

# Railway Network Timetabling and Dynamic Traffic Management

I. A. Hansen\*

Received: September 2009

Accepted: February 2010

**Abstract:** The paper discusses the current state of research concerning railway network timetabling and traffic management. Timetable effectiveness is governed by frequency, regularity, accurate running, recovery and layover times, as well as minimal headway, buffer times and waiting times. Analytic (queuing) models and stochastic micro-simulation are predominantly used for estimation of waiting times and capacity consumption along corridors and in stations, while combinatorial models and stability analysis are suitable for network timetable optimisation. Efficient traffic management can be achieved by real-time monitoring, fusion, analysis and rescheduling of railway traffic in case of disturbances. Real-time simulation, optimisation and impact evaluation of dispatching measures can improve the effectiveness of rescheduling and traffic management. The display of dynamic signal and track occupancy data in driver cabins, as RouteLint developed by ProRail, can support anticipative actions of the driver in order to reduce knock-on delays and increase throughput.

**Keywords:** timetabling, attractiveness, waiting times, punctuality, conflict detection, traffic management,

## 1. Introduction

So far, railway timetables are based on deterministic running, dwell and headway times between stations. These times are mostly scaled in minutes and refer to a virtual stopping point at the stations. Small variations of the service times are compensated by standard running time and dwell time supplements, as well as margins (buffer times) between the train paths. The determination of supplements and buffer times in practice, however, is mainly based on rules of thumb, sometimes validated by simulation, and only seldom verified by means of statistical analysis of real-world operations data.

Stochastic analytical approaches, like queuing models [1, 2, 3, 4, 5] assume the train intervals and the service times to be independent random variables, which is questionable in case of periodic timetables with high frequencies. The variation of inter-arrival times and minimal headway times is modelled mostly on the basis of assumed, not validated random distributions for inter-arrival and service times. The estimated waiting time of a timetable is a function of the

track occupancy and the coefficients of variation of the scheduled headway and service times of individual lines and/or stations, which cannot be easily extrapolated to multi-channel service systems and complex networks. Scheduled waiting times generated by stochastic variables of the timetable are clearly distinguished from estimated original and consecutive delays during operations.

Combinatorial optimisation models are used more and more for strategic line planning in large complex networks, timetable design, rolling stock and crew scheduling [6, 7, 8]. The models aim at solving the formulated (timetable) problem for a certain objective function under predefined constraints to optimality and, thus, generating an optimal design for the individual departure and arrival times in a network. They are computed via (Mixed) Integer Linear Programming ((M)ILP) by means general-purpose solver or by using Lagrangian relaxation and heuristic methods. In general, optimisation models apply deterministic variables for searching the optimal value of the objective function, like minimisation of overall running times in networks, at given constraints like minimal headway and transfer times between trains. The first known stochastic optimisation approach for estimation of the robustness of railway timetables is presented by Vromans [9].

---

\* Corresponding author. Email: I.A.hansen@tudelft.nl

Professor, Department of Transport & Planning,  
Delft University of Technology.

Micro-simulation models, like STRESI [10], RailSys [11], OpenTrack [12] or ATTPS [13] are used to estimate the effect of exogenous random primary delays on track occupation and consecutive delays of hindered trains. The induced primary delays are drawn from assumed or empirical distributions for a given timetable, track infrastructure and signal system. Kaminski [14] introduced a heuristic limit for the buffer time distribution at bottlenecks in order to compensate for 80 % of the primary delays. Carey & Carville [15] presented a heuristic approach for solving conflicts between train paths and routes and simulation of random delays in order to test the reliability and robustness of timetable options.

This paper will first describe the principles of scheduling and periodic railway network timetables focusing on the estimation of capacity consumption and the optimisation of timetable parameters. Then, the requirements and characteristics of advanced information and decision support systems for dynamic railway traffic management are presented in order to evaluate their impact on train drivers', dispatchers' and network performance. The paper concludes with remaining issues for further research and development.

## 2. Timetabling

Railway schedules are necessary for the coordination of resources in different planning and production stages in order to match transport demand and capacity and to inform stakeholders and customers. Timetables must assure that the expected transport demand can be realised according to the requirements of passengers, shippers, train operating companies, infrastructure manager and public authorities effectively and efficiently. Effectively means a high quantity and quality of available infrastructure, rolling stock, personnel, transport and traffic services, while efficiently requires a maximum output with the least possible input.

The principal goal of railway transport is to attract a maximum number of customers and load on planned or existing lines with a minimum of investment cost, personnel, equipment, energy

consumption, operating and maintenance costs. The acceptance by passengers, shippers and public authorities depends in a competitive market on performance criteria as speed, frequency, comfort, reliability, punctuality, safety and price of services [16, 17].

The effectiveness of a timetable can be expressed by indicators as:

- Number of trains, passengers and load per time period,
- Amount of passenger-kilometre and ton-kilometre per time period,
- Operating and circulating speed of trains,
- Headways and buffer times,
- Scheduled waiting times,
- Time and effort for modification and updating (reschedule).

Distinction is made between non-periodic and periodic timetables. The latter are more and more international standard, because cyclic ('clockfaced') timetables are easy to remember for passengers and easier to handle for railway personnel. The scheduled intervals between the trains of the same line of a cyclic timetable are regular over the (daily) service period, but may be increased to an integer multiple of the base

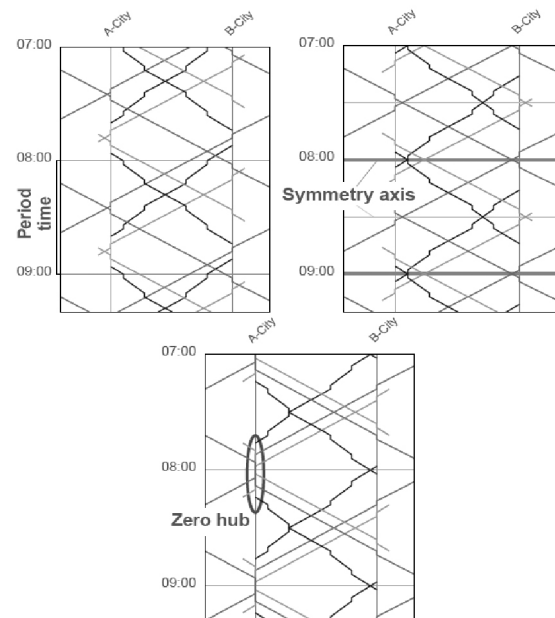


Fig. 1. Periodic timetables (source: Liebchen [18])

interval or decreased by an integer divisor e.g. during peak periods. The trains from both directions of a line then meet each other twice during one interval creating a symmetry axis of the train graph if the running times per direction are not (much) different. A symmetric cyclic timetable (Fig. 1) exists if the symmetry axes of all lines are identical e.g. situated at every full hour. Integrated cyclic timetables in networks are characterised by scheduled transfer connections between different lines at (major) railway stations ('hubs'), where the trains meet each other at regular intervals (at least hourly).

