DYNAMIC RAILWAY TRAFFIC MANAGEMENT DURING DISTURBANCES: FOCUS ON THE COMPLEXITY IMPOSED BY DEREGULATION

Johanna Törnquist Krasemann

Ph D, Assistant Professor
Department of Software Engineering and Computer Science,
Blekinge Institute of Technology, Soft Center
Box 520, 372 25 Ronneby, Sweden
Johanna.Tornquist@bth.se

ABSTRACT

While the railway traffic volumes in Europe continuously are increasing, the networks are facing difficulties to meet the demand and suffer from congestion and disturbances that cause insufficient reliability. The need to forecast the effects of the disturbances and efficiently re-schedule the traffic becomes evident, and especially in a deregulated network, where several private operators with competing objectives share the same tracks. This paper presents results from an experimental study where five re-scheduling policies were evaluated by simulation using real data: Three optimisation-based policies that minimise the total final delay, the accumulated delay and the delay costs respectively, one First-Come-First-Served policy, and one policy prioritising trains on time. The optimisation-based policies performed overall best, but required more computation time.

Keywords: Scheduling, Timetabling, Slot allocation, Disturbance management, Railway traffic, Deregulation, Optimisation.

INTRODUCTION

Freight as well as public transportation is a large and important part of our economy and daily life, and railway transportation has a significant share. As an effect of the increasing environmental awareness and desire to decrease emissions, noise pollution and accidents, political aims of increasing the market share of railway freight transportation have been stated, see e.g. (1). However, in line with the increasing traffic flow and density, the railway networks are facing difficulties with congestion and insufficient reliability. The railway traffic networks in several European countries and regions are partly oversaturated, highly sensitive to even small disturbances and have low average punctuality (2). For instance, some parts of the Swedish railway network have such a high capacity usage that even a minor incident can propagate and cause large disturbances. During the two most traffic-intensive hours per day, 38.5 % of the entire Swedish railway network is considered saturated with a low average speed and high sensitivity to disturbances, and 29.4 % of the network has a capacity usage of 60-80 % also generating sensitivity to disturbances (3). Recent statistics from the UIRR (the International Union of combined Road-Rail transport companies) also show that 41% of the trains in the analysed major freight transport corridors arrived 30 minutes later than scheduled, or more (4).

In order for the railway to become and remain an attractive means of transportation, the occurrence of disturbances needs to be limited as well as the consequences of the disturbances that do occur. While the most straightforward way to decrease the effects of disturbances would be to eliminate the risk of primary disturbances arising, it is simply not feasible. Some of the causes can be predicted and prevented from happening, while others cannot. Therefore the ability to deal with the disturbances that do occur can be argued to be as important as eliminating potential causes of primary disturbances. This paper focuses on how to handle disturbances in railway traffic by effective re-scheduling rather than limiting the occurrence of primary disturbances (i.e. initial disturbances). We will present results from an experimental study where a collection of different disturbance management policies have been applied in a simulated context and their performance evaluated based on a set of performance measures. The simulation experiments have been based on the Swedish railway traffic system and real data provided by Banverket (the Swedish National Rail Administration).

RAILWAY TRAFFIC DISTURBANCE MANAGEMENT

In this paper, a disturbance is considered to be a situation where the master schedule, or established timetable, has become invalid because one train (or several) is deviating from its schedule and the prerequisites consequently change. The event triggering a disturbance could be a signal malfunction on a track section which temporarily decreases the maximum allowed speed and causing trains to have an increased running time on that section. It could also be e.g. a no-show of staff resulting in a delayed train departure, or reduced speed of a train set due to partial engine failure or an unannounced increase in train set length and weight, etc.

