Optimizing Train Traffic: Demonstrating Benefits in a Case Study

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Abstract

The Dutch railway network is one of the worlds busiest networks. Future growth of transport demand and less money for extending the network capacity cause a need for exploring and implementing new traffic control strategies. The use of a traffic management system, that minimizes the scatter in the operation and provides actual information about upcoming conflicts and system performance, might help to keep the operations as close as possible to the planning/timetable. To investigate the potential benefits, ProRail, the Dutch rail infrastructure manager, has developed a combined simulation and optimization tool. A railway simulator based on a microscopic infrastructure model (FRISO) and a traffic management system and decision support system (TMS), are coupled in a scalable architecture. The paper explains the application of TMS compared to two other controlling strategies in a detailed and realistic simulation study of the station Den Bosch, a capacity bottleneck in the network. In addition to the simulation experiments the development of TMS, it's architecture, algorithms and improvements are described.

Keywords

Capacity, Optimization, Traffic Management, Decision support, Simulation

1 Introduction

On the Dutch railway network about 6500 trains run on a daily basis nowadays. It is one of the worlds busiest railway networks. To construct a timetable that incorporates all trains of all train operating companies is a challenging process year by year. Because capacity resources like railway infrastructure, rolling stock and crew are expensive and scarce, timetable planners have to search intensively for feasible solutions. A feasible solution should meet design standards, that guarantee operational quality, and criteria that measure commercial attractiveness, capacity and safety aspects. In the daily operation a similar even more complex challenge waits for the traffic and transport controlling departments. They have to deal with deviations, changing circumstances and less time. At this point the difference between the planning and the operation of the timetable should be as small as possible. Deviations might cause a decreased level of product quality and a higher risk for unsafe situations.

The use of a traffic management system, that minimizes the scatter in the operation and provides actual information about upcoming conflicts and system performance, might help to keep the operations as close as possible to the planning/timetable. To investigate the potential benefits, ProRail, the Dutch rail infrastructure manager, has developed a combined simulation and optimization tool. Two applications - FRISO, a railway simulator based on a microscopic infrastructure model and TMS, a traffic management and decision support system - are coupled in a scalable architecture. In a simulation study of the station Den Bosch, a bottleneck in the railway network, the contribution of the TMS is compared with other traffic controlling strategies.

This paper explains the TMS architecture and algorithms, describes the simulation experiments for the case study Den Bosch and quantifies the benefits of using the TMS in this case. Note that infra, timetable, rolling stock and disturbances all reflect the actual situation in great detail. This study therefore provides a highly realistic example.

2 Problem Description

2.1 Background

The railways in The Netherlands have received major criticism for the quality of its operations. Traditional measures to improve it have been utilized already and now innovative approaches are needed. The urge to change is emphasized by a number of incidents that immobilized the public train services for several days last year. Those caused a radical shift of focus towards improving the robustness and the safety of the railway system. The ambition to introduce higher frequencies earlier, thus on existing infrastructure, causes an uncertain impact on quality and safety aspects.

2.2 Capacity for Higher Train Frequencies

The Dutch railway sector formulated an ambitious program to face a growth of transport demand in the forthcoming decade. It is called 'Space on the Railways" ('Ruimte op de Rails', in Dutch) and it is aiming towards an increase in the number of trains on the network by 50% in the year 2020 or earlier where possible. This growth is expected in both passenger and freight transport. At the same time the costs have to decrease by 20%.

One of the major components of this program is to switch to a timetable with high-frequency passenger trains on the major corridors. Currently there are (on average) 4 intercity, 2 to 4 local and 1 or 2 freight trains passing the major corridors every hour. This should increase to 6 intercity, 6 local and 2 freight trains. Passengers may catch a train every ten minutes. This new frequency of trains is often called 'un-timetabled travelling', as the passenger is able to go to a station without checking departure times: the next train will be there soon. The official title of the schedule is High Frequency Train Transport ('Programma Hoogfrequent Spoor' in Dutch). Currently, the Dutch railway is already approaching its maximum capacity given the current infrastructure and control mechanisms. The projected increase in transport demand requires a step-change in both the physical and the control aspects of the railways. The increase of capacity cannot be achieved by building new infrastructure alone: the costs for the complete program would be around 9 billion Euro and the time for procedures and construction would frustrate the transport demand for years. ProRail has taken up the challenge to achieve the goals with only half of this budget by combining strategic choices for new infrastructure with new control and management solutions.

2.3 Case Study Den Bosch

One of the major corridors in the Dutch railway network is the line between Amsterdam and Eindhoven, including its feeding links. On this line the railway companies aim to introduce the new higher frequencies earlier. At the same time the layout of some major stations on this line are being reconstructed, including the Den Bosch station. These building activities cause a temporarily reduction of capacity.

The Den Bosch station is an important node in the Dutch network. Several transport flows pass through the station, thereby crossing each other, see Figure 1.