The quality of timetable design for a given traffic demand, rail infrastructure and train mix depends mainly on:

- Frequency
- Regularity
- Precise and realistic running and dwell times
- Sufficient but not too large recovery times
- Exact minimal headway times between different pairs of trains,
- Estimated waiting time.

## 2.1. Frequency

The higher the train frequency the more attractive it is for the customers, but the higher are the operating costs. Depending on the trip distance, transport demand, car ownership and competition with other modes in the area served, an average frequency of e.g. 6(12) times/(peak) hour and direction can be considered as excellent for heavily loaded national (regional) passenger railway lines, while 2(4) times/hour is satisfactory for less loaded lines and time periods (Tab. 1). Only in densely populated metropolitan

areas higher frequencies than 12 times per hour per track might be needed. A passenger train frequency of less than once per hour frequency per direction must be considered as poor.

For freight trains a frequency of twice a day per direction is good, while less than once a day (week) per direction for regional (international) lines may be considered by shippers as rather inappropriate.

## 2.2. Regularity

A high level of regularity of scheduled services is very important for high frequent passenger lines in order to avoid hinder due to overloaded platforms and trains. Irregularity of a timetable can be easily computed through the standard deviation of the scheduled intervals between trains at stations in a network. The smaller the standard deviation, the higher is the regularity of the planned train services. The regularity of lines or certain stations in a network may be weighted differently according to their importance. Regularity of train operations is generally more critical than that of schedules.

## 2.3. Running and Recovery Times

Deterministic running times at a scale of minutes are standard in most railway timetables. Only very densely occupied railway lines in some countries as Japan or metro lines, so far, apply more accurate scheduled running times scaled at 10 to 15 seconds. A major reason is the inability of train drivers to perform better without more precise on-board information and advanced support. Another reason is the common practice to add certain running time supplements to the

**Table 1.** Quality levels of train frequencies

	<i>Passenger train lines/h dir</i>				<i>Freight train lines/d dir</i>		
	<i>Local</i>	<i>Regional</i>	<i>(Inter-)</i>		<i>Regional</i>	<i>(Inter-)</i>	
	<i>National</i>				<i>National</i>		
<b>A Excellent</b>	<b>12</b>	<b>6</b>	<b>3</b>	<b>4</b>	<b>4</b>	<b>2</b>	<b>4</b>
<b>B Good</b>	<b>6</b>	<b>3</b>	<b>1</b>	<b>2</b>	<b>2</b>	<b>1</b>	<b>2</b>
<b>C Satisfactory</b>	<b>4</b>	<b>2</b>	<b>0.5</b>	<b>1</b>	<b>1</b>	<b>0.5</b>	<b>1</b>
<b>D Poor</b>	<b>2</b>	<b>1</b>	<b>0.25</b>	<b>0.5</b>	<b>0.5</b>		<b>0.5</b>

nominal 'technical' running times in order to enable easy recovery from small delays without hinder for other trains. Many railways apply a standard running time supplement of 7%, as recommended by UIC, which is meant to cover running times up to 93% of the right tail of a normal distribution. In fact, the scheduled running times and required supplements can be estimated much more accurate, provided detailed statistical analysis is made of empirical track occupation and release data (see chapter 3.1).

Empirical distributions of exact running times can be easily derived from track occupation and release data which are recorded and saved automatically by the existing signalling and safety system.

As these data only contain the passing times per train number at main signals and these are distant from the stopping points at platforms the additional deceleration and acceleration time respectively from and to the last (first) main signal needs to be estimated taking into account the remaining distance between the last/first measuring point and the stop location, as well as the train characteristics (length, weight, power, standard deceleration/acceleration rate). At TU Delft the tools called TNV-Prepare and TNV-Filter [20] have been developed by which the recorded passing times at signals and insulation joints of any train can be filtered and the real running times and delays per train series be computed automatically according to their route,

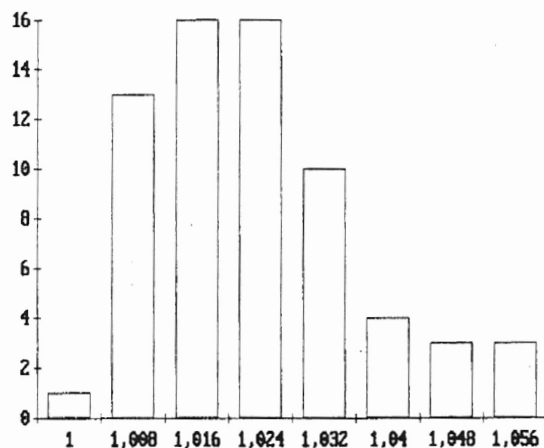


Fig. 2. Frequency of running time peak factors of passenger trains [19]

type and period of the day.

The true minimal running times per link can be revealed at a precision of seconds by selecting only those trains that were delayed at the preceding departure station and experienced no hinder. The percentile of running times at a certain level of probability can be estimated by statistical analysis of the precise running times per train line.

The running times depend on the alignment, number of dwell times at intermediate stops, type, length and weight of rolling stock operated as on the behaviour of the train drivers and weather conditions. The running time distributions per train line can be used for estimation of the amount of recovery time instead of using a standard supplement.

#### 2.4. Minimal Headway and Buffer Times

In practice, timetable designers mostly apply standard mean minimal headway times (2 to 5 min) between train paths depending on the type of conflict and train sequence. The existing buffer times in a conventional graphical timetable which indicate only the train paths and headway times at a scale of minutes cannot be determined sufficiently, because these do not indicate the precise start and end of the capacity consumption according to the prevailing signalling and safety system.