Handling a disturbance in a railway network and re-scheduling the traffic is typically handled manually by traffic managers that only have very limited access to support systems to analyse the consequences of a disturbance and the effects of their decision-making. This limitation hampers the possibilities to achieve sustainable and system-optimal decision-making and to provide the stakeholders (e.g. train operators, cargo owners, commuters) with reliable prognoses about the situation. The time available for decision-making and consequence analysis is also limited and depends on the situation. The aim is thus to find sustainable and sufficiently good solutions within reasonable time. For illustrative purposes, let us consider the small-scale example of re-scheduling the traffic in Figure 1. It shows a graph of the planned railway traffic (train 101, 102 and 103) on the single-tracked line between the stations Enstaberg and Åby with several intermediate stations, and where the time is on the y-axis. The trains belong to three different private transport companies; 101 is a heavy block train, 102 is a long-distance high-speed passenger train while 103 is an express cargo train. Shortly before train 101 leaves Ålberga for Kolmården the track section suffers from a signalling problem (indicated by the thick line below the section) which decreases the maximum speed to 70 km/h. Thus, all trains passing through get an increased running time of 15 minutes and the revised timetable for each train (the dotted lines) is thus postponed 15 minutes each. This results in conflicts when the paths of the trains cross on the single-tracked line between stations, and that is forbidden due to safety restrictions. When and how the trains now should meet in order to resolve the conflicts need to be decided by the traffic managers. One policy could be to let the first train that can enter a section are given priority to that section, i.e. First Come, First Served (FCFS) while another could be for example to give highest priority to all long-distance trains.

In Figure 2, two solutions are illustrated. In the first solution, train 103 and 101 meet at Getå (as in the initial timetable) but that forces train 103 to wait a long time at the station and since the train is a long-distance high-speed train, the corresponding operator does not accept that it will be delayed that much and in favour of a cargo train. Instead, the operator wants the traffic manager to arrange for the trains to meet in Kolmården instead and thereby reducing the waiting time for 103 at Getå significantly. When the traffic manager considers that alternative he discovers that in the end, the waiting time for train 103 over all stations will be the same in both solutions, while in the second solution train 101 will get an additional delay. So, at first it seems like train 103 is disfavoured by the first solution while that solution turns out to be the best one. The initial and updated ETA (Estimated Time of Arrival) for each train is given in Figure 2.

The example illustrated by Figure 1 and 2 describes how difficult it is to achieve sustainable re-scheduling solutions and to communicate the motivation behind each decision to the operators so that they realise their incentive to co-operate and follow the plans made by the traffic managers. Today, the safe strategy is often to keep the important trains rolling and prioritise them to reduce the risk of them becoming further delayed, but it does not always mean that it is the best solution.