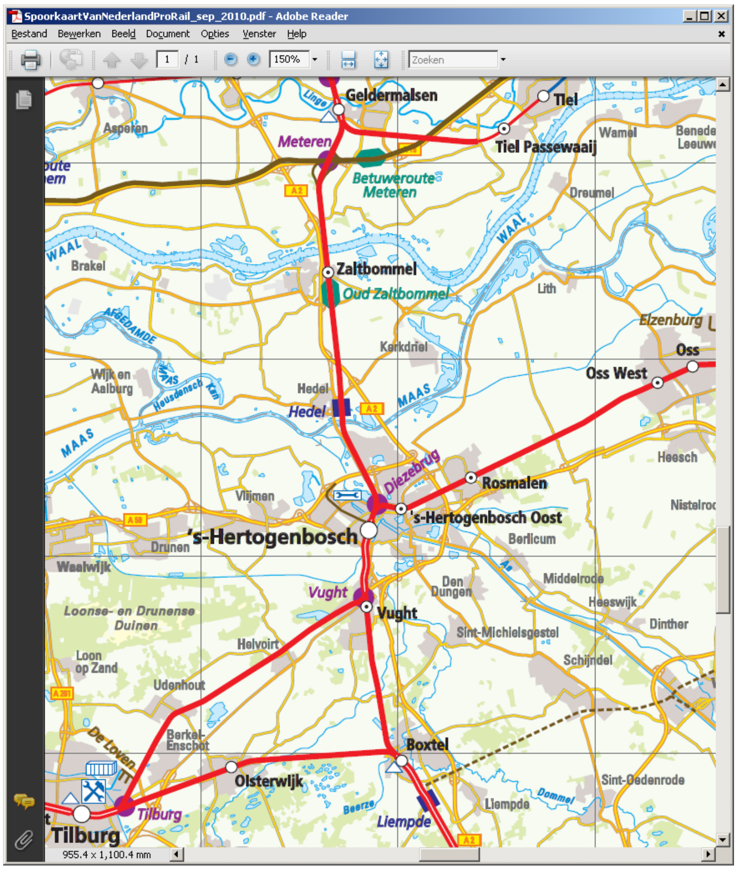

Figure 1: Den Bosch study area.

The infrastructure configuration has no fly-over to separate crossing train movements. On both sides of the station, train services cross when heading from north to south v.v.

and other services cross while going from east to west v.v., see Figure 2. The station Geldermalsen (Gdm) lies northbound of Den Bosch (Ht), station Boxtel (Btl) is on the southside, station Tilburg (Tb) is on the west side and station Oss (O) is in the east.

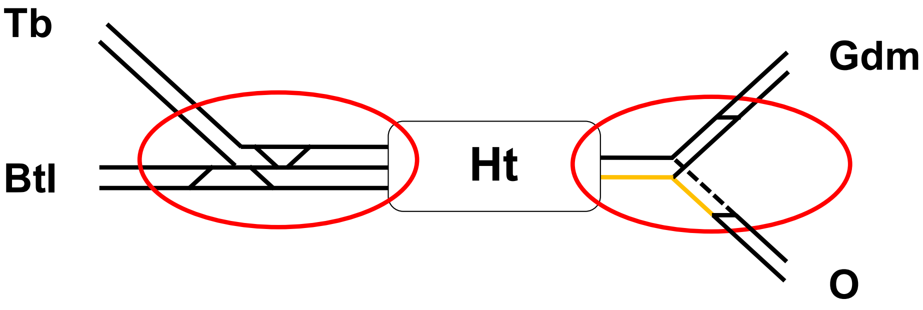

Figure 2: The Den Bosch (Ht) area.

Due to the growing number of trains there is a need to build flyovers to separate the train services on both ends of the station. Construction works have begun last year. The available layout will change several times during the reconstruction, causing a decrease in capacity for the timetable construction and the operation.

In 2012, one of the tracks (marked dashed in Figure 2) heading north/east was out of service. Therefore train traffic in two directions had to use the same tracks (marked orange in Figure 2). This busiest part of the layout did not allow for a feasible timetable given the higher frequencies and the capacity reduction. It is possible to process the 18 trains an hour over the orange tracks, but not without the trains hindering each other. That is, they need to follow each other that closely that signal aspects will be less than optimal. The question was how to minimize the ‘costs’, measured by delays, delay propagation and unplanned stops.

3 Approach

If the timetable is constructed solidly it should contain enough buffer times to overcome small disruptions and to prevent variations in arrival and departure times. To test the sensitivity for disruptions a simulation approach is required. The next sections describe the performance indicators, the simulaton experiments and the tools being used

3.1 Performance indicators

The quality of a timetable is to be measured by a set of criteria. Next to transport quality where indicators like travel times and frequencies count, there is a set of indicator addressing operational quality and stability. Performance indicators like punctuality, delays (primary and secondary), delay propagation and delay reduction are well used criteria here. To evaluate safety aspects the probability to come close to a stopping signal on locations where trains normally don’t have to stop can be used. If trains follow the planning accurately, that is if they minimize the deviation from the planning, these unplanned stops should be minimal.