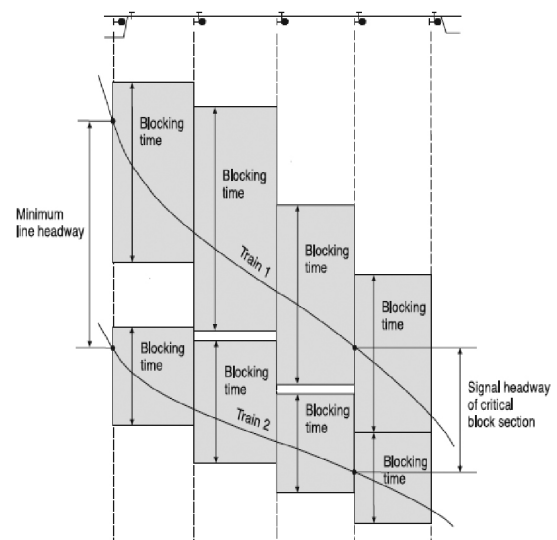


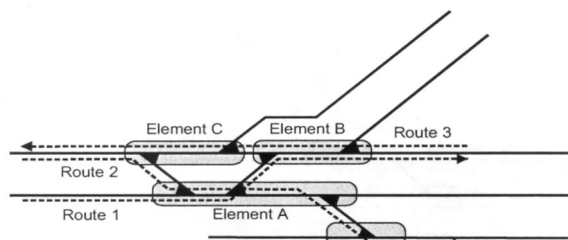
Fig. 3. Blocking time diagram [21]

The minimal time headway between two trains on a railway route is governed by blocking times of trains and its speed differences [21, 22]. The blocking time diagram of a train (Fig. 3) represents the time instances that a train needs to run safely without hinder at design speed over a sequence of track sections. The scheduled train paths virtual as well as the track occupancy times are represented in a time-distance diagram and indicate clearly the remaining buffer times. Any overlap between the blocking times of different trains clearly indicates a timetable conflict, which needs interaction in order to avoid a deceleration or stop of the following train.

The blocking times depend not only on the signal spacing and train length, but also on the actual train speed and deceleration rate. If the movement authority for the train at sight distance of the distant signal is given late because of insufficient headway to the preceding train, the following train would be decelerated automatically, which means an increase of the blocking time.

Furthermore, the scheduled dwell times are often exceeded during operations, which lead to an increase of the blocking time of the routes serving the platform tracks. The quality of timetable design would be enhanced considerably if the estimated blocking times reflect well the variation of train speed and dwell times in practical operations.

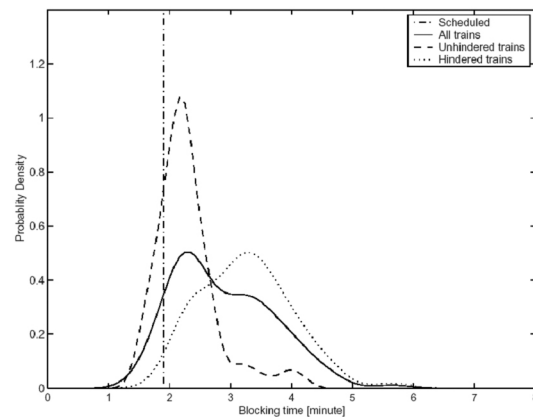
So far, the blocking times in timetables are assumed to be deterministic and estimated with a precision of seconds. The arrival and departure times of trains and the headway times between trains in most railway timetables, however, are determined currently with a precision of minutes due to rounding-up of the estimated running times and easy comprehension by the passengers.



**Fig. 4.** Division of an interlocking arrangement into route nodes [21]

This practice includes hidden scheduled waiting times, which could be exploited if the determination of the arrival, departure and headway times (for in-company planning and operation purposes) was done at a higher precision in steps of 5 to 10 sec (according to current practice in Japanese railways).

For capacity estimation of heavily occupied routes in bottlenecks the track infrastructure needs to be subdivided in individual route nodes: the smallest track elements that can be used by one train at a time (Fig. 4). The variations of time headway and train speed at heavily occupied junctions may lead to knock-on delays and queuing of trains before network bottlenecks. On the routes approaching to level crossings close to main stations we observed a significant drop of the mean train speed by a bout 20 to 50 % with regard to design speed which means a clear reduction of infrastructure performance. This means the scheduled speed and headway times should correspond better to real operations and the train drivers need to be supported by dynamic speed advices in order to avoid hinder to and by



**Fig. 5.** Distribution of blocking times of Intercity trains approaching to the Dutch station The Hague HS [27]

**Table 2.** Recommended capacity consumption by UIC norm 406 [22]

Type of line	Peak hour	Daily period	Comment
Dedicated suburban passenger traffic	85%	70%	The possibility to cancel some services in case of delays allows for high levels of capacity utilisation.
Dedicated high-speed line	75%	60%	
Mixed-traffic lines	75%	60%	Can be higher when number of trains is low (smaller than 5 per hour) with strong heterogeneity.

other trains at junctions. In fact, the blocking times are stochastic and not deterministic, and so are the remaining buffer times (Fig. 5).

The total track occupancy and the remaining timetable slack of a given line is estimated finally by means of a virtual compression of the blocking time graphs according to UIC norm 406, which recommends maximal track occupancy rates of e.g. 75 % during peak hours and 60 % a day for lines used in mixed traffic (Tab. 2).

## 2.5. Waiting Times

Every timetable comprises scheduled waiting times and generates, in practical operations, non-scheduled waiting times (delays). Scheduled waiting times result from differences between the scheduled and desired running, headway, departure/arrival times by train operating companies, as well as timetable constraints. The scheduled waiting times depend on the market demand, track possession times due to maintenance and synchronisation conflicts between train graphs at railway nodes and bottlenecks, whereas non-scheduled waiting times can emerge from technical failures of track infrastructure or rolling stock, accidents, and train delays. The amount of scheduled waiting times can be used as indicator of timetable quality. The total waiting time during a time period, in general, increases exponentially with the number of trains operated. The research challenge is to determine the optimal track occupancy at a desired level of service.

Schwanhäusser [1] developed already in 1974 a stochastic approach for the estimation of the mean queue length as function of the distribution of primary delays, buffer time, mean headway, train sequence and priority by a queuing model of type  $M/D/1$ . This led e.g. to an estimated mean buffer time of 1 min in case of a minimal headway of 2 min and all trains delayed (p. 59). As the assumed Poisson distribution of train arrivals has been questioned later on, queuing models of the type  $G/G/1$  and  $M/G/1$  have been developed by Wakob [2] and Hertel [3] respectively.