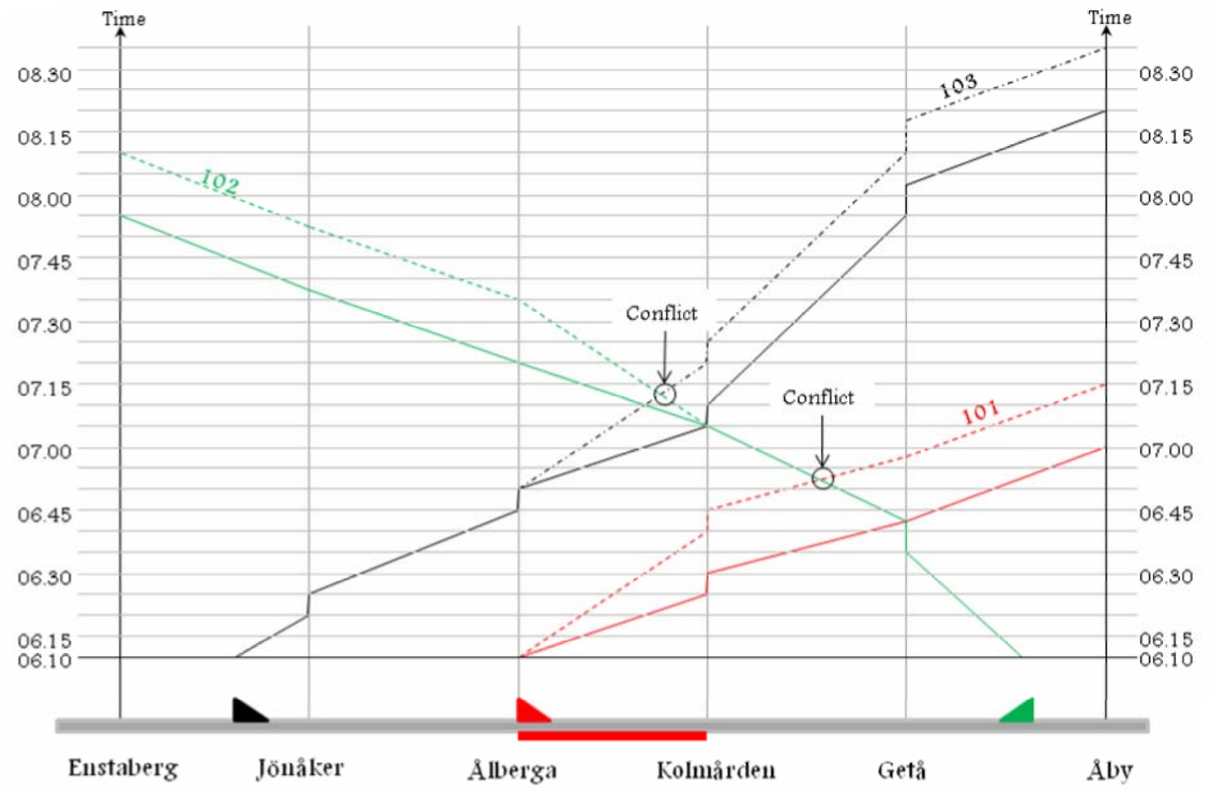

Figure 1. The initial schedule of the railway traffic and the consequential change of arrival times when a signalling problem occurs generating a revised schedule (indicated by the dotted lines) with two conflicts which need to be resolved into a conflict-free revised schedule.

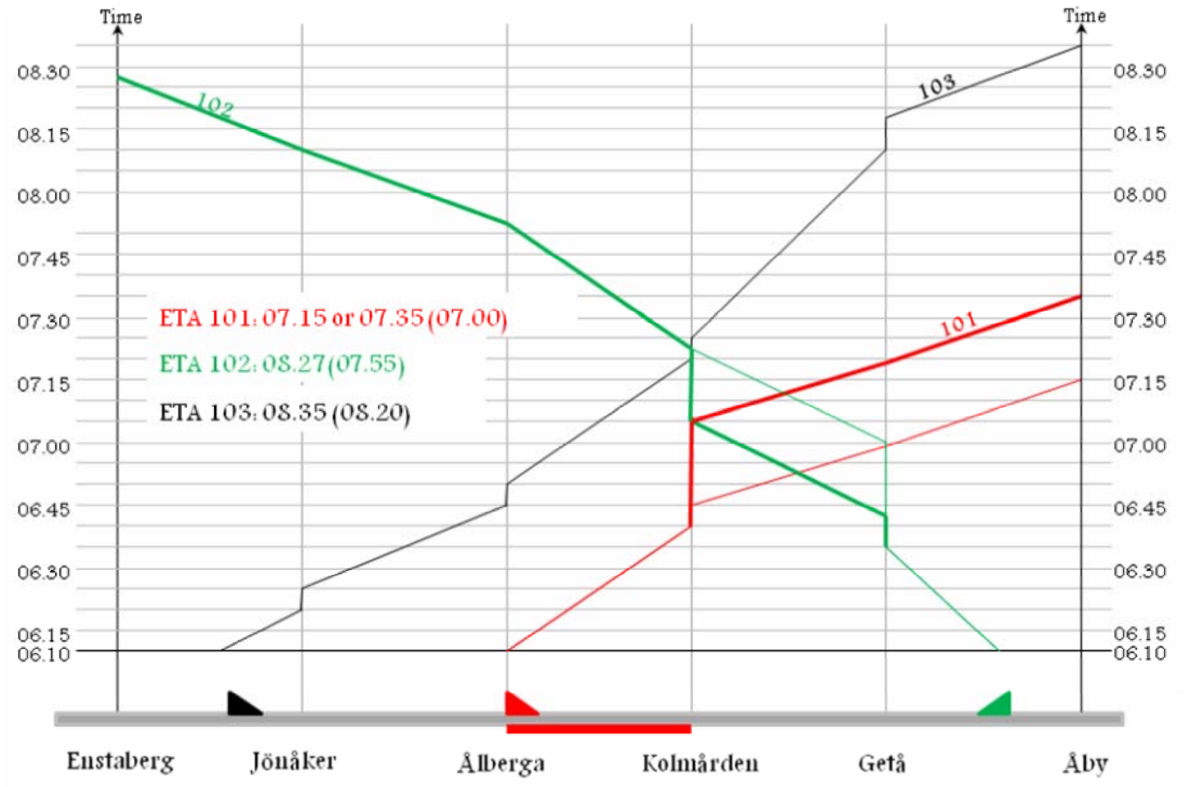

Figure 2. Two alternative solutions to the disturbance problem illustrated in Figure 1.

