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Evaluating disturbance robustness of railway schedules

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ABSTRACT

Railway traffic is operated according to a detailed schedule, specifying for each train its path through the network plus arrival and departure times at its scheduled stops. During daily operations, disturbances perturb the plan and dispatchers take action in order to keep operations feasible and to limit delay propagation. This paper presents a thorough assessment of the possible application of an optimization-based framework for the evaluation of different timetables and pro-active railway traffic management over a large network, considering stochastic disturbances. Two types of timetables are evaluated in detail: “regular” and “shuttle” timetables. The former is the regular plan of operations for normal traffic conditions, while the latter plan is designed to be robust against widespread disturbances, as adverse weather, track blockage and other operational failures. A test case is presented on a large Dutch railway network with heavy traffic, for which we compute by microsimulation detailed train movements at the level of block signals and at a precision of seconds. When comparing the timetables, a trade-off is found between the minimization of train delays, due to potential conflicts and to delayed rolling stock and crew duties, and the minimization of passenger travel time between given origins and destinations.

Keywords: *Railway Traffic Management, Train Delay Propagation, Timetable Assessment, Distributed Rescheduling, Microsimulation*

1 INTRODUCTION

ITS in railway practice

The continuous growth of frequency of passenger and freight railway traffic is increasing the pressure on European railway companies, facing the challenge of accommodating the expected increase of transport demand while improving punctuality. Intelligent Transportation Systems (ITS) tools for the management of railway operations, from timetabling to real-time rescheduling, have been developed lately. In this work, an advanced ITS tool is combined with different planning strategies in order to recover traffic disturbances that involved a large number of passengers.

In practice, railway operations follow detailed train plans, defining several months in advance the train order and timing at crossings, junctions and platform tracks. Due to the interaction of trains along open tracks, station interlocking areas and station platforms, delays propagate widely in heavily loaded networks, causing further delays to other trains with a relevant impact on service quality.

Robust timetables are able to deal with minor perturbations (i.e., few minutes of delays) occurring in real-time by using smart planning computed by ITS tools [14, 18, 19], and distributing time reserves along the train paths. However, no reasonable railway plan is robust enough in case of large delays or the blocking of some tracks. Despite the big effort spent, technical failures and other disturbances (such as train delays, reduced operating speeds, bad weather, temporary unavailability of some routes) result in traffic disturbances that require multiple adjustments to the traffic plan and result in longer travel times.

This paper studies the disturbance robustness of a timetable as the assessment of the quality of a train schedule, in terms of performance indicators related to trains and passengers, when dealing with severe traffic disturbances: multiple train delays, light disruptions (speed restrictions) and heavy disruptions (blocked tracks).

Evaluation of service quality

Planned operations can be evaluated based on implicit methods such as queueing theory [28], or by microsimulation, as in the tool OpenTrack [23]. Those systems compute how delays would propagate given the timetable order and some basic scheduling rule. However, the scheduling actions taken are myopic and do not give any guarantee regarding delay and travel time minimization.

In an operational perspective, the train operating companies adjust, in short-time, the personnel and rolling stock plans to comply with the actual traffic situation, while experienced dispatchers foresee simple route conflicts due to perturbed operations and take compensatory control actions based on local information.

Advanced ITS approaches have been recently proposed to design rolling stock, crew and passenger service plans and/or to update them during various traffic situations (see e.g. the recent research contributions in [1, 2, 4, 14, 15, 17, 18, 25]). A drawback is the imprecise macroscopic model used, neglecting capacity constraints at stations and along open tracks, even though the available railway infrastructure may result in heavy limitations when dealing with serious traffic disturbances.

Dispatching support systems

Current traffic flow management is still *reactive*: traffic operators are mainly directed towards maintaining the tactical day plan and recovering from disruptive events as quickly as possible back to the original timetable. Traffic control centers use basic rule-based decision support for the control of railway networks [15]. Many knock-on delays, however, could be prevented if traffic was *pro-actively* managed by intelligent automated tools [12, 21], i.e., dispatchers can spend their time on preventing traffic disturbances instead of only solving them when they have already happened. Based on an accurate monitoring of the actual train positions and speeds the potential conflicting routes can be predicted in advance and must be resolved.

