Current operational traffic management is reactive: a train driver tries to adhere to the original schedule and responds to the actual signalling aspects when the route ahead happens to be occupied. Dispatchers only reschedule the route setting plan when trains have a considerable delay, and network traffic controllers become active only when train traffic is already highly disrupted. Many knock-on (or consecutive) delays, however, could be prevented if traffic was pro-actively managed, i.e., dispatchers can spend their time on preventing traffic disturbances instead of only solving them when they have already happened.

Based on an accurate monitoring of the actual train positions and speeds the potential conflicting routes can be predicted in advance and might be resolved in real-time. The adjusted targets (location-time-speed) would then be communicated to the relevant trains by which the informed drivers could be able to anticipate better on the changed traffic conditions. Such a traffic management system would be effective in coordinating the speed of successive trains on open tracks, securing time windows at junctions/crossings, or synchronizing the arrival of the trains at stations in case of delays and expected route conflicts.

Network dispatchers regulate the railway traffic by sequencing the train movements and setting the routes with the aim of ensuring smooth train movements and limiting as much as possible existing delays. Due to the strict time limit available for computing a new timetable, which so far is rather infeasible by using existing tools, operators usually restrict themselves mostly to a few manual modifications of the timetable. Experienced dispatchers have developed strategies allowing them simply to foresee possible disruptions well in advance and to take compensatory control actions based on local information. In general, minor changes are preferred instead of extensive rescheduling in order to alter as little as possible the original timetable.

Basic practical dispatching systems have been developed to aid traffic controllers, whose computer support is often limited to graphical interfaces and simple automatic route setting systems (a system which provides the automatic setting of a given route when a train approaches a signal). The usual policy still consists of scheduling trains following the order in the timetable or according to pre-determined dispatching rules. A practical application of simple local measures, e.g. train reordering at crossing points on a first come first served basis, has recently been introduced in the Dutch railway network (see e.g. Hemelrijk et al. (2003) and Schaalma (2005)). Another example is the ARI system, which includes some limited conflict detection and resolution measures (Berends & Ouburg, 2005). However, such systems do not provide an effective support when dealing with heavy disturbances in complicated networks and extensive rescheduling would be necessary to obtain feasibility. Furthermore, there is a need for more effective conflict resolution systems which are able to exploit more information about the actual status of the network.

With the goal of exploiting existing railway potentials to provide reliable, frequent and integrated transport services, attractive to passengers and freight transportation, legal frameworks have been recently put into existence by the European Communities and governmental bodies. Deregulation of the sector (cf. European Directive 2001/14/EC) separates the concerns of the railway infrastructure manager, that has the duty to make accessible, available and exploitable the railway infrastructure, and the train operating companies, which offer transport services to passengers and goods in a market environment. Similarly, compensation schemes are introduced, with the aim of explaining in a fair and non-discriminatory way the sources causing delay to traffic, that could be traced back either to negligence of the infrastructure manager, a train operating company, or some external cause. In this way, the interaction of the multiple competing actors must be unbundled and become transparent, and reasons of train delays and unreliable operations need to be spotted and dealt with (Daamen et al. 2009). Furthermore, in the Netherlands, performance contracts between the government and train operating companies specify some minimum required punctuality levels and impose fines for poor performance (European Commission, 2001).

Efficient rescheduling and rerouting in saturated interconnected national and international railway networks depend on the availability of reliable information for schedules, train circulation plans, crew rotation schemes and their integration with the actual state of operations. Furthermore, online information such as the actual
and short-term passenger demand between railway stations and interconnected urban and regional public transport lines, as well as the actual travel speed and vehicle capacity load are needed. Due to the huge complexity of such a large-scale multi-modal network, our current research work focuses on priority international railway passenger and freight corridors of the European Union under various signalling system technologies. It is also intended to make use of our published train rescheduling work in the proposal for the EU FP7 SST.2011.5.2-5 project 'A system approach for railway operations management'.

New methodology for distributed traffic control

This paper applies recent optimization approaches for quick and efficient support of dispatching decisions during the management of disrupted traffic situations on a large, complex and busy network. To cope with a network composed of multiple dispatching areas, we incorporate the single-area dispatching support system ROMA (Railway traffic Optimization by Means of Alternative graphs) (D'Ariano et al. 2008 and D'Ariano, 2008-2010) in a novel framework that addresses the control and coordination of dispatching procedures over multiple local areas.

Figure 1 reports the general layout of the overall large scale dispatching support system (DSS) architecture. Graph theoretical models plus exact and approximate re-timing, re-ordering and re-routing solution algorithms for single-area and multi-area dispatching problems are described in D'Ariano (2008-2010) and Corman (2010), respectively.

Figure 1. Architecture of the multi-area disruption handling approach.