Re-scheduling railway traffic during disturbances is a complex task and we have seen three main challenges. The first is associated with the estimation and quantification of disturbance consequences and consequently the evaluation of different re-scheduling decisions and their effect. Depending on the structure and organisation of the railway industry, the relation between the infrastructure managers and traffic operators differs. In many European countries, the same company that manages the railway infrastructure also provides the railway services while in others, like Sweden, the administration of the network and the traffic is handled by one neutral authority and private operators provide the transport services. Consequently, the considerations and objectives of the traffic manager in a deregulated context may be different from the ones related to a regulated market and delays are weighed differently depending on the context and the stakeholder. A 60 minute delay for a cargo train on the arrival at its final destination may be insignificant, while a delay of e.g. 30 minutes for another train which is planned to board a ferry may result in it failing to get its connection. The requirement to consider the interests of multiple, possibly competing traffic operators in parallel to maintaining system stability, naturally complicates the disturbance management problem.

The second challenge is to create a viable representation of the re-scheduling problem accounting for the wide range of influencing factors and uncertainty about their properties such as infrastructural restrictions and traffic parameters (e.g. separation time, signal system response time, the position of other trains) as well as operator behaviour. Also, how to decide which time frame and geographical area that should be included in the re-scheduling process is difficult.

The third challenge is to find a mechanism that given the prerequisites and data sufficiently fast generates a sufficiently good re-scheduling solution.

RELATED WORK

The research analysing effects of disturbances in railway traffic and approaches for disturbance management is extensive. Some studies focus on the primary (i.e. initial) reasons behind the disturbances and preventive counter measures, others focus on the approximation of disturbance propagation effects, while a few address the topic of this paper and present approaches for scheduling and re-scheduling of a railway traffic timetable. Surveys by Assad (5), Cordeau et. al. (6) and Törnquist (7) provide an extensive overview of these. More recent re-scheduling approaches are presented by e.g. Zhou and Zhong (8) who propose a branch-and-bound algorithm for railway traffic timetabling in a single-tracked network. Törnquist and Persson (9, 10) present an optimisation-based approach for real-time re-scheduling of railway traffic during disturbances, while D'Ariano et. al. (11) present an iterative algorithm that in real-time resolves conflicts in a pertubated railway traffic timetable.

THE APPLICATION OF OBJECTIVES AND POLICIES

The Swedish Railway Traffic System

The Swedish railway market is deregulated, which means that a neutral authority, Banverket, is governing the infrastructure management including responsibility for maintenance, timetable construction and train dispatching. The railway services are provided by separate public and private railway operators. The railway network is used for a mix of different kinds of passenger and freight transport services. There are approximately 16 freight traffic operators, nine passenger traffic operators and two operators providing both freight and passenger transport services. All these 27 operators share the Swedish railway traffic network and create a quite heterogonous traffic flow. During disturbances, Banverket - as a neutral party – must act impartial and applies one main policy to resolve any conflicts between the trains and their operators. The policy gives trains on time priority over delayed trains. That is, trains that depart and run according to their timetable have priority to their initial slots according to the master schedule. The reason behind this rule is that trains on time shall not be disturbed by trains that are delayed or ahead of their schedule. Exceptions to this rule can, however, be made and in practise there often are. Operator preferences are considered to some extent and fulfilled if possible. For the passenger traffic, connections are highly important and that the exchange time is sufficient for the passengers. Depending on the alternative solutions for the passengers, some connections may be more important and possible to maintain. The freight operators may also have connections related to swapping locomotives or train drivers. Furthermore, all operators have rolling-stock and crew schedules to follow. The operators sometimes also negotiate with each other about being given priority if conflicts occur. The conflict resolutions are therefore often context-dependent, and for example during morning rush hour commuting trains in one direction may be prioritised and in the evening instead trains in the other direction. There are obviously various considerations and objectives and these are difficult to formalise and sometimes they are also conflicting. These context-dependent resolutions serve to create a smooth traffic flow and to limit the negative consequences for the network users. Meanwhile the Swedish railway traffic system performance primarily is measured by *punctuality* and *train delays*. Punctuality refers to the percentage of the trains that arrive at their final destination with a maximum delay (i.e. deviation from initial timetable) of five minutes, and *train delays* refer to the sum of the delays (exceeding five minutes) of trains at their final destination. Banverket works continuously to decrease the overall train delays and to increase the punctuality, but also to decrease the frequency of disturbances. The punctuality for the Swedish railway traffic system during 2006 was approximately overall 89.1 %, where the punctuality for passenger traffic was 90.9 % and 78.1 % for freight traffic (3).