Hertel presented, too, an analytical approach

for the waiting time (Fig. 6) as function of traffic flow, relative waiting time sensitivity (partial derivative of mean waiting time to track occupancy) and maximal traffic 'energy' (defined as product of train intensity and speed). According to Hertel the recommended area of train intensity as function of waiting time sensitivity and traffic 'energy' of a track operated in one direction would be about 150 to 200 trains per day, while the waiting time per train may increase up to 10 min.

Kaminski [12] analysed the timetable and compared the estimated waiting times by micro-simulation with the recorded train delays of a large network (>2000 km) in Germany and found a good fit of the buffer times with a negative-exponential distribution.

He estimated the impact of buffer time length corresponding to 80 % of the train delays

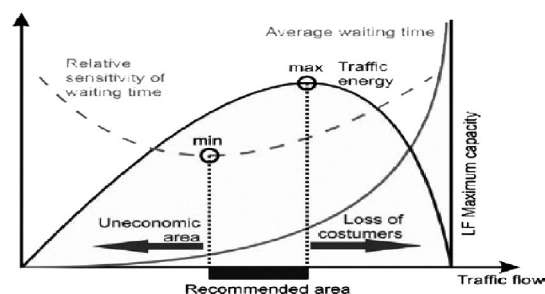


Fig. 6. Waiting time as function of traffic flow, relative sensitivity of waiting time and traffic 'energy'[3]

recorded at a number of stations by multiple simulation, while maintaining the train orders. The mean consecutive delay per delayed train was estimated at about 30 sec.

The expected total waiting times of railway lines and networks are estimated in several European countries by means of micro-simulation tools like STRESI [8], RailSys [9] or OpenTrack [10] that draw and insert samples of random primary delays from predefined distributions to a timetable. The virtual hinder between trains, which is simulated through modification of the scheduled blocking time graphs (bending of train paths, increasing of dwell times, change of train order and routing), while its impact is estimated by the distribution of delays, the kind and percentage of hindered

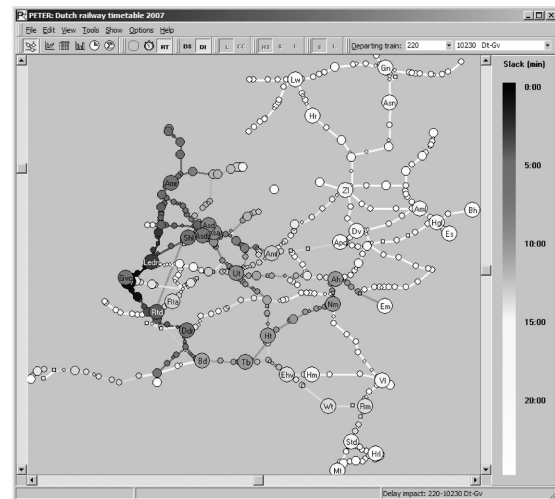
trains and the punctuality level.

The timetable slack of interconnected lines in networks with periodic timetable depends not only on the buffer times of the individual lines, but also on the buffer times between the scheduled train arrivals and departures at the transfer stations. The following constraints for the design of an integrated network timetable hold:

- The round trip time of a line must be integer multiple of the headway,
- The travel time between the nodes (sum of the running and dwell times) must be an integer multiple of half of the cycle time (mostly 60 min),
- The scheduled arrival and departure times of interconnected lines at the nodes must overlap sufficiently,
- The sum of the travel times on a circuit between three nodes must be an integer multiple of the cycle time and of the time headway.

As such constraints lead in large networks with many nodes and lines to a great complexity of periodic timetables, combinatorial operations research methods like MILP were developed in order to search for the optimal solution of a given timetable [6, 7]. The network timetable problem, however, is known to be NP-complete and requires the development of intelligent algorithms to find a solution within a reasonable computation time – if existing under given constraints – and/or to relax some constraints. Predefined constraints like minimal headway and transfer times, however, don't guarantee the timetable feasibility in complex junctions and, therefore, need to be proven by a detailed analysis of blocking times and/or micro-simulation.

The existing buffer times and its distribution in periodic timetables of large networks can be calculated analytically by means of the  $(\max, +)$  algebra approach, which transforms the network timetable and constraints into an extensive set of simple recursive linear equations [23]. This technique enables to identify the critical circuits within a large complex railway network and to



**Fig. 7.** Recovery time sensitivity of initial delay of Intercity train Delft to The Hague on the Dutch railway network [24]

calculate the minimal cycle time of the whole timetable and the existing timetable slack. The basic periodic network timetable of the Dutch Railways can be automatically transformed by the tool PETER [24] into a  $(\max, +)$  state matrix of the travel times, minimal headway times and transfer times in order to identify the critical circuits, to calculate the stability margin and to perform a delay propagation and recovery time analysis. The impact of an increase or decrease of travel times and buffer times on the timetable slack and on the location of the critical circuit of periodic network timetable can be estimated rapidly, as well as the propagation of train delays in the network (Fig. 7). a

### 3. Dynamic Traffic Management

#### 3.1. Performance of Train Operations

The operations performance can be assessed by means of different analytical approaches and micro-simulation. A high level of performance, of course, requires that the basic timetable is feasible, a high availability of infrastructure, experienced personnel and a low failure rate of rolling stock.

Schwanhäusser [1] defined in 1974 the smoothness of operation as the share of unscheduled waiting trains at any location in order to proceed. He developed an analytical

approach for estimating consecutive delays in case of hinder based on queuing theory. The admitted level of hinder during operations was determined empirically by certain maximal queue lengths and described by a simple exponential equation as function of the share of passenger trains:

$$L_W = \alpha \cdot e^{-\beta \cdot pP}$$

$L_W$  : queue length

$\alpha, \beta$  : coefficients

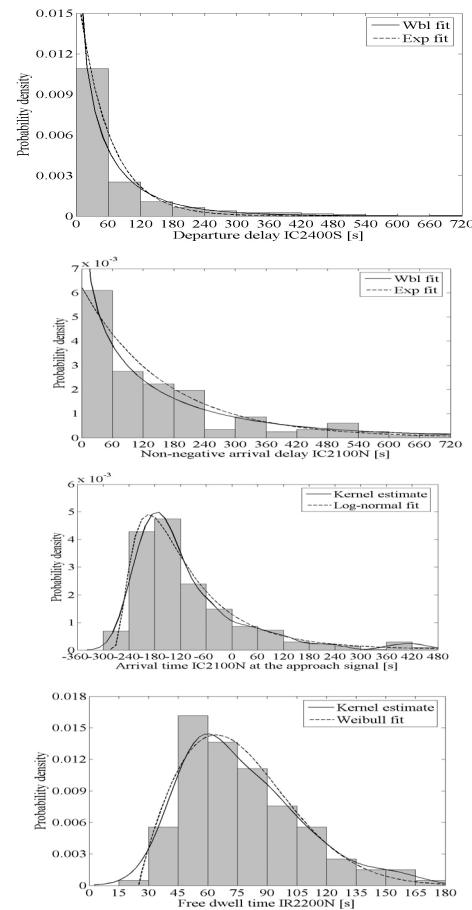
$pP$  : probability of passenger trains

$L_W = 0.257 \cdot e^{-1.3 pP}$  (calibrated function for Deutsche Bahn AG).