Systems based on the above concepts have been proposed in order to compute quickly detailed train schedules (see e.g. the literature review regarding models, methods and test cases in [3, 10, 12, 16, 20, 24, 26, 27]). However, most of the existing approaches and tools for on-line rescheduling lack of a thorough computational assessment, limit the analysis to simple networks or simple perturbation patterns, are often simplified and do not capture entirely the consequences of delays and other disturbances, limited capacity, resolution of conflicts and deadlocks. During rescheduling of train operations, another main assumption is often that a feasible schedule exists for crew and rolling stock resources.

Paper contribution

The goal of this research is to evaluate the robustness of alternative plans towards potential disturbances by optimization-based decision support. The main research questions are the following: "How to quantify robustness of different timetables to light and heavy disturbances in large railway networks? Which are the advantages and disadvantages of using specific timetables and dispatching measures? Which is the impact in terms of train delays and passenger delays?". In fact, railway companies are seeking ITS to better use the existing railway infrastructure and to improve the management of train traffic flows, specially in presence of severe disturbances and densely used networks.

To answer these questions we use an advanced traffic management system and assess various timetables and dispatching measures in case of traffic disturbances. We adopt the dispatching support tool ROMA (Railway traffic Optimization by Means of Alternative graphs) [11, 12, 13] embedded in a schedule evaluation framework introduced by Corman et al. [6]. Specifically, the models and algorithms of [7, 8, 9] are adopted to manage traffic flows in a large network composed of multiple dispatching areas. Corman et al. [7] introduced a distributed approach based on spatial decomposition of a railway network in two dispatching areas. Corman et al. [9] extended the methodology to k areas and proposed an exact method to solve small disturbances. Corman et al. [8] worked on the disturbance management problem and developed heuristics to compute globally feasible solutions in case of multi-area networks and severe disturbances, including track blockage situations. Train schedules are found by developing more advanced local procedures and an improved global coordination procedure.

This paper presents a comprehensive study to evaluate timetables and dispatching measures and does not focus directly on the timetable development process and how to increase its disturbance robustness, since in that case significantly different problems are to be addressed. To the best of our knowledge, this is the first approach to study how to manage disturbances by means of the combination of dispatching measures and regular and "shuttle" timetables.

Figure 1 gives a schematic view of a shuttle timetable concept with regard to a regular timetable concept (the bottom plot is labeled shuttle timetable, and the top plot is labeled regular timetable), considering three stations (nodes) and three lines for shuttle services (bidirectional arrows). In the shuttle timetable, train services arrive at the designated station and leave from it to operate a new service on the opposite direction after a turnaround time.

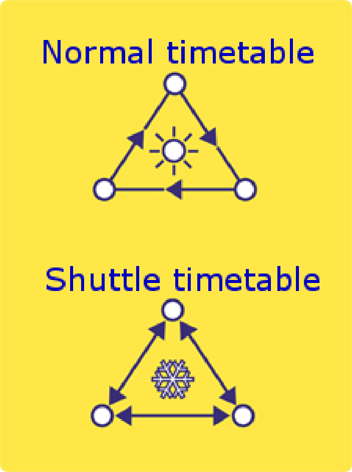

Figure 1: Regular (top) and shuttle (bottom) timetables (adapted from NS Reizigers).

In the computational experiments, stochastic disturbances are considered based on realistic delay data. We study the South-East part of the Dutch railway network, that is densely occupied and includes several station platforms. The effects of regular and shuttle timetables are analyzed in microscopic detail for large networks. Different solutions are thoroughly evaluated from the points of view of dispatchers and passengers. We show the travel time for specific OD (origin-destination) pairs in order to fully assess the impact of the dispatching decisions.

Summarizing, the specific contributions of this paper are:

- We extend an existing schedule evaluation framework in order to deal with the assessment of disturbance robustness and to compare train retiming and rescheduling measures for shuttle and regular timetables.
- We propose a detailed analysis of various sources of disturbances over a large network and multiple hours of traffic prediction, including disruption scenarios, i.e., speed restrictions, temporarily blocked tracks, transition between the track blockage and the return of regular infrastructure use.
- We evaluate a comprehensive set of performance indicators, including train-related indicators (such as total and consecutive delays) and passenger-related indicators (such as generalized travel times for a set of OD pairs).