Thus reducing the amount of scatter in the operation both prevents delay propagation and unplanned train stops. Therefore ProRail developed a Traffic Management System (TMS) that optimizes the train traffic performance in terms of delays, energy consumption and throughput. To investigate the potential benefits on different locations this system is coupled to the railway simulator called FRISO. In the case study the new timetable is tested on the reduced capacity of the infrastructure using three variants of traffic control. The next section describes the simulation experiments and the tools in further detail.

3.2 Simulation experiments

The introduction of a new timetable with higher frequencies was not possible using the current traffic control strategy. The simulation experiments are meant to show if and how alternative control strategies might perform better in this case. In total three control strategies were tested:

1. Current practices (VaVo): in case of a shared claim on the infrastructure by two trains, the control system applies a first come first served strategy when both train routes cross each other. If the trains also share the destination track, the timetable order is applied/maintained.
2. First come first served (FCFS): in all cases the first train gets the claimed route/infrastructure first
3. Speed and time instant of Route Setting Control (TMS): application of the TMS which prevents conflicts by calculating advisory speeds for trains, together with timely route setting in accordance with these advisory speeds. If necessary the train order is changed.

3.3 FRISO: Train traffic simulation

FRISO stands for Flexible Rail Infrastructure Simulation of Operations. It is a simulator that enables the user to perform simulation studies for problems that have dynamic, discrete and either deterministic or stochastic characteristics. Given a specific timetable, railway infrastructure, rolling stock and optional disturbances, FRISO simulates the behaviour of trains and their mutual interactions Its main purpose is assessing the robustness of timetables and detecting bottlenecks. FRISO consists of railway modules that describe concepts and functions representing railway practices on a microscopic level. Regarding railway data, FRISO, and hence TMS, use a detailed and realistic model. It includes:

- Infrastructure elements like:
    - Signals, signal aspects relations. Also taking into account continuous signal improvement in the train cab.
    - Speed signs.
    - Sections, to determine when infra is released for use by a next train.
    - Switches and their characteristics.
    - Road crossings and their special safety precautions for trains.
    - Slopes.
- Rolling stock characteristics with different models for different rolling stock compositions.
- Train plan with:
    - Arrival, departure and passing event times
    - Routes and partial routes.
    - Trains relations (connections for passenger and/or rolling stock).
    - Alternative routes and stop locations.

- Disturbances on the following events:
  - Entry.
  - Stop.
  - Departure.
  - Acceleration.

  Disturbances can be drawn from a variety of distributions or sequences of measured data can be used.

The Den Bosch model contains the real Dutch infrastructure and timetable.

As an illustration, a snapshot of a part of the Den Bosch study area is given in Figure 3.

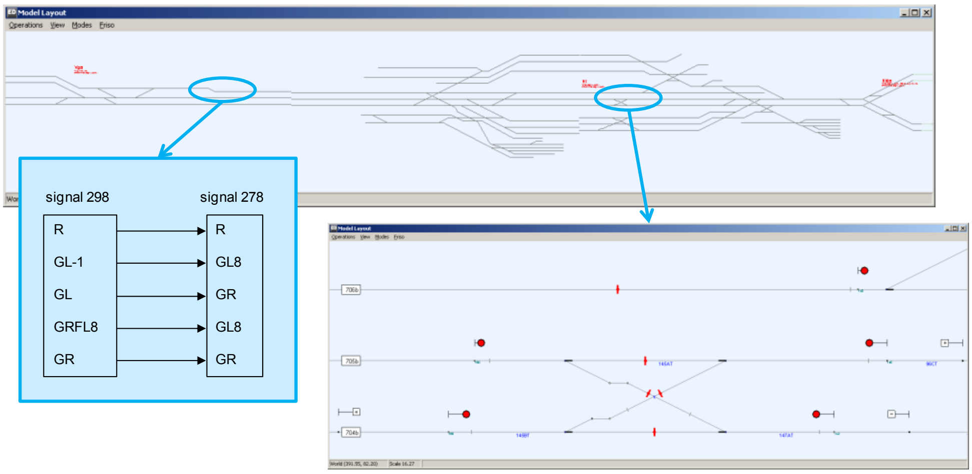

Figure 3: The upper window shows a part of the Den Bosch area. The lower left window shows an example of a signal aspects relation. The lower right window zooms in on a part of the infrastructure, showing signals, speed signs, section delimiters and switches.