Simulating the Application of Re-scheduling Policies and Objectives

One main strategic objective for railway network managers is often to maintain a high performance which can be measured by the share of trains that are punctual, the amount of aggregated delay, or specified as a more qualitative parameter. One challenge is thus to specify ways to measure performance on a strategic level and then to formalise traffic management policies and corresponding performance measures that on an operational level reflect the strategic ones. Often performance is a given by a set of different parameters and sometimes these could be indirectly in conflict. For example, delaying a number of trains a little bit may result in a smaller aggregated delay then delaying only one train consistently. In this paper, we use the term *policy* to refer to a traffic management strategy which is applied to strive to fulfil certain *objectives* or *goals*. A *performance measure* is one (out of possibly several) ways to quantify the extent to which the objectives are met. For example, an objective can be to decrease the secondary effects of a disturbance and these effects can be measured as number of trains that are delayed, total final delay, median and minimum non-zero delay, the duration of the disturbance (i.e. how long it takes before it dies out), etc. In this chapter we will present an experimental study that evaluates the performance of a number of disturbance management policies based on a set of performance measures.

Simulation Study Set-up

The policies which we have applied in the simulation study are of two kinds: The first two are somewhat myopic basing the decision on the immediate conflict situation and do not enforce any explicit objective, while the latter three are planning ahead to estimate the longer term effects in line with an explicit goal function.

- FCFS – First Come, First Served
- OTTP – On-Time Trains Prioritised
- MDC - Minimise Delay Costs (using the HOAT approach described below)
- MTFD - Minimise Total Final Delay (using the HOAT approach)
- MAD - Minimise Accumulated Delay (using the HOAT approach)

The FCFS policy allocates a track to the train that first is ready to use it (if that is feasible given the safety restrictions and technical limitations in the system). The OTTP allocates a track according to the FCFS principle unless the first train is delayed. It then checks whether that train would delay the next train in turn if it was to be assigned the track, and if so, the train is given a lower priority in favour of the non-delayed trains, if feasible. The MDC, MTFD and MAD are using a heuristic optimisation approach called HOAT with an explicit goal to re-schedule the trains in a way that minimises the delay costs, the final delay and accumulated delay, respectively, based on the initial timetable. The purpose with HOAT is to within a certain time frame find a solution (i.e. a revised timetable) that is good enough with a trade-off between computation time and solution quality. HOAT originates from an MILP (Mixed Integer Linear Program) representation of the re-scheduling problem, where binary variables are used to represent the order of trains on the tracks while continuous variables are used to allocate departure and arrival times for the relevant tracks and trains. Then, instead of solving the complete problem by potentially evaluating all possible train sequences on the tracks and the corresponding values of the binary variables, HOAT applies an algorithm that independent of disturbance scenario tries to identify a limited number of promising modifications of the initial timetable and specifies these as new, additional constraints in the MILP. The reduced problem is then solved by Cplex 8.0 (an off-the-shelf optimisation software from ILOG). A complete presentation of the heuristic approach HOAT can be found in (10).

We have also compared these five policies to the policy of maintaining the initial train sequence (ITS) as well as to the optimal train sequence (OTS) when minimising the total final delay. The policies, or rather the re-scheduling solutions they generate, are evaluated using four performance measures: Delay cost, total final delay, accumulated delay and number of trains delayed (including all non-zero delays and the primary, delayed train). We are also considering the computation time required by the policies to find a solution.