In the following sections, we introduce the modeling of railway operations and the timetable structures, describe the approach to solve large train scheduling problem, present a practical test case based on the Dutch railway network, discuss the computational results and give directions of further research.

2 PROBLEM DESCRIPTION

Basic definitions

A block section is a track segment between two main signals and may host at most one train at a time. The passage of a train through a particular block section is called an *operation*. A train route is a sequence of operations to be performed in a railway network during a service. Each operation requires a given running time which depends on the actual speed profile followed by the train while traversing the block section. The minimum time separations among the running trains translate into a minimum setup time between the exit of a train from a block section and the entrance of the subsequent train into the same block section.

A set of trains cause a *deadlock* (i.e., circular waiting) when each train in the set claims a block section ahead which is not available, either due to a track blockage or to the occupation/ reservation for another train in the set. Instead, a *potential conflict* arises when two or more trains claim the same block section at the same time. A decision on the train ordering has to be taken and one of the trains involved has to change running, departure, passing times according to the constraints of the signaling system.

The *total delay* is the difference between the calculated train arrival time and the scheduled time at all station stops, and is divided into two parts. An *initial delay* is caused by external sources of disturbances (e.g. blocked tracks, rolling stock or infrastructure failures, entrance delays) and cannot be recovered by rescheduling train movements (i.e., changing their sequence). A *consecutive delay* is caused by the interaction between trains running in the network, i.e., trains that are held in front of a red signal or brake for a yellow signal.

Regular versus shuttle services

During disruptions (such as train malfunctions, speed limitations or infrastructure failures) the capacity is strongly reduced for a long period of time. The time reserves in the timetable are not sufficient to prevent delay propagation and a new plan of operations is required. Trains may be scheduled along a different route, with a different stopping pattern, or even canceled or short-turned between stations.

Managing disrupted traffic is one of the most challenging dispatching tasks on complex networks and high density passenger traffic. To reduce the propagation of delays in case of severe disturbances, shuttle timetables can be considered. These timetables are designed to improve reliability of the railway system during wide-spread disruptions (for instance, in the Netherlands they were considered in case of heavy snowfall or similar adverse weather).

Most of the traffic is short-turned at major stations and trains provide shuttle services going back and forth between two consecutive major stations and serving the stops in between according to their plan. In case of shuttle services, train circulation plans might require a significantly increased use of resources (platforms, rolling stock and staff) in order to keep the same service frequency. Alternatively, a reduced service frequency on a disrupted network would be available for a fixed number of train units.

The following traffic management strategies are combined for generating shuttle timetables: (i) keeping train paths short, so that the propagation of delays cannot exceed regional boundaries, (ii) keeping only limited passengers connections for the trip that is interrupted and (iii) keeping drivers and rolling stock together so as to avoid any inconvenience due to repositioning trips, or further knock-on effects between train lines.

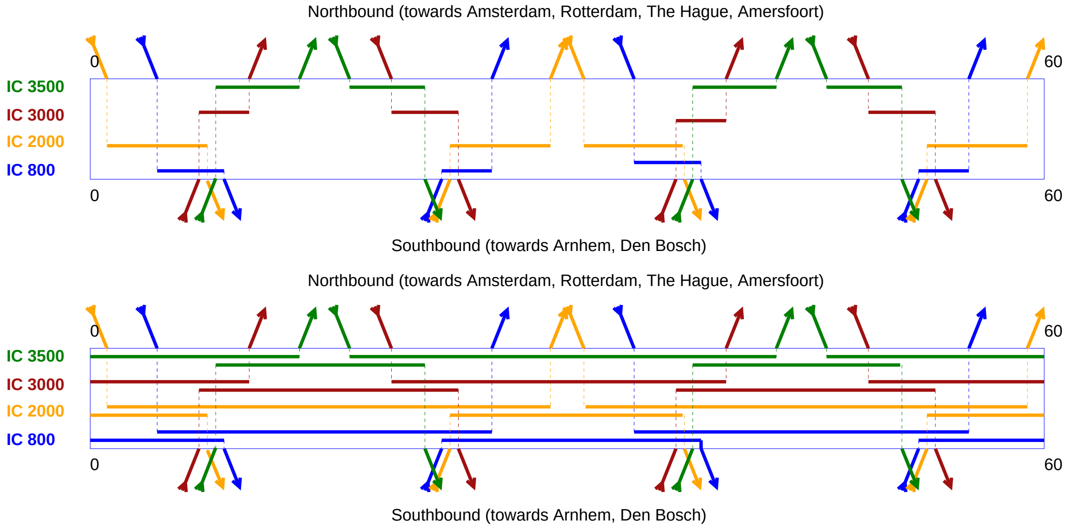

Figure 2: Regular (top) and shuttle (bottom) services at Utrecht Central Station.