In the simulation, trains are running along the tracks, and accelerate and decelerate when speed limits are changing. The operation of the timetable may be disturbed by delaying the departure of trains, extending dwell times with an extra delay and by varying acceleration and deceleration parameters. The internal train control module handles requesting and (phased) setting of routes

A key feature of the tool is its flexibility. This is reflected in the user friendliness and the scalability of the concepts. FRISO is based on a standard simulation platform called Enterprise Dynamics, which is widely used in a variety of industries. Simulation models are generated automatically from the Infra Atlas database that holds the digital representation of the current Dutch railway infrastructure. This, in combination with smart editors for making timetable and infrastructure variants, reduces the time efforts significantly for implementing a simulation study. It allows users to spend most of their time on defining simulation experiments and analyzing the results rather than building (often manually) and validating simulation models.

FRISO has the possibility to connect to other/external applications that may take over parts of its functionality. Therefore a federation of applications following the framework of the High Level Architecture [6] has been developed. The current version has connections to the Traffic Management System (TMS) described in the next section.

3.4 TMS: Traffic optimization

TMS is a Traffic Management System for the complete real-time railway traffic management [2]. The system predicts potential conflicts when disturbances occur during operations, and optimizes the traffic in real-time by shifting timetable target times, modifying train ordering at junctions, using alternative routes and calculating optimal speed profiles for trains. TMS takes into account the all trains in the controlled area and the solutions are calculated through considering the global impact on the chosen traffic performance indexes (delay, tardiness, punctuality, etc.). TMS is also responsible for the complete route booking management, that includes the assignment of routes to trains, the optimal choice of booking times, the control and update of route status (booked, set, cancelled, released).

The methods and algorithms were originally developed in the COMBINE project [7] for a railway system using flexible and moving (safety) blocks. To make it applicable for a real life pilot TMS was adapted to work in a fixed block safety system like the Dutch NS'54-system. The pilot "Green Wave" ("De Groene Golf" in Dutch) proved potential benefits in punctuality level, energy consumption and preventing non commercial stops. Nowadays similar effects on safety issues are to be expected. After the pilot the TMS development moved to adaption for simulation studies. Next to improvement of the algorithms also the automatic generation of simulation models was introduced, following the FRISO approach to minimize the effort on building simulation models. Goals were:

- to determine candidate locations for real life application as a control system,
- to extend the options for TMS-use: besides the original real time application also use TMS as a decision support system, enable use in stochastic (multiple runs) simulation studies and connect it to a High Level Architecture [6],
- to investigate TMS settings (e.g. the required accuracy of train positions) and algorithms.

More details about TMS, the algorithms and recent developments will be described in the next chapter

4 TMS: algorithms and recent developments

The core of TMS architecture is based on a hierarchical structure consisting of two modules: the Conflict Detection and Resolution (CDR) module, responsible for real-time scheduling and routing, and the Speed Regulator (SR) module, responsible for speed regulation. Additionally, TMS includes a graphical user interface, where the original plan, the new plan and the actual operation are shown, as well as the current traffic situation is shown.

TMS optimizes all trains simultaneously over a certain time horizon, by the combined actions of CDR and SR. Several objective functions are possible, using for instance delay, tardiness, punctuality (number of trains with delay less than a given value), energy consumption, combined with max or total operators. In the Den Bosch case study the CDR objective function is to minimize the total tardiness, while the SR objective is to minimize the total energy consumption. The optimization is performed over all trains currently running in the controlled area or expected to enter in the next T minutes (T is typically set to 15min). So, all trains, the whole network and a sufficient part of the future are taken into account. This time horizon is easily adaptable. Also the optimization criterion itself is adaptable on the basis of study requirements (e.g. total tardiness was replaced with punctuality in some case). TMS also shows the capability to deal with unpredictable events, compensating them with short term forecasting.

The real-time scheduling engine of TMS is based on the alternative graph model [3] properly adapted to the rail traffic scheduling problem. Over the years, the TMS model has been continuously extended and improved. To assure higher adherence to the real world and to reach significant performance results, new features and capabilities have been added to TMS since [2]. The current TMS model incorporates characteristics and rules of the rail infrastructure and traffic elements, at a very detailed level, to be able to produce feasible solutions, which are applicable in reality

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4.1 New TMS functionality

In relation to [2], TMS has been extensively improved as regards both its capability to incorporate and manage new data about railway elements and rules, and its internal optimization model and strategies.

Regarding railway data TMS, uses a detailed and realistic microscopic model, described in section 3.3.

Many features and functions have been added to TMS throughout years, in order to make TMS much more close to real models and to improve its ability to cope with real requirements and constraints. The most important developments are:

- Management of train relations constraints, including: passengers changing trains on a station and turning of rolling stock of trains.
- Continuous signal aspect improvement: to improve performance of trains, train drivers should react on signal aspect improvements shown in front of them. TMS foresees signal aspects from signal relations table, and emulates this behaviour.
- Phased route setting: TMS is able to work with composed routes and book either the entire route or a number of partial routes from which it is composed.
- Ability to use alternative routes and stop locations if the preferred route is not available
- Ability to use the height property and the information for all rolling stock types concerning acceleration and deceleration values for different speeds on different slopes.
- Definition in TMS of the brake pressure building time model for freight trains
- Management of road crossings and stop-through circuits, related to safety issues.
- Management of single track situations: TMS incorporates in its model data and rules, to avoid deadlock situations on single open tracks