In the simulation study, we have chosen the timetable for the traffic in the region of Norrköping traffic control centre, Sweden (see Figure 3) and for a typical weekday (the 3rd of October, 2005), which contains the regular amount of passenger and freight traffic. The traffic data includes 74 cargo trains, 211 passenger trains and 28 service trains and where approximately half of the trains are south-bounded and the other north-bounded. The data set includes 28 train connections. All tracks are bi-directional and the backbone of the region is double-tracked while the connecting lines are single-tracked. Stations and sidings have between one and 14 tracks. The traffic data set is classified into six types of trains: Long-distance high-speed trains, intercity trains, local commuter trains, low-speed and high-speed cargo trains, and service trains. We have then created 40 scenarios by for each scenario randomly selected one train and a time to inflict a delay of random size onto that train. The disturbance situations then differ due to that the delay size varies and that the delay occurs at different times and locations that may be more or less sensitive to deviations. Also which train that is delayed in each scenario affects the severeness of the disturbance depending on if the delayed train interferes with many other trains during its journey after the initial delay. The corresponding disturbance management and re-scheduling for the 40 scenarios was then simulated by applying the different management policies. A more detailed presentation of the scenarios, the experimental setting and how the simulations were set up can be found in (9).

Figure 3. The railway (sub-)network used for the scenarios and corresponding experiments. Stations and sidings are connected by one or several segments that are either single- or double-tracked. Segments that are stations or other meet points can be n-tracked, i.e. have *n* parallel tracks.

Experiment Results

An overview of the results from the simulation study is presented in Table 2 in Appendix A, and we can see that in 25 scenarios it is beneficial to do some re-sequencing of the trains. In the other 15 scenarios the ITS policy achieves an equally good solution. With respect to total final delay, MTFD generated a lower or equally low value as FCFS and OTTP and in Table 1 the differences can be seen. In scenario 3, MTFD found the optimal solution and reduced the delay with approximately 22 minutes more than FCFS and OTTP, and required a solution time of 73 s. In scenario 10, the policies performed equally well but whether their solutions were close to optimum or not could not be decided other than by considering a lower bound (45.5 minutes) which is pretty close to the values found by the policies.

In scenario 14, OTTP had a 10 minutes smaller reduction than FCFS and MTFD, but where MTFD required long computation time. The corresponding reduction for MTFD* was 8.5 minutes smaller than FCFS and approximately one minute smaller than OTTP.

In scenario 19, MTFD performed better than FCFS and OTTP although it could not find the optimal solution and it required long computation time. The solution found by MTFD* was worse than both FCFS and OTTP. In scenario 28, there was a minor difference in performance while in scenario 36 the largest difference can be found and MTFD outperforms the other two policies.

With respect to the number of delayed trains, MTFD performs better or equally well compared to the other policies apart from scenario 29, where OTTP was superior.

SCENARIO	MTFD	MFTD*	FCFS	OTTP	OTS
3	77.27	83.57	99.22	99.22	77.27
10	51.67	51.67	51.67	51.67	175.67 (74.1%)
14	41.23	52.87	41.23	51.63	41.23
19	48.17 (7.89%)	73.20	50.07	64.05	43.10 (23.9%)
28	47.10	47.10	47.60	47.60	47.00
36	57.33 (31.22%)	67.60	251.53	251.53	38.20 (2.4%)

Table 1. An overview of the results (Total Final Delay, given in minutes) for the scenarios where the performance of the policies differ. MTFD* refers to the use of the MTFD policy with a time limit of 30 s instead of 2.5 h. Values within parenthesis refers to the gap for the corresponding problem formulation and solution after 2.5 h.

An analysis of the comparative performance of the three optimisation-based policies shows that a minimisation of the total final delay (MTFD) and a minimisation of the delay cost (MDC) result in similar values for all four performance measures. A minimising of the accumulated delay (MAD) generates solution with a lower value of accumulated delay than the other two objective functions, but also tends to delay more trains. The required computational time using any of the three optimisation approaches is in principle the same.