Figure 2 shows a comparison of the train circulation in a regular timetable (top) and a shuttle timetable (bottom) for the major hub of Utrecht Central Station. Time axis goes from left to right and defines one hour of the periodic timetable. For each timetable, the station of Utrecht is reported on the central box of the diagram. The top plot of Figure 2 refers to the northbound direction towards Amsterdam, Rotterdam, The Hague and Amersfoort, while the bottom plot of Figure 2 refers to the southbound direction towards Den Bosch and Arnhem. We show four intercity lines since these are the most affected by the shuttle principle. The other services are Intercity with terminal station in Utrecht and local services limited to a single dispatching area. The circulation of trains is separated by different rows, each referring to a train line and a particular platform.

In the regular timetable, trains come from one direction and continue towards another side of the station after their dwell time (shown as the horizontal line), while trains in the shuttle timetable come from a direction and after longer dwell times they go back. In fact, train circulation for shuttle timetables requires that train units stay at the platform during the required turnaround time.

For the traffic situation of Figure 2 shuttle services are provided at the stations of Utrecht, Arnhem and Den Bosch, where short turning of trains can be performed. In fact, only stations with suitable platform capacity and additional availability of rolling stock, crew and other dedicated staff can be chosen as shuttle bases.

3 METHODOLOGY EMPLOYED

Figure 3 shows a schematic view of the framework introduced by Corman et al. [6] in order to assess timetables by scheduling optimally trains in large networks in case of disturbed traffic conditions, even in case of disruptions. We assume that a set of timetables is provided. The variability of train position and speed defines delay instances. In addition disrupted traffic conditions can also be included. The framework generates a set of detailed train schedules (feasible plans of operations) that are evaluated by a microscopic scheduler on a number of performance indicators.

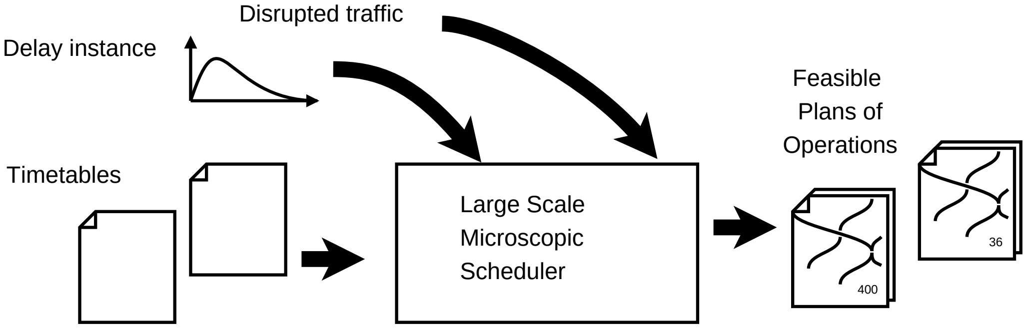

Figure 3: Scheme of the schedule evaluation framework.

Large scale microscopic scheduler

In order to study the network-wide effects of disturbances by the microscopic scheduler, the overall network is considered as divided into local areas, so that the scheduling decisions in each local area are taken in a fully parallel fashion. Each local scheduler considers the decision level of a local area dispatcher. Since the composed solution must be globally feasible, a global coordinator sets coordination actions in such a way that the union of all local solutions is globally feasible.

The decomposition is inspired by the actual structure of the dispatching process within the traffic control centers. Network coordinators are responsible for general supervision of their part of the network and communications with neighboring control centers. Dispatchers supervise all train traffic in their control area based on real-time monitoring of track occupation and clearance, as well as train-number records. They are responsible for route setting within the interlocking limits of the station, supported by automatic train control systems.

Figure 4 presents the distributed system architecture based on the bilevel approach of [7, 8, 9]. Each dispatcher is supported by a local scheduler, while the network coordinator is supported by a global coordinator system that supervises the local schedulers and fixes coordination constraints at the borders between areas. The final output of the bilevel (global coordinator and local schedulers) scheduling system consists in a set of feasible plans of operations that can be described by time distance graphs and detailed performance indicators.