Three different levels of quality of operations (0.5 = very good, 1.0 = satisfactory, 1.5 = unsatisfactory) are defined as ratio of the estimated queue length divided by the maximum admitted queue length. The amount of daily knock-on delays at stations that are tolerated by Deutsche Bahn is determined at 130 min up to 300 min depending on the share of passenger trains. The estimation of scheduled and unscheduled waiting times as a measure of operations quality of a given timetable, infrastructure and signalling system is implemented in the software tool ANKE developed at RWTH Aachen [25].

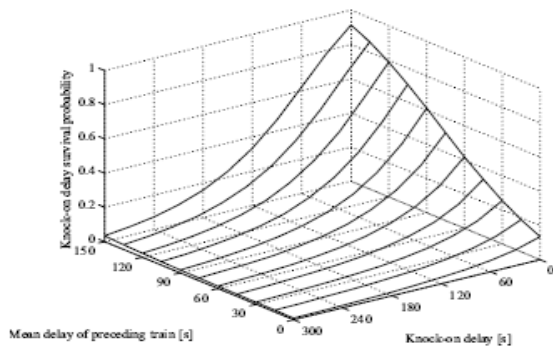
Detailed statistical analysis of train delays at several major Dutch stations [26] confirmed that train departure delays can best be described by negative-exponential or Weibull distributions, while the lognormal distribution fits better to initial and arrival delays of all trains, because trains may arrive early due to running time margins, whereas early departures are not permitted.

The impact of primary and consecutive train delays on the robustness of train services in station areas is estimated according to Yuan [27] by means of coupling the (conditional) probabilities and distributions of sequencing train delays at arrival, departure, and of the corresponding running and route release times. The survival probability of knock-on delays at a route node for a given delay of the preceding train is shown in Fig. 9.



**Fig. 8.** Density distributions of train delay, arrival and dwell time distributions of individual lines at the Dutch station The Hague HS [26]

The propagation of delays in large networks of interconnected lines can be modelled also by micro-simulation. Watson [28] compared the characteristics of current commercial simulation tools and concluded that ‘signal berth’ level tools are necessary for stochastic simulation. Simulation tools mostly require interaction of the user in case of conflicts between blocking time graphs or the application of a predefined automatic conflict resolution strategy. In order to evaluate the different dispatching measurements on the stability margin and the location of network bottlenecks in case of disturbance different options can be computed. The analysis of individual link and train dependent recovery times would allow a variety of experiments to estimate the robustness of different re-scheduling options (re-timing, re-ordering, re-routing). The



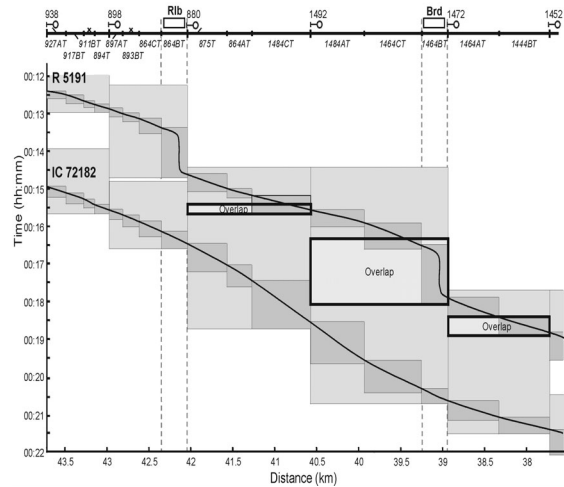
**Fig. 9.** Knock-on delay survival probability for a northbound departing train as function of frequency of trains passing a critical level crossing at the Dutch station The Hague HS [27]

effectiveness of different conflict resolution strategies can be evaluated on the basis of the amount of disturbance (primary delay, knock-on delays, punctuality) and fading-out time. However, the available micro-simulation tools need to be coupled to accurate on-line train detection, speed and delay monitoring systems in order to be used real-time for conflict detection, delay prediction and dynamic traffic management support.

### 3.2. Automatic Monitoring of Initial and Knock-on Delays

Actual passenger train delays monitored to passengers waiting at stations and to dispatchers by means of displays are based on standard train describer systems and track occupation and release data, which has been compared with scheduled arrival, departure times at previous locations. These records do not distinguish between initial and knock-on delays, which should be considered by infrastructure managers and train operating companies in order to identify the cause and responsible party and to take the most effective measures to reschedule the traffic in case of larger delays.

A software tool called TNV-Conflict [29] has been developed recently by TU Delft that identifies automatically all signalled headway and route conflicts including the critical track sections, involved train numbers, and the amount



**Fig. 10.** Example of conflicting train graphs between a local and an Intercity train south of Rotterdam generated by TNV-Conflict [29]

of initial and, separately, consecutive delay at a precision of less than 5 seconds. The output of the tool containing chronological infrastructure and train description messages can be used offline for analysis of timetable, infrastructure use and train performance, as well as online input for decision support systems of dispatchers. The comparison of measured track occupation and blocking times of the train graphs with the scheduled ones clearly indicate the difference of individual train process times (Fig. 10).

The acquired information include the locations and number of route conflicts, their effect on capacity consumption and punctuality, the assignment of knock-on delays to conflicting trains in a non-discriminatory way, and the identification of structural route conflicts from timetable flaws (e.g. infeasible minimum headways, late trains due to preceding bottlenecks, and early trains due to excessive running time supplements). The tool provides essential information to improve capacity allocation and to construct reliable train paths. Furthermore, data on actual train length, speed, headway, dwell time at platform and precise delay is collected that is needed for adapting rapidly the timetable and adjusting real-time the prediction of downstream arrival, departure times.