Also some smaller developments were made required for the use in simulation models and specific locations or situations:

- Ability to maintain planned entry order in case of entry disturbances.
- Ability to cope with stop disturbances (longer stop duration), departure time disturbances (delayed departure after stop duration), acceleration and deceleration disturbances.
- Management of initial speed limits for trains (they can be unknown to the train driver and/or TMS when entering the model)

- Incorporation in TMS model of pre-signals and free standing L/H signals
- Ability to model short movements
- Ability to use section name to specify stop position
- Ability to start on tracks that end at a buffer stop

4.2 Real-time re-scheduling and train control

In response to disruptions, disturbances or other problems, the real-time railway traffic optimization module of TMS produces new schedules by applying strategies which address:

- The reference times (timetable) for all trains for defined points in the network
- The train sequence at junctions and merging points
- The routes used by trains (rerouting)
- The booking of the routes used by trains
- The reference speeds
- The minimum headway distance between trains.

The resulting train schedule is guaranteed to be feasible with respect to train dynamic characteristics and constraints from signalling and safety system. Besides, the new schedule is also compatible with the already booked routes. Route booking policy is a key aspect of TMS, as being strongly related to traffic smoothness. Route booking is performed generally as late as possible, in order to improve resource allocation. However, it can also be anticipated in order to allow the so-called “green wave” traffic flow.

In TMS the real-time re-scheduling process is strictly combined with the train control, as the two main modules of TMS core (CDR and SR) are designed to complement each other, see Figure 4. This way the new schedule produced by CDR is executed through route booking timing and train speed advises calculated by SR and continuously updated on the basis of actual train positions, signalling and infra elements conditions.

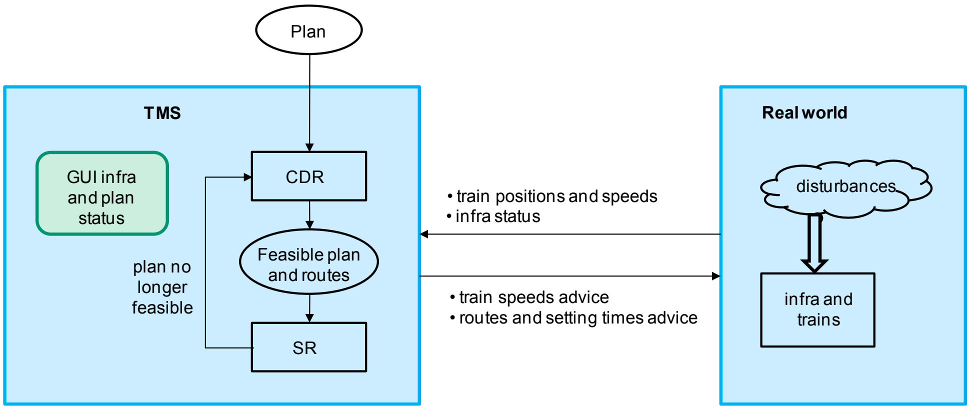

Figure 4: TMS components.

An important element of TMS model is the efficient headway management (that is, the management of the distance between subsequent trains). Recent experiments and tests proved that a general good choice of minimum headway distance is strategic for traffic control with respect to different objectives: punctuality, capacity, safety, reduction of unplanned stops, energy saving. In the current implementation of TMS, a two-blocks configuration is used as minimum headway distance between trains. This choice has resulted successful in preventing or limiting ripple effects over the network, if properly combined with optimal speed control.

The characteristics of this approach enable TMS to realize a sort of integrated real-time re-scheduling, making it possible to reduce unplanned signal braking and stops, thereby reducing time lost due to train acceleration and deceleration and making it possible to maximise rail traffic flow for desired areas.

A significant amount of research on improving the railroad re-scheduling process is described in the technical literature, and a broad survey of it is out of the scope of the present paper. Among all, a complete analysis concerning the potential benefits of a re-scheduling process can be found in [5]. Such reference accounts also TMS as an innovative closed-loop train re-scheduling system for ETCS/ERTMS Level 3.

4.3 Robust heuristics for train scheduling

The TMS core scheduling algorithm implemented into the CDR module has been extensively redesigned over the years. The original greedy approach based on AMCC (Avoid Maximum Current C_{max}) heuristic [3] has proven to be effective in many cases, but in complex and heavily constrained cases it does not provide sufficient flexibility and accuracy. This because its concept is strongly connected to a single objective function (the maximum delay) and its operation is based on the comparison of only two trains at each time.