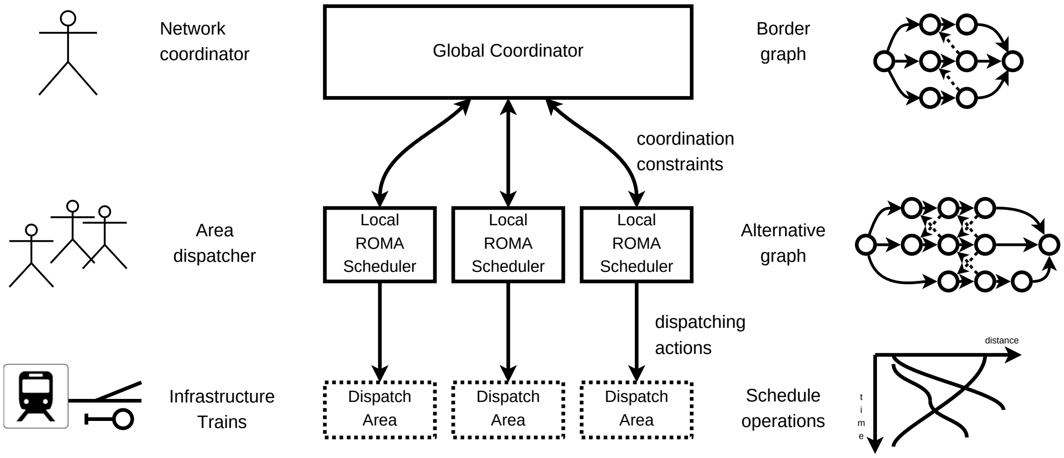

Figure 4: Scheme of the bilevel scheduling system for large networks.

Model of the local schedulers

The ROMA tool [11, 12, 13] is used to compute train schedules in each dispatching area. The problem is viewed microscopically as a job shop scheduling problem with additional constraints. The mathematical model, introduced by [10], is based on the alternative graph formulation [22], that is a generalization of the classical disjunctive graph formulation, and on the blocking time theory [15], that is used to compute minimal train headways at the level of block sections and traffic signals. This model is also rich enough to represent precisely the detailed train movements within station interlocking areas, as well as shunting movements.

The alternative graph is a triple $G_A = (N, F, A)$, where N is the set of nodes, F is the set of fixed arcs and A is the set of pairs of alternative arcs. Each arc in F and A is directed and weighted by the minimal required time gap between the operations associated to its start and end nodes. A *selection* S of arcs from A is obtained by choosing at most one arc from each alternative pair in the corresponding set. The selection S is *complete* if exactly one arc is chosen from each alternative pair. A problem *solution* is represented by an alternative graph solution $(N, F \cup S)$ in which S is a complete selection. The solution is *feasible* if the graph contains no positive length cycles. This latter condition would correspond to an operation preceding itself, i.e., a deadlock [5]. The problem of deciding whether a feasible schedule exists or not is NP-hard [22].

In case of fixed block signaling (e.g. the Dutch signaling system NS54), each block signal corresponds to a node in G_A and the arcs between nodes are used to model the blocking times. The alternative graph represents the routes of all trains in a given dispatching area along with their precedence constraints (minimum setup time) and release times. Since a train must traverse the block sections in its route sequentially, a train route is modeled in the alternative graph with a job that is a chain of operations (modeled by nodes from the set N) and associated precedence constraints (modeled by fixed arcs from the set F). In this work, a feasible route for each train is given and a fixed running time for each block section is known in advance, except for possible additional waiting times between operations to solve train conflicts.

A train schedule therefore corresponds to the set of the starting time of each operation. Since a block section cannot host two trains at the same time, a potential conflict occurs and a passing order between trains must be defined. This constraint translates to a suitable pair of alternative arcs for each pair of trains traversing the block section. A feasible schedule (i.e., conflict-free and deadlock-free) is next obtained by selecting one of the two alternative arcs from each pair in the set A, in such a way that the resulting selection S has no positive length cycle in G_A.