### 3.3 Real-Time Rescheduling

Regulation of railway traffic aims at ensuring safe, seamless and as much as possible punctual train operations. Due to the strict time limits for computing a new timetable in presence of disturbances, train dispatchers usually perform manually only a few timetable modifications (i.e. adjust train routes, orders and speeds), while the efficiency of the chosen measures is often unknown. Some computerized dispatching support systems have been developed, so far, which can provide good solutions for small instances and simple perturbations. Recent reviews on the related literature can be found e.g. in Törnquist & Persson [30]. However, most existing dispatching systems operate based on local information and decisions are taken locally, "on the spot and now". These systems are able to provide viable solutions only if few trains are delayed and the chosen traffic control actions are often sub-optimal. They cannot deal with heavy disturbances in larger networks as the actual train delay propagation is simply extrapolated and does insufficiently take into account the train dynamics and signalling constraints. Therefore, extensive control actions are necessary to obtain globally feasible solutions.

Advanced real-time traffic management systems should take into account the whole traffic in a larger area, detecting future conflicts among train movements (that have direct impact on the level of punctuality), automatically

calculating optimal traffic flow and suggesting possible change of orders or routes to the dispatcher, as well as displaying advisory speeds to the train drivers. Efficient traffic management support systems must be able to simulate the effects of different dispatching measures and support traffic controllers by frequently updating the actual timetable and ranking the dispatching options according to their expected performance.

The recently developed advanced real-time rescheduling tool ROMA (Railway traffic Optimization by Means of Alternative graphs) estimates the future evolution of the railway traffic considering actual train positions, signalling and safety operating rules and conditions, as well as dynamic train characteristics (fig. 11). ROMA computes a dispatching solution that minimizes train delays and their propagation by pro-actively detecting train conflicts by means of blocking time graphs and solving headway and route conflicts by iterative adjustment of train speeds and/or reordering and rerouting of trains within short computation times [31, 32, 33]. The effectiveness of extensive rerouting strategies is explored by incorporating the search for new routes in a tabu search scheme, in order to escape from local minimal [32].

The investigated dispatching area comprises the 50 km long line from Utrecht to Den Bosch offering a number of possibilities of train reordering and local rerouting (Figure 12). For each train a default route and a set of local rerouting options are given.

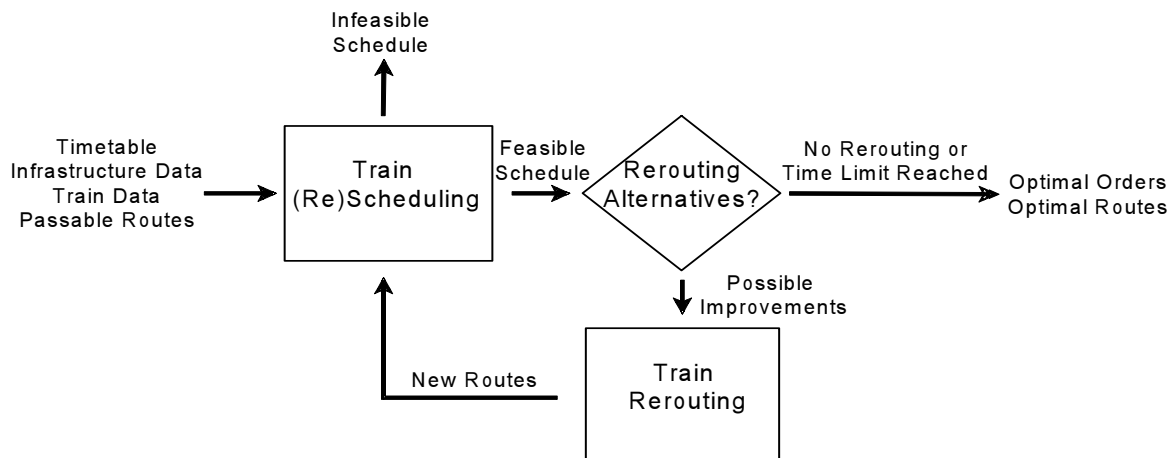


Fig. 11. Architecture of the real-time railway traffic optimization module

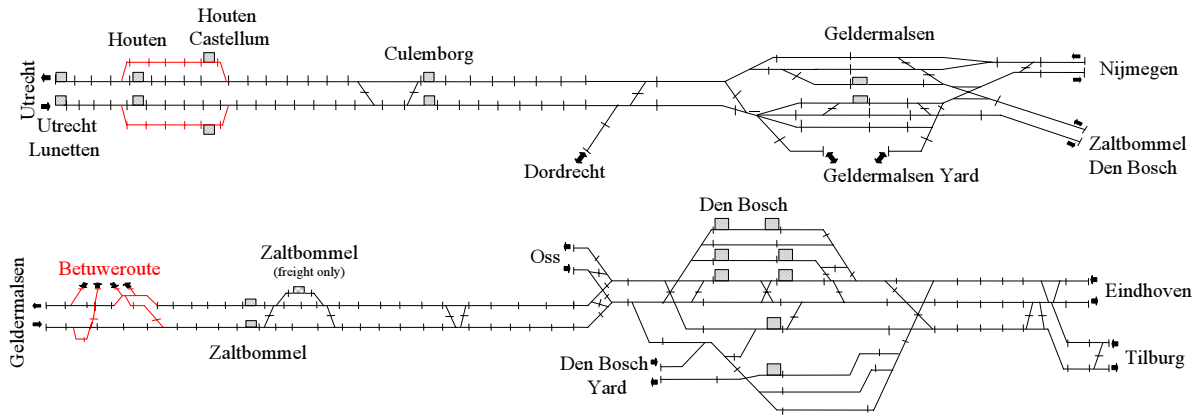


Fig. 12. Railway dispatching area between Utrecht and Den Bosch

Table 3. Performance of the ROMA configurations in case of timetable perturbations [32]

Roma Configurations	Max Cons Delay	Avg Cons Delay	Total Comp Time	% Train Route Changed	% Train Orders Changed
Automatic route setting (ARI)	342.0	38.7	4.8	-	12.3
Scheduling Algorithm (BB)	246.4	27.8	3.9	-	16.9
Rerouting Algorithm (TS)	238.7	24.6	127.9	15.5	12.2

During peak hours, 26 passengers and freight trains in both directions are scheduled each hour for the area around Geldermalsen and up to 40 trains at Den Bosch station. The minimum time for passenger connections varies from two to five minutes, depending on the distance between the arrival platforms. 32 instances with different timetable perturbations have been simulated and tested during a simulation period of one hour. The test results are listed in Table 3.