The current CDR module implements a more robust optimization algorithm based on a rollout scheme, introduced by [4] in the job-shop case. In the rollout approach, a solution is found solving a conflict at a time by analysing the values of a generic scoring function. In the alternative graph formulation, conflicts are represented by couples of paired arc, and for each couple one arc only can be selected. The scoring function evaluates the impact of a single decision (e.g. a train ordering decision) in terms of final delays of all trains. Doing so, the scoring function can be freely chosen in order to match a desired objective function, achieving higher design flexibility. With respect to AMCC and similar simple heuristics, the rollout approach has proven to be more robust in terms of performance stability with different scenarios.

However, the evaluation of the whole final delays after a (tentative) arc selection must be very accurate, keeping in account the implications on the whole traffic, by a propagation of the (tentative) selection inside the whole graph for all trains. As a consequence, this process could be time consuming. To speed-up the process, the concept of arc implication is widely adopted. In railway terms, an implication means that, when a precedence relation is selected for a couple of trains sharing a given layout element, it must be maintained for all the following shared elements. In the alternative arc formulation this means that an alternative arc selection implies a set of similar selections on other arc pairs connected to the first one. Implications are evaluated once at graph building, being a static concept, and this reduces significantly the number of decision loops needed to solve conflicts.

4.4 Re-routing

Recently, a new optimization scheme for the use alternative routes has been developed and integrated in the graph model of TMS, to allow a more efficient and effective choice of alternative routes. Alternative routes improve the flexibility of TMS when looking for solutions to prevent heavy conflicts or to avoid traffic congestion.

The final aim of a re-routing action is to cope with conflicts that could not be solved efficiently by acting on train ordering only, and so to improve traffic fluidity and to reduce delays. The role of re-routing is dramatically evident in stations, where fixed platform occupation policy limits performances and causes delays when the platform assigned to a train is occupied by another one, but there are other empty platforms available.

Keeping into account railway practice and computational issues, it is clear that re-routing can be applied only within a suitable time window. The main reasons behind this limit are:

- it is not possible to modify a train route too close in time and space to the current train position (physical constraints on route setting, time needed to inform the public)
- it is not a good practice to modify a train route too far in time and space, because the solution based on long-time forecasting could be not still optimal in a dynamically changing environment.

Moreover, the same train cannot be re-routed many times, in order to avoid confusion. So when a re-routing action has been decided for a given train in a given station, such decision must be considered as definitive. However, even if these constraints narrow the re-routing problem, the search for the best re-routing action is a complex optimization task with a huge search space to be explored, even with a small set of alternative routes for trains. Exhaustive strategies are obviously not feasible in real-time optimisation, and only sub-optimal algorithms must be considered.

In order to include an efficient re-routing capability in TMS without affecting too much the computational performance of the system, we proposed an approach in which, at every new schedule generation, a few re-routing alternatives are explored, in order to look for a schedule better than the current one, even if not the best one in general terms. We exploit the fact that new schedules are generated quite often in practice, due to possible effects of disturbances, so we can distribute the computational extra effort needed for re-routing analysis in different activations of the scheduling module (CDR).

The key idea is to look for all the typical delay patterns in which a train A induces a heavy delay over another train B, as represented by an alternative arc between A and B whose activation causes a large variation in passing times of B. When A and B routings are fixed, such a delay is unavoidable, but the delay may be reduced if the routing of B can be changed. So we have to define:

1. which couple of trains A-B presents a high delay pattern
2. which alternative route for B can be chosen as a good candidate

Answering to such questions, we can build a new graph and perform a new schedule generation as usual, obtaining an "alternative schedule". Then we can compare the alternative schedule with the original one, by a suitable cost function, and select the best one. The cost function can be simply the total delay or tardiness or punctuality (e.g. the percentage of trains with delay lower than a given threshold). The proposed approach belongs to the local search scheme for combinatorial optimization, in which a current solution is locally modified in order to explore a smaller search space to find a better solution

In order to save computational time, it is highly opportune that TMS keeps track of all the already explored alternatives, even if they are not beneficial, in order to focus its attention elsewhere in the successive searches. This can be done using a taboo list in which storing all the unsuccessful tests, while the successful ones become part of the current schedule.

The implementation of the proposed re-routing approach relies on the definition of two new heuristics. The first one (called re-routing check) selects the candidate trains and the location (e.g. the block section) for the intervention, the second one (called route selection) selects the alternative route to be tested. A complete description of such heuristics is out of the scope of the present paper, and we will give only a brief sketch about how they work in practice.

The *re-routing check* is based on the evaluation of the added delay on a train graph node, that means the delay added on train B by a train A which shares a block with B and it is before train B. In normal flow, such added delay is zero, and it grows when hindering occurs. In some cases, for instance at stops, the train B may suffer for high added delay caused by A, when B has to wait for a platform currently occupied by A. So, the proposed heuristic selects, by scanning each delayed and re-routable train path, the arc producing the maximum added delay. This identifies a train and the block section to be avoided (if possible) by a re-routing action.

The *selection* of the best alternative route to be tested is performed by looking at the alternative route, minimizing the occurrences of other trains in the same station in a given time window (e.g. a few minutes) around the conflict time. So we look for all the trains passing through the same station in the same time window and evaluate a numeric score for each alternative route, simply by counting how many elements are in common between this route and the routes already used by other trains. The aim is to choose the alternative route minimizing possible train interactions.