The shuttle services use the rolling stock and crew units to travel from an origin station to a destination station on a specific line and to operate the (specular) service in the opposite direction after a given turnaround time. In this paper, rolling stock and crew plans are modeled by connection and turnaround constraints (see [11, 13] for a description of these two types of constraints). Each train cannot depart from a station if the rolling stock and crew units, that are planned to operate that service, are not yet available.

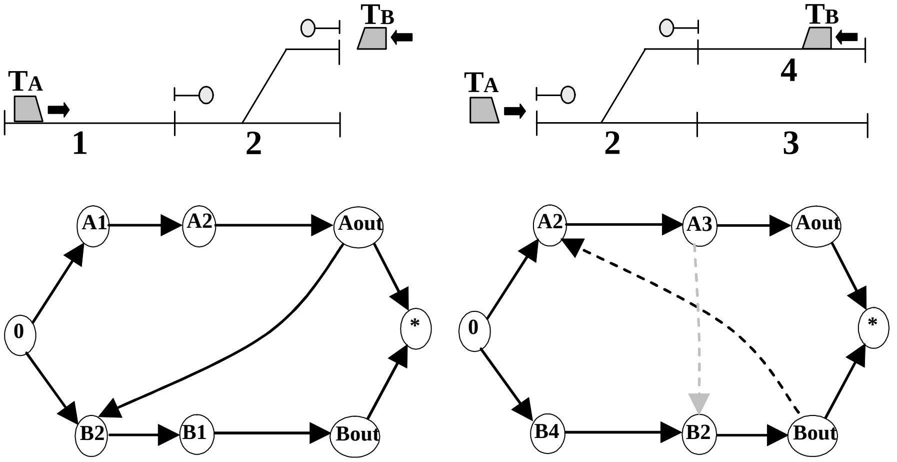

Figure 5: A traffic situation in two areas (top) and the alternative graphs (bottom).

Figure 5 (top) presents a traffic situation with two trains (named T_A and T_B) that run in a simple network with four block sections (named 1–4). The network is further divided into two areas, at the left-hand and right-hand of Figure 5 (top). Block section 2 is the border of both areas. The order of trains in the left area (that includes block sections 1 and 2) cannot be changed, since at the starting time of the prediction horizon T_A is located on block section 1 and T_B is still outside the area. The timing of the two trains needs to be coordinated in order to keep a minimum headway distance. Trains in the right-hand area (that includes block sections 2, 3 and 4) are to be scheduled on the block section 2, and there is a potential conflict between T_A and T_B.

Figure 5 (bottom) shows the alternative graphs related to the traffic situation on each local area. Node 0 and $*$ are dummy nodes modeling respectively the start and end times for all operations. In each graph, a train route is represented by the two nodes related to traversing the block sections, plus an additional node that models the exit time from the network. In the left-hand graph, the position of T_A implies the order between the two trains, i.e., T_A is the first train to traverse block sections 1 and 2. The right-hand graph, instead, has a myopic view of the situation, since at the starting time of the prediction horizon T_A is located outside the area and T_B is on block section 4. The scheduling decision on block section 2 is therefore to be decided by the local scheduler.

In the right-hand graph of Figure 5, the possible train orders are modeled by the alternative pair ((A3,B2),(Bout,A2)). Any selection of the two arcs would result into a locally feasible graph. However, the selection of arc (*Bout*,*A*2) would cause a deadlock in the network, since opposite scheduling decisions are taken in the local areas. A feasible schedule can only be obtained by selecting the arc (*A*3,*B*2).

Model of the global coordinator

Given a division of the network, the compact local area representation of [7, 8, 9] is adopted in order to limit the size of the set of data to be managed by the coordinator, avoiding the coordination task to become the bottleneck procedure.

Each local dispatcher sends to the coordinator the entrance/exit time of each train traversing its borders and, for each pair of trains entering/leaving the local area, the minimum temporal distance between the two events. This information is used to build the *border graph* $G_B = (V, W)$, in which V is the set of all border nodes and W is the set of all border arcs (that are directed and weighted). Border nodes are associated to the operations representing trains crossing the borders. Let b_i, $b_j \in V$ be two border nodes, the set of border arcs in the border graph includes all arcs $(b_i, b_j) \in W$ for which a directed path from b_i to b_j exists in the alternative graph associated to a solution of a local area. Each arc $(b_i, b_j) \in W$ has a weight equal to the length of a longest path from b_i to b_j. As proved in [7], the local solutions produced by the local schedulers are globally feasible if and only if there are no positive length cycles in the resulting border graph.