The automatic route setting represents the base case of current rail operations. The second and third lines refer to the average results by using the advanced scheduling algorithm (BB) and the rerouting optimization algorithm (TS), respectively. Each column of this table shows the average results on the 16 timetable perturbations. The fifth column presents the percentage of train routes that have been changed by the real-time railway traffic optimization module starting from the set of default routes given by the disruption recovery module. The last column indicates the percentage of train orders that have been changed with respect to the timetable. The computation results show the effectiveness of using real-time railway traffic optimization algorithms with respect

to simple and local dispatching procedures.

### 3.4. Advanced Driver Assistance

Apart from advanced rescheduling systems, new ICT-tools for the support of train drivers in order to anticipate hinder from other trains have been developed recently. Currently, train drivers receive only movement authorities and speed limit information in signal-controlled network passing at trackside discrete signal locations and/or by on-board automatic train control displays. In general, drivers are not informed about their train delay, except when comparing

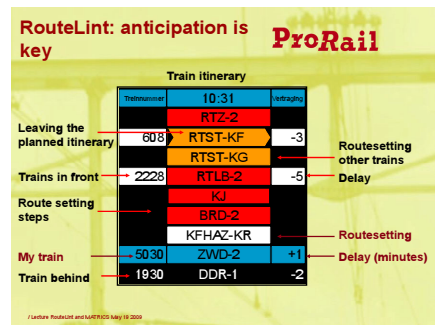
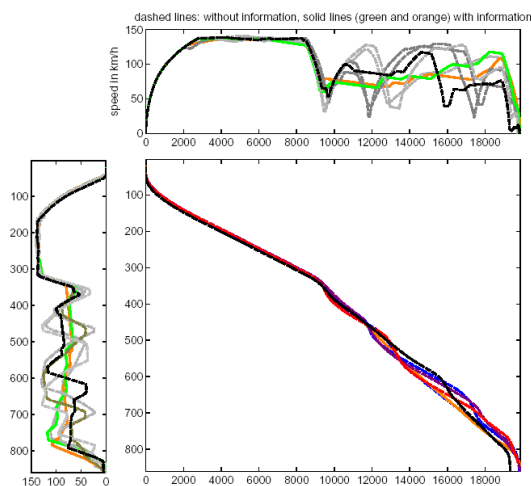


Fig. 13. Hand-held signal and track occupancy information RouteLint



**Fig. 14.** Plot of train performance with(out) dynamic on-board information system RouteLint [34]

the actual time with the scheduled times at stations on their own or if traffic controllers contact them via train radio.

Continuous update of information about changes of actual signal aspects and route release can be transmitted via radio to on-board handheld PADs (Fig. 13). The Dutch infrastructure manager ProRail has developed and demonstrated the effectiveness of transmitting such actual data to train drivers that enabled to start coasting or decelerating even before they come close to a danger signal in order to follow more closely their scheduled path or to avoid a train stop on the open track because of a still occupied track and route section further ahead. The dynamic on-board information system called 'RouteLint' [34] may reduce energy consumption of Intercity and freight trains by about 5% (Fig. 14).

A further development step consists in the application of head-up displays of downstream information on the windscreen. Such, driving trains on 'electronic sight' would become reality.

#### 4. Conclusion

The current methods and tools for railway timetable design enable a high precision of the estimated travel times, headway times and time margins in order to achieve high-quality, conflict-free timetables of lines and networks. Queuing models and micro-simulation tools have been applied successfully to improve the timetable

quality and to estimate the propagation of stochastic train delays. The key for high-quality timetabling is a precise estimation of blocking times based on realistic running, dwell and headway times taking into account the signal spacing and train processing at critical route nodes and platform tracks. Statistical analysis of empirical track occupation and release data in major Dutch stations has revealed that the trains often leave later and operate at speeds less than scheduled due to hinder by other trains, late route clearance, excess dwell times as well as drivers' and conductors' behaviour. Deterministic models for stability analysis and optimisation of network timetables like max-plus algebra technique or linear programming still need to incorporate the impact of dispatching measures on perturbed train traffic.

Queuing and simulation models for the estimation of unscheduled delays in daily traffic still reflect insufficiently the impact of speed variations and behaviour of railway staff. A new probabilistic model of TU Delft enables an estimation of the survival rate of knock-on delays at platform tracks and junctions based on empirical distributions of running and release times of the involved train pairs. The maximal number of trains and amount of consecutive delays at a given initial delay and required level of punctuality can be computed.

Efficient traffic management support systems need to compile actual monitoring data on train positions, headways and detect automatically conflicts between trains in advance in order to support dispatchers by regularly the actual timetable, incorporate standard conflict resolution measures and simulate their effects. Simple headway conflicts between only two trains might be solved automatically, whereas route conflicts in heavily occupied networks and complex stations require accurate real-time simulation and optimisation of dispatching options according to their expected performance. The effectiveness of different measures may be evaluated and ranked on the basis of the total amount of consecutive delays, links and stations affected and the time to fade out. More detailed, accurate and continuous traffic information with regard to actual deviation from the train schedule, location of trains ahead and occupation and

release of block and route sections can help train drivers to anticipate and solve conflicts better.

More research is still necessary to develop more powerful analytical, simulation and optimisation models of train rescheduling in complex networks in order to improve the reliability, efficiency and robustness of railway operations.