At local level, the main problem is the definition of train routes and orders at stations, junctions and passing points. The blocking time theory (see e.g. Hansen and Pachl, 2008) is adopted to compute the minimum required separation between consecutive trains. With these assumptions, we consider this problem as a job shop scheduling problem with additional constraints. A truncated branch and bound procedure (D'Ariano et al., 2007) computes a train schedule that is a deadlock-free and conflict-free, and optimal for each local area, given the route of each train and the variables associated to operations at the borders of the area.

At global level, the global coordinator is in charge of detecting whether the local solutions are compatible with each other. If the solutions are not compatible, the coordinator has to find an assignment for the border variables (i.e. deciding particular train orders and times at the borders) and to transmit it quickly to the local ROMAs, so that the overall rescheduling solution is globally feasible. To this end, relevant local information is exchanged between the coordinator and the local solvers in the form of aggregate data describing the interactions between trains running in adjacent areas. A compact representation of variables and constraints regarding relevant border information between the areas limits the size of the set of data to be managed, avoiding the coordination level to become the bottleneck of the procedure (more detail regarding the solution procedures can be found in the recent contributions of Corman et al., 2011).

Test case and computational results

A test case is evaluated on a large part of the Dutch railway network (300 km long) with hourly heavy traffic (150 trains), shown in Figure 2. Every thin line corresponds to a train line that schedules two services per
hour per direction. The thick lines identify the three areas considered. On this network we consider a disruption blocking the track between Den Bosch and Geldermalsen.

Figure 2: Schematic view of the traffic flow in the network, and its division into 3 areas.

We assess the potential impact of applying a set of disruption resolution scenarios (identified by the notation a-b-c, where a is the number of services along the considered line that are locally rerouted in the vicinity of the disruption; b is the number of services that are globally rerouted via Nijmegen and Arnhem, and c is the number of cancelled services compared to the regular timetable). The scenarios are evaluated in terms of "generalized" travel times (i.e., weighing waiting times twice as much as travel times) for the OD pair Utrecht-Den Bosch, minimal cycle time to operate the services, level of track occupation, and average output delay considering all trains in the network.

Figure 3 reports examples of scenario evaluations. The red, yellow, and green background highlights respectively a small, medium, great attractiveness of the solutions according the solution quality indicator considered in each column. Resolution scenarios result in an interesting trade-off for the performance indicators given in Figure 3. For instance, scenario 12-0-0 achieves the smallest generalized travel time for the given OD pair, while scenario 4-0-8 achieves the smallest average train output delay, and the other scenarios perform the best if combined indicators are favourite.

<table>
<thead>
<tr>
<th>Disruption Resolution Scenario</th>
<th>Generalized Travel Time for Utrecht-Den Bosch (sec)</th>
<th>Minimum Cycle Time (sec)</th>
<th>Track Occupation (Percentage)</th>
<th>Average Output Delay (sec)</th>
<th>Train Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-0-0</td>
<td>4048</td>
<td>4252</td>
<td>118</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>8-4-0</td>
<td>4737</td>
<td>4008</td>
<td>111</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>8-0-4</td>
<td>4218</td>
<td>3843</td>
<td>106</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>4-4-4</td>
<td>5655</td>
<td>3600</td>
<td>74</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>4-0-8</td>
<td>6309</td>
<td>3600</td>
<td>74</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Evaluation of five disruption resolution scenarios.
Through our disruption handling procedure, the proposed approach finds feasible train schedules within around 3 minutes of computation and evaluates alternative resolutions of disrupted situations, such as global rerouting or cancellation of train services. Multiple performance indicators assess the negative effect of disruptions on the quality of the railway services, so that the local dispatchers and the network coordinator can choose the most effective resolution scenario and the corresponding microscopic plan of operations for dealing with the disrupted traffic situation.

Roadmap of future steps for practical application of the rescheduling system

In the current status of the system, we include stochasticity to describe train delays and perturbations; however, parameters and realization of delays are characterised as deterministic input to the system, i.e., exactly known at the beginning of the time horizon of traffic prediction. The impact of small stochastic variations in input data, unmodelled dynamics or inaccurate parameter values toward solution quality of advanced dispatching solutions need to be further studied. From preliminary computational assessment, the optimised multi-area ROMA solution algorithms offer a better delay reduction than simple dispatching rules, and also prove to be more robust to variations in input parameters than myopic rules based only on local information.