DISCUSSION AND FUTURE WORK

In this paper we have illustrated and presented the urgent need for approaches that can assist the traffic managers in handling disturbances in railway networks and the consequential re-scheduling of trains in line with network restrictions, traffic management objectives and operator preferences. Today, the traffic managers often carry out the re-scheduling manually with very little support to analyse the situation and the longer-term effects of their decisions. We have performed an experimental study and analysis of the application of five different policies for re-scheduling the railway traffic. Three of the policies are based on optimisation methods, and two are myopic rule-based policies of which one, OTTP, currently is partly used by the Swedish National Rail Administration. One advantage of the optimisation approaches is that they estimate and account for the upcoming and overall effects of each decision while policies like FCFS and OTTP do not consider the longer-term effects. For traffic areas with a high traffic load and many train movements, it is important to find and make use of any margins to achieve a good solution, and an optimisation approach could have that ability. However, one important aspect of the re-scheduling process is the time available for making decisions. Sometimes decisions need to be made fast and in some cases, and the use of an optimisation approaches can become complex and consequentially result in an increase in computational effort required. The computational effort for straightforward policies like FCFS and OTTP is rather modest and quite independent of the scale of the problematic traffic area. Principles like FCFS and OTTP are also easier to grasp and apply by a traffic manager, but are difficult to tailor to include context-dependent restrictions and preferences without getting complex.

Some of the mentioned general characteristics can also be seen in the experimental results and the performance of the approaches varies significantly depending on the type of disturbance that occurs. The ability of the optimisation approaches to generate good solutions is stable while the computational effort required varies a lot. FCFS and OTTP generate solutions in less than 1 s but in some situations, e.g. scenario 36, they perform very poorly. In the majority of the scenarios analysed the five policies performed similarly well though.

Hence, one conclusion is that these two types of solution approaches do complement each other and one policy may perform better in one traffic region or situation while another policy is more appropriate in another depending on e.g. the traffic density, type of traffic and infrastructure and the preferences and objectives. Also, one should make use of the expertise of the traffic managers and have them interact in the solution process, or in parallel have them specifying a solution that is simulated and evaluated.

Ongoing research focuses on developing hybrid approaches that have the ability to generate a sufficiently good solution sufficiently fast independent of disturbance situation. One part of this includes to implement, evaluate and benchmark other currently applied (but not yet formalised) policies or rules of thumb within Banverket as well as to refine or improve these if possible. We also want to conduct a more detailed analysis of how the optimisation -based approaches perform over time and depending on type of disturbance. The collection of performance measures and system objectives used strategically as well as operationally, is also currently being extended and analysed. One trend is to measure punctuality partly in relation to a time window within certain trains should arrive instead of a at specific time. This is most beneficial for cargo trains and other types of trains that have few stops and no strict timetable.

Finally, as important as it is for the traffic managers to have the support to compute good re-scheduling solutions, as important is the means to simulate, demonstrate and communicate the plans and intentions of the decisions taken by the traffic managers to the operators that are expected to follow the plans.

ACKNOWLEDGEMENTS

The research presented has been financially supported by Banverket (the Swedish National Rail Administration) and Blekinge Institute of Technology, Sweden. Furthermore, support and have been provided by Thomas Franzén, Banverket and Prof. Paul Davidsson and Dr. Jan A. Persson at Blekinge Institute of Technology.