## References

- [1] Schwanhäusser, W., "Die Besetzung der Pufferzeiten im Fahrplangefüge der Eisenbahn", Veröffentlichungen verkehrswissenschaftl. Institut RWTH Aachen, PhD thesis, H. 20, 1974.
- [2] Wakob, H., "Ableitung eines generellen Wartemodells zur Ermittlung der planmäßigen Wartezeiten im Eisenbahnbetrieb unter besonderer Berücksichtigung der Aspekte Leistungsfähigkeit und Anlagenbelastung", Veröffentl. verkehrswissenschaftl. Institut RWTH Aachen, PhD thesis, H.
- [3] Hertel, G., 1992, "Die maximale Verkehrsleistung und die minimale Fahrplanempfindlichkeit auf Eisenbahnstrecken", Eisenbahntechn. Rundschau ETR, 41, H. 10, 665-672, 1985.
- [4] Wendler, E., "Analytische Berechnung der Planmäßigen Wartezeiten Bei Asynchroner Fahrplankonstruktion", Veröffentl. Verkehrswiss. Institut RWTH Aachen, PhD thesis, H. 55, 1999.
- [5] Huisman, T., Boucherie, R.J., van Dijk, N.M., "A solvable queueing network model for railway networks and its validation and applications for the Netherlands", EJOR., 142, 30-51, 2002.
- [6] Cordeau, J.F., Toth, P., Vigo, D., "A Survey of Optimization Models for Train Routing and Scheduling", Transportation Science, Vol 32, (4), 380-404, 1998.
- [7] Caprara, A., Kroon, L., Monaci, M., Peeters, M., Toth, P., Passenger Railway Optimization, in: Barnhart, C. & Laporte, G. (eds.) Handbooks in Operations Research and Management Science, Chapter 3, Vol. 14, Elsevier, 129-187, 2007.
- [8] Kroon, L., Huisman, D., Maróti, G., Optimisation Models for Railway Timetabling, in: Hansen, I.A., & Pahl, J., (eds.) Railway Timetable & Traffic, Hamburg: Eurailpress, 135-154, 2008.
- [9] Vromans, M.J.C.M., "Reliability of Railway Systems", PhD thesis, Erasmus University Rotterdam, 2005.
- [10] Schultze, K., "Modell für die asynchrone Simulation des Betriebes in Teilen des Eisenbahnnetzes", Veröffentl. Verkehrswissenschaftl. Institut RWTH Aachen, PhD thesis, H. 38, 1985.
- [11] Radtke, A., Hauptmann, D., "Automated Planning of Timetables in Large Railway Networks Using a Microscopic Basis and Railway Simulation Techniques", Computers in Railways IX, 615-625, 2004.
- [12] Nash, A., Huerlimann, D., "Railroad Simulation Using OpenTrack", Computers in Railways IX, 45-54, 2004.
- [13] Carey, M., Carville S., "Testing schedule performance and reliability for train stations", Journal of Operational Research Society, Vol. 51, 666-682, 2000.
- [14] Kaminsky, R., "Pufferzeiten in Netzen des Spurgeführten Verkehrs in Abhängigkeit von Zugfolge und Infrastruktur", Wissenschaftl. Arbeiten Institut für Verkehrswesen, Eisenbahnbau und -betrieb Universität Hannover, H. 56, PhD thesis, Hestra: Darmstadt, 2001.
- [15] Carey, M., Carville S., "Scheduling and platforming trains at busy complex stations", Transportation Research, Part A, Vol. 37 (3), 195-224, 2003.
- [16] ISO 9000, [http://www.iso.org/iso/iso\\_catalogue](http://www.iso.org/iso/iso_catalogue)

/management\_standards/iso\_9000\_iso\_14000.htm

- [17] EN 13816, [http://www.standardsdirect.org/standards/standards1/StandardsCatalogue24\\_view\\_11167.html](http://www.standardsdirect.org/standards/standards1/StandardsCatalogue24_view_11167.html).
- [18] Liebchen, C., Periodic Vs. Non-Periodic Timetables, IAROR Summer Course, July 14-18, Delft University of Technology, 2008.
- [19] Steckel, J., "Strategische Optionen für Die Zufällige Fahrzeit im Eisenbahnbetrieb" (Strategic Options for the Random Running Time in Railway Operations), PhD Thesis, Hochschule für Verkehrswesen „Friedrich List“, Dresden, 1991.
- [20] Goverde, R.M.P., Hansen, I.A., "TNV-Prepare: Analysis of Dutch Railway Operations Based on Train Detection Data", Computers in Railways VII, 779-788, 2002.
- [21] Pahl, J., "Timetable design Principles", in: Hansen, I.A. & Pahl, J., (eds.) Railway Timetable & Traffic, chapter 2, Hamburg: Eurailpress, 9-42, 2008.
- [22] UIC Union International des Chemins de Fer "Leaflet 405-1 Capacity", 2003.
- [23] Goverde, R.M.P., "Punctuality of Railway Operations and Timetable Stability Analysis", PhD thesis, TRAIL Thesis Series T2005/10, Delft, 2005.
- [24] Goverde, R.M.P., "Timetable Stability Analysis", in: Hansen, I.A. & Pahl, J. (eds.) Railway Timetable & Traffic, chapter 7, Hamburg: Eurailpress, 118-134, 2008.
- [25] Vakhtel, S., "Rechnerunterstützte analytische Ermittlung der Kapazität von Eisenbahnnetzen", Veröffentl. Verkehrswissenschaftl. Institut RWTH Aachen, PhD thesis, H. 59, 2002.
- [26] Yuan, J., Goverde, R.M.P., Hansen, I.A., "Evaluating Train Process time Distribution Models on the Basis of Empirical Train Detection Data", Computers in Railways X, 631-640, 2006.
- [27] Yuan, J., "Stochastic Modelling of Train Delays and Delay Propagation in Stations", PhD thesis, Delft University of Technology, TRAIL Thesis Series no.T2006/6, 2006.
- [28] Watson, R., "Using stochastic simulation to predict timetable performance – status and developments in the UK", 1st Int. Seminar on Railway Operations Modelling and Analysis, Delft, 2005.
- [29] Goverde, R.M.P., Daamen, W., Hansen, I.A., "Automatic Identification of Route Conflict Occurrences and their Consequences", Computers in Railways XI, 473-482, 2008.
- [30] Törnquist, J., Persson, J.A., "N-Tracked Railway Traffic Re-Scheduling during Disturbances, Transportation Research B, Vol. 41 (3), 342-362, 2007.
- [31] D'Ariano, A., M. Pranzo, I.A., Hansen, "Conflict resolution and train speed co-ordination for solving real-time timetable perturbations", IEEE Transactions on Intelligent Transportation Systems, Vol. 8 (2), 208-222, 2007.
- [32] D'Ariano, A., M., Pranzo, "An Advanced Real-time Train Dispatching System for Minimizing the Propagation of Delays in a Dispatching Area Under Severe Disturbances", Networks and Spatial Economics, Vol. 9 (1), 63-84, 2009.
- [33] Corman, F., A. D'Ariano, D. Pacciarelli, M., Pranzo, "Evaluation of Ggreen Wave Policy in Real-time Railway Traffic Management", Transportation Research Part C, in Press, 2009.
- [34] Albrecht, Th., J. Van Luipen, I.A. Hansen, A. Weeda, "Bessere Echtzeitinformationen für Triebfahrzeugführer und Fahrdienstleiter", EI-Der Eisenbahningenieur, Vol. 58 (6), 73-79, 2007.