A further step would evaluate the advanced mathematical models proposed using real-time data of position and speed of trains. Such data can be either derived from currently available information like train describer data, combined with intelligent data mining tools (Daamen et al. 2009), or measured directly by devices as GPS and communicated via channels such as GSM-R. By doing so, it will be possible to forecast precisely the train position in the short-term future. In actual operations, a closed control loop will address uncertainty in position, speed and parameters considered, with the dispatching support system updating successively its prediction in reaction to undergoing changes of the status of the network. In this way the full potential of advanced dispatching can be evaluated and compared with the decisions of experienced human dispatchers, at local and global level. To develop such systems, interesting lessons can be learnt from a train driver assistance system that is recently being introduced in the Netherlands (Albrecht and Van Luipen, 2006). In their approach, the status of the block sections along the expected train path is transmitted to the driver, basically giving him an extended sight. Even though no optimization approach is considered, just by having available such information, drivers can anticipate braking and coasting decisions, saving energy and reducing delay.

Acceptance by dispatchers and train drivers is a crucial factor. The dispatcher needs to be supported during operations by having a broader view of the current status of the network compared to what it is available now, with the expected conflicts identified at microscopic level, and suggesting potential solutions. For this reason, the interface must be designed simple, unambiguous, and easily comprehensible, in order to hide the underlying complexity of the algorithms and avoid overwhelming the decision process when reporting required information on large areas, with dense traffic, and for longer time horizons. A dispatching decision support system could either present a solution in detail, or deliver a set of possible solutions, each being more suitable according to one of the multiple objectives that are relevant in railway operations, other than reduction of delay propagation. In fact, most real-life problems are characterised by many conflicting objectives, related to multiple actors, interests and operational requirements. Considering only a particular aspect of the problem might have a negative effect on the others, and benefits on one side could easily be hidden by (sometimes unavoidable) drawbacks on different sides; a clear combined view of the multiple objectives is required to avoid sub-optimal solutions. To consider additional objectives and deliver more attractive dispatching solutions, alternative approaches should be investigated, considering extra objectives when optimising railway traffic. A possible approach addresses scheduling trains according a green wave traffic policy, in fact combining two important dispatching objectives: the minimization of train delays and of energy consumption. In this way, the benefits of that particular policy could be determined in relation to the characteristics of train traffic, timetable, and infrastructure. Another systematic approach concerns the joint problem of reducing delay propagation (mainly a goal of the railway infrastructure manager) while avoiding to cancel passenger connections (a problem affecting railway operating companies).

Concerning the setting of such a system during real-time operations, it is important that the dispatcher receives a detailed forecast of the future traffic flow and train delays. During operations the interaction between the decision support tool and the dispatcher needs to be simple, clear and fast since the dispatcher has to decide which solution should be implemented among a set of possible solutions. In very disturbed traffic conditions with multiple delayed trains and track blockage situations, several timetable modifications are 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. Moreover, big disruptions are always associated with (and are the cause of) minor
perturbations; a ranking between the proposed dispatching actions is beneficial to identify the relevant actions that differ from the scheduled ones, and their effects towards feasibility and delay propagation, avoiding unnecessary corrections of the paths of on-time trains.

**Real-time dynamic setting of the rescheduling system**

In real-time railway traffic management, time is one of the most important aspects that should be represented in a realistic way. In reality, real-time traffic management is an ongoing dynamic process with permanently changing circumstances due to new disturbances. However, railway traffic management in the large-scale dispatching support system is reduced to a deterministic optimization problem that is solved in a single run. We now discuss how our decision support tool could be used in a dynamic setting with operations. We observe that the applicability of the proposed dispatching solutions is influenced not only by the accuracy of the dispatching support tool in representing the actual and future traffic situations, but also by the reliability of the control actions (i.e., the ability to precisely forecast their outcome).

For these reasons, we next focus our attention on the following time intervals necessary to close the loop with operations (see Figure 4):

- $t_0$: time at which the current position and speed of each train are updated;
- $t_1$: time at which the DSS starts computing a dispatching solution;
- $t_2$: time at which the DSS returns a dispatching solution;
- $t_3$: time at which the DSS solution is accepted by the dispatcher;
- $t_4$: time at which the dispatching actions are implemented;
- $t_0'$: next time $t_0$.

![Figure 4: Time intervals to apply the dispatching support tool during operations](image)

The above times can be interrelated as follows. The time between $t_0$ and $t_1$ is needed to record actual train positions and speeds and communicate these to the traffic control centre. At time $t_0$, we make use of the best prediction of all train positions and speeds obtained before that time. This can be transmitted via GSM-R on-board units of trains or by interpolating real-time train detection and signalling data. The time step between $t_1$ and $t_2$ is needed by the DSS to reconstruct the current traffic conditions, simulate the future evolution, detect possible conflicts and provide solutions. The time between $t_2$ and $t_3$ is used by the dispatcher to check the dispatching solutions given by the DSS and, eventually, to compare those with other dispatching options. The time between $t_3$ and $t_4$ considers the delay due to the transmission of the control actions as well as the time needed to implement the dispatching actions in practice, such as switching signals and setting up routes.