REFERENCES

(1) European Commission, *European transport policy: time to decide 2010*, White paper, 2001.
(2) Gunnar Jansson, Oskar Jonsson, ”En pilotstudie av punktligheten i europeiska godstransporter på järnväg”, *TFK Rapport 2003:7*, TFK, 2003, Stockholm, Sweden.
(3) Banverket, *Årsredovisning 2006* (in Swedish), 2007, Borlänge, Sweden.
(4) UIRR (International Union of combined Road-Rail transport companies), *Punctuality statistics for Jan-Sept 2007*, Dec 5th 2007.
http://www.uirr.com/?action=page&page=52&title=Quality.
(5) Arjang Ali Assad, ”Models for rail transportation”, *Transportation Research Part A,* Vol.14A, Elsevier Science Ltd, 1980, p. 205- 220.
(6) Jean-Francois Cordeau, Paolo Toth, Daniele Vigo, “A survey of optimization models for train routing and scheduling”, *Transportation Science*, Vol. 32, No. 4, INFORMS, 1998, p. 380-404.
(7) Johanna Törnquist, “Computer-based decision support for railway traffic scheduling and dispatching: A review of models and algorithms”, *Proceedings of ATMOS2005*, Palma de Mallorca, Spain, October 2005, Published within the Dagstuhl Research Online Publication Server (DROPS) http://drops.dagstuhl.de/portals/ATMOS/, 2006.
(8) Xuesong Zhou, Ming Zhong, “Single-track train timetabling with guaranteed optimality: Branch-and-bound algorithms with enhanced lower bounds”, *Transportation Research Part B*, Vol. 41, No. 3, Elsevier Science Ltd, 2007, p. 320-342.
(9) Johanna Törnquist, “Railway traffic disturbance management: An experimental analysis of disturbance complexity, management objectives and limitations in planning horizon”, *Transportation Research Part A*, Vol. 41, No. 3, Elsevier Science Ltd, 2007, p. 249-266.
(10) Johanna Törnquist, Jan A. Persson, “N-tracked railway traffic re-scheduling during disturbances”, *Transportation Research Part B*, Vol. 41, No. 3, Elsevier Science Ltd, 2007, p. 342-362.
(11) Andrea D’Ariano, Dario Pacciarelli, Marco Pranzo, “A branch and bound algorithm for scheduling trains on a railway network”, *European Journal of Operational Research*, Vol. 32, No. 2, Elsevier Science Ltd, 2007, p. 643–657.

APPENDIX A

SCENARIO	INITIAL DISTURBANCE (S)	TOTAL FINAL DELAY (S)				MTFD SOLUTION TIME (S)
		ITS	FCFS	OTTP	MTFD	
1	938	1 876	1 876	1 876	1 876	9.38
2	633	870	870	870	870	3.08
3	1 325	24 465	5 953	5 953	4 636	73.27
4	1 406	1 406	1 406	1 406	1 406	4.87
5	1 090	1 090	1 090	1 090	1 090	1.3
6	1 218	3 654	1 770	1 770	1 770	0.54
7	966	6 246	1 260	1 260	1 260	2.26
8	591	2 979	1 182	1 182	1 182	2.04
9	622	1 142	1 082	1 082	1 082	7.89
10	1 216	11 074	3 100	3 100	3 100	8.41
11	775	3 835	775	775	775	4.35
12	1 018	19 636	1 194	1 194	1 194	10.36
13	1 109	2 218	1 614	1 614	1 614	7.23
14	998	16 266	2 474	3 098	2 474	7 196.39
15	1 352	8 082	1 380	1 380	1 380	5.58
16	1 186	13 148	2 896	2 896	2 896	6.76
17	1 266	3 186	1 860	1 860	1 860	3.18
18	1 024	1 024	1 024	1 024	1 024	8.86
19	1 553	25 451	3 004	3 845	2 890 (7.89%)	2.5 h
20	1 491	17 595	1 980	1 980	1 980	12.35
21	595	5 059	655	655	655	1.58
22	628	656	656	656	656	5.48
23	981	981	981	981	981	1.09
24	1 494	1 494	1 494	1 494	1 494	0.19
25	1 608	1 620	1 620	1 620	1 620	1.32
26	1 572	9 414	1 572	1 572	1 572	4.88
27	1 788	3 576	1 788	1 788	1 788	6.24
28	1 269	8 877	2 856	2 856	2 826	≈2.5h
29	1 169	8 141	1 181	1 272	1 181	2.33
30	506	3 320	506	506	506	4.78
31	523	523	523	523	523	2.28
32	1 025	6 675	1 906	1 906	1 906	3.18
33	1 580	1 580	1 580	1 580	1 580	5.08
34	1 564	1 564	1 564	1 564	1 564	5.75
35	1 582	1 582	1 582	1 582	1 582	2.16
36	1 436	23 924	15 092	15 092	3 440 (31.22%)	2.5 h
37	659	1 318	1 318	1 318	1 318	8.64
38	830	1 576	830	830	830	0.21
39	1 452	14 286	1 452	1 452	1 452	4.73
40	1 235	1 235	1 235	1 235	1 235	5.74

Table 2. Values within parenthesis indicate that no optimal solution was found within 2.5 h with respect to the heuristic problem formulation, but a solution with a gap for the problem.