After train and route selections, a new graph can be built and a new schedule can be produced by the graph optimization procedure in CDR. It remains only to decide whether the new schedule is better than the old one or not, using the chosen cost function. The number of train/route pairs to be tested depends on the available time for the process. However, even with a single test at a time, the continuous schedule adaptation ensures that a sufficient number of re-routing alternatives is explored.

5 TMS benefits for the case study Den Bosch

Simulation of the 2012 situation was done using a detailed map of the infrastructure (similar to the one used in reality for traffic control), the real timetable and entry disturbances for trains based on measurements made in 2010 when a similar timetable was used [8]. That is, the situation simulated is not an abstract one but is highly realistic.

To gather results, 25 runs of 6 hours were executed, where the first 2 hours were used as warm-up time to fill the simulation model and were discarded in the analyses.

Performance indicators address delay distribution and the number of unplanned stops. esults are summarized in Table 1, showing performance indicators at entry and exit for the different traffic control strategies (see section 3.2). Note that ′tardiness′ measures trains that are too late. That is, trains that are too early get delay 0 before performance indicators are calculated. In this way a train that is too early cannot compensate a train that is too late (for instance, train 1 has delay -300 sec and train 2 has delay +300 sec, then average delay is 0 sec, while average tardiness is 150 sec).

All trains		FCFS	VaVo	TMS
	entry	exit	exit	exit
delays [sec]				
average per train	114	68	74	69
std	**129**	**177**	**169**	**140**
tardiness [sec]				
average per train	**120**	**94**	**101**	**88**
std	121	157	146	122
punctuality				
1 min	39.1%	57.4%	51.9%	51.4%
3 min	**75.4%**	**85.5%**	**79.6%**	**86.1%**
5 min	**90.7%**	**89.0%**	**89.6%**	**94.6%**
7 min	97.0%	92.4%	94.3%	96.7%
delay percentiles [sec]				
5%	-48	-118	-121	-110
10%	**-18**	**-83**	**-89**	**-81**
50%	86	33	48	55
90%	**287**	**352**	**307**	**219**
95%	365	488	436	313
unplanned stops				
number/hour	**-**	**6.42**	**6.73**	**1.19**
# trains	2660	2660	2660	2660

Table 1: Simulation results. The bold lines denote the core performance indicators.

As can be seen, TMS achieves a lower average tardiness and at the same time achieves less scatter (lower standard deviation and smaller 10%-90% percentile bandwidth) than FCFS or VaVo. The 5 minutes punctuality achieved by TMS also is much higher. Additionally, TMS has less unplanned stops, which increases safety and decreases energy consumption. The improvements shown are considerable; e.g. improving the 5 minutes punctuality with a few percent is not easy at all and quite valuable.

Table 2 shows the performance at exit with respect to entry and the performance of TMS with respect to FCFS or VaVo. Note that for most performance indicators, FCFS and VaVo perform worse at exit when compared to entry, while TMS actually performs better at exit, which given the busy timetable and constrained infrastructure is quite impressive.

All trains	Improvements at exit with respect to entry			Improvements TMS w.r.t. FCFS and VaVo at exit	
	FCFS	VaVo	TMS	FCFS	VaVo
average tardiness	22%	16%	27%	7%	13%
std delay	-38%	-32%	-9%	21%	17%
5 min punctuality	-2%	-1%	4%	6%	6%
90% delay percentile	-23%	-7%	24%	38%	29%
10%-90% bandwidth	-43%	-30%	2%	31%	24%
number of unplanned stops	-	-	-	81%	82%

Table 2: Relative improvements.

The number of unplanned stops for different control strategies is depicted in Figure 5.

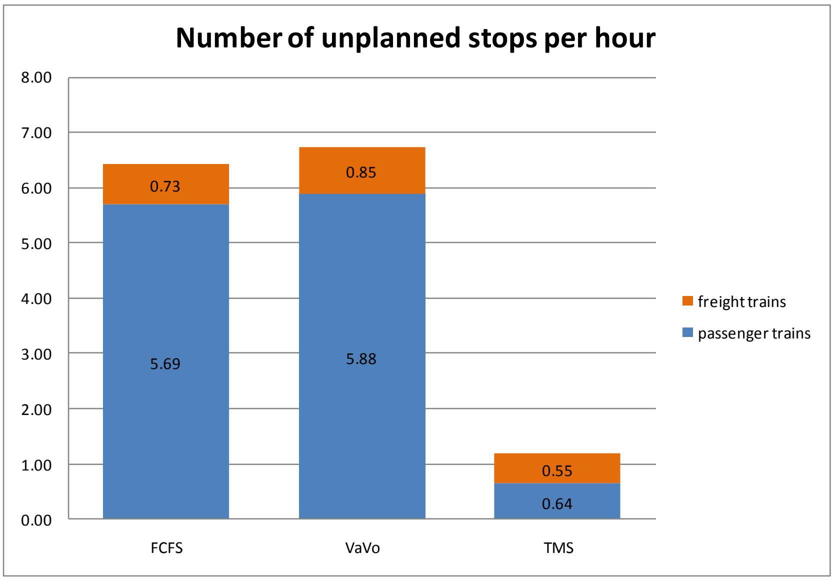

Figure 5: Number of unplanned stops.