We now introduce the starting time $\pi$ of the traffic prediction, the time horizon length $T$ and the time $t$ to compute a dispatching solution, and describe how to set them up with respect to the other times. The DSS provides control actions in the time interval between $\pi$ and $\pi + T$. It is assumed that no relevant unplanned action will occur from $t_0$ to $\pi$ and the traffic flow in the network is determined exactly. However, an error between the simulated traffic and the actual traffic always exists due to the dynamic nature of the real-time operation and the inherent inertia of the dispatching process. If the dispatching support tool is not able to model the current status of the network with sufficient precision, the control actions suggested by the tool after $\pi$ might be sub-optimal, obsolete or even infeasible.

The suggested actions would be physically applicable only if $\pi$ is larger than $t_4$. From a practical point of view, the longer the interval $t_4 - t_0$ is the larger is the error between the simulated and actual network status. To limit this error, the dispatching tool must achieve a sufficient precision in simulating the status of the system within the required computation and communication times. Since the available computation time is rather limited, the time horizon of traffic prediction $T$ may be also limited. So, the computation of downstream possible conflicts too far away in time should be avoided since the prediction uncertainty increases. However, the computation of optimal dispatching solutions requires taking into account global information regarding train traffic. The dispatching tool should thus manage traffic in a large interconnected area with dense traffic.
An important issue to assess is the frequency of rescheduling. In fact, \( t'0 \) is a variable time since the dispatching support tool may be run periodically or event-based (discussions on rescheduling under uncertainty can be found e.g. in (Aytug et al. 2005, Hozak and Hill 2008, Vieira et al. 2003)). In general, important parameters for choosing the frequency of rescheduling are the traffic prediction horizon \( T \), the accuracy of the simulation procedure and the robustness against random variations in the dynamic traffic flow evolution. The more often the dispatching tool is used the less is the divergence between the train operations simulated by the tool and by the actual traffic conditions. On the other hand, the dispatching tool could be adopted when a particular condition triggers, i.e., when the error for an observed variable exceeds a given threshold or when an unplanned disruption has occurred and the current solution is infeasible. A deeper analysis on the choice of the relevant times \( t0; t1; t2; t3; t4 \) and their link with the time horizon \( T \) and the starting time of traffic prediction \( \pi \) would be necessary. To this end, experimental verification must still prove the applicability of the support tool in a real-world setting and the effectiveness and promptness of advanced dispatching measures compared to the current dispatching process.

Additional discussions on the interaction between dispatchers and decision support tool, the times characteristics of the tool when put in a dynamic setting with actual operations, and more practical issues concerning the implementation, applicability and real-time accuracy of the rescheduling actions can be found e.g. in D’Ariano (2008-2010), Corman (2010) and Corman et al. (2011).

Summary and further research

This paper described an advanced laboratory dispatching support tool for the control of large networks. The tool is implemented in C++ language, is compatible with Linux and Windows platforms and uses the AGLibrary developed by the “Aut.Or.I.” Research Group of Roma Tre University. We adopted automatic scripts to convert infrastructure, timetable and rolling stock data from existing formats supplied by the Dutch network infrastructure manager to our specific format.

Future research should address the automatic generation of multiple scenarios and dispatching solutions based on the actual infrastructure availability. The advanced rescheduling system here used to evaluate plans during operations can also be used be used in the planning stage in order to evaluate the feasibility and performance of alternative timetables from a microscopic point of view.

The dispatching tool can be used in real-time to support dispatching. The local dispatcher may choose a single train schedule associated with a pair timetable and dispatching solution. The final output would include blocking time graphs, the evaluation of train delays and travel time for passengers, and measures of robustness against possible traffic perturbations. Another use of the dispatching tool can be for the off-line evaluation of draft timetables. Currently, timetables are mostly evaluated by considering limited stochastic factors, by neglecting capacity constraints in complex areas and by assuming fixed train orders during perturbed operations. With the proposed tool, variability of operations is modelled by random distributions of delays and other inputs characteristic in a Monte Carlo scheme. Further study of the combined effects of input variability, different timetables and dispatching policies would represent a step forward for the assessment of timetables during the planning stage. When computing train schedules, the circulation of rolling stock and crew could be evaluated on a more granular level of investigation in order to better evaluate passengers’ discomfort and robustness against network-wide delay propagation.

Acknowledgements

This work has been partially supported by the Italian Ministry of Research, Grant number RBIP06BZW8, project FIRB “Advanced tracking system in intermodal freight transportation” and by Dutch Technology Foundation, project STW: “Model-Predictive Railway Traffic Management” (project no. 11025).

References

T. Albrecht and J. Van Luipen, What role can a driver information system play in railway conflicts? In H. J. Van Zuylen and F. Middelham (Eds.), Proceedings of the 11th IFAC Symposium on Control in Transportation Systems. Delft, the Netherlands, 2006.