Considering the busy timetable and constrained infrastructure, we were also interested in whether the situation was stable. That is, how do the performance indicators evolve over time? For the average tardiness this is depicted in Figure 6.

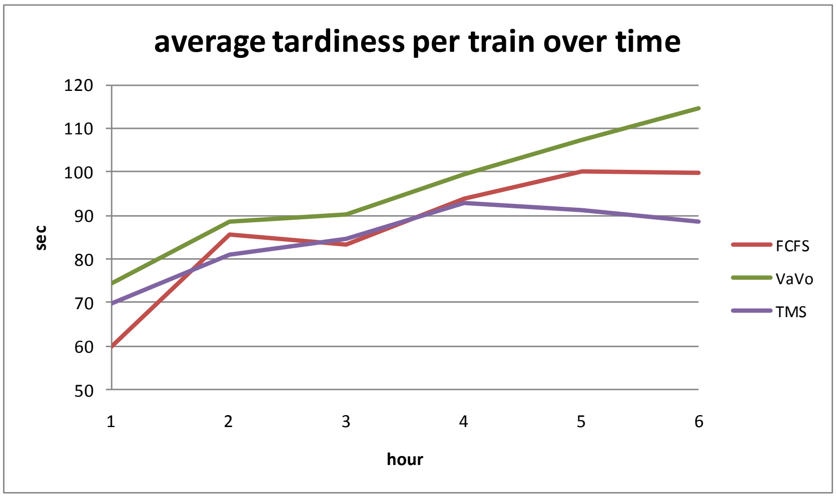

Figure 6: Average tardiness over time.

As can be seen, FCFS and TMS seem to stabilize, while VaVo appears to be instable (which also actually occurred during a pilot in reality where punctuality decreased over time). This can be understood from the fact that VaVo imposes more constraints on traffic control then FCFS or TMS, see section 3.

Summarizing the results, when compared to FCFS and VaVo the TMS achieves:

- Less scatter (lower standard deviation and smaller 10%-90% percentile bandwidth). Keeping trains closer to their schedule is advantageous, for train control operators, passengers and future planning (less margin might be sufficient).
- Lower tardiness.
- Higher punctuality and better 90% delay percentile. There are less trains with big delays. The 90% delay percentile is better at exit than it was at entry, while for FCFS and VaVo it is worse at exit than it was at entry.
- Less unplanned stops. Implying a decrease of safety risks and a lower energy consumption.

Note that this is achieved on a busy part of the Dutch railways network in a situation where the infrastructure capacity is restricted. In the bottleneck trains will hinder each other, even if there are no external disturbances.

Additional benefits of a TMS can be:

- TMS detects future conflicts and makes a new feasible plan. This plan can be communicated to passengers, so that passengers are informed earlier and more accurately.
- The optimization criterion used by a TMS can be used to reflect agreements between different train operating companies and between train operating companies and traffic control, making the way in which trains are processed more consistent and transparent.
- TMS can take care of ´routine´ conflicts effectively, allowing dispatches to focus on

higher level decisions.

- Future plans in the Netherlands contain more trains driving closer together. As a result, to prevent or soften ripple effects over the network, speed control as done by a TMS becomes more important.

Finally, using alternative routes was not allowed in this study because the focus was on the possible benefits of speed control. TMS can use alternative routes, and in all probability this will further enhance TMS results.

6 Future Work

The potential benefits for the FRISO-TMS combination are promising. A next step is to investigate whether the benefits can be realized in the operation. Two developments that are required have been started at the end of 2012. First we need an interface to real life train position services (with varying levels of accuracy) and second TMS must be able to cope with trains that are not equipped with systems to receive the TMS-information and with trains that may not follow given advisory speeds.

The results of the Den Bosch case study will be followed by more stations where capacity bottlenecks and/or low performance of punctuality occurs. In the beginning of 2013 the analysis of a new timetable for 2015 at Schiphol (Amsterdam airport) will be finished.

The architecture (HLA) also enables the possibility to investigate an enhanced level of the situational awareness of the traffic controller and the train driver. FRISO also provides a connection to a dispatching module that allows traffic controllers to interact with the simulation model, which provides a man machine interface for route setting tasks with a similar appearance (look and feel) as the systems used in daily operation. In a serious gaming approach the availability of more and better information is and will be tested in a series of interactive experiments [1]. Next developments are a connection with real life train position services and a connection with a testbed for train signalling software.

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