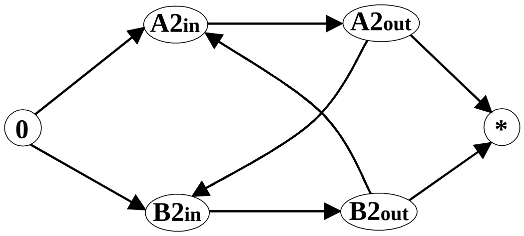

Figure 6: An infeasible border graph for the example of Figure 5.

Figure 6 shows a border graph for the example of Figure 5. This graph represents the entrance and exit of T_A and T_B on the border block section, identified by the suffix *in* and *out*. An infeasible traffic situation is shown in the border graph, since there is a positive length cycle on the arcs: (*A*2*in*, *A*2*out*), (*A*2*out*, *B*2*in*), (*B*2*in*, *B*2*out*), (*B*2*out*, *A*2*in*). The former two arcs are the longest paths of the alternative graph of the left-hand area, while the latter two arcs are given by the right-hand area solver. The infeasibility on the border graph represents a conflicting train ordering decision on the two areas.

4 COMPUTATIONAL EXPERIMENTS

This section describes the framework application to evaluate different timetables and dispatching measures. The framework is implemented in C++ language, uses the AGLibrary software, and runs on a 4-processor PC running at 2.8 Ghz.

Railway network and timetables

We study a large, complex and densely utilized railway network in the South-East of the Netherlands that spans over ten dispatching areas of the Dutch railway network, including the main stations of Den Bosch, Nijmegen, Arnhem and Utrecht. Figure 7 illustrates the network layout, with a roughly circular shape and a maximum distance between borders of about 100 km. In total, there are more than 1200 block sections. In the bilevel rescheduling approach, the overall railway network is divided into 3 local dispatching areas (as shown by the dotted lines in Figure 7).

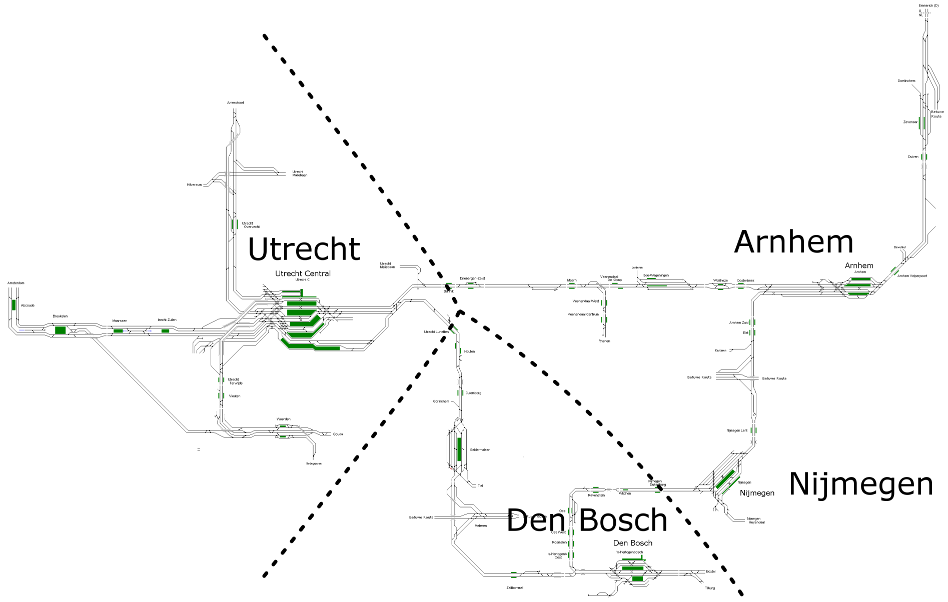

Figure 7: The railway network and its decomposition in local areas.

In the experiments two types of timetable are tested: the regular one and a shuttle timetable. The regular timetable has a cycle time of one hour and schedules around 150 trains. We assumed to keep the same hourly frequencies and the same arrival/departure times in the shuttle timetable, thus offering the same transport service to passengers in both cases. In Figure 8, the frequency of the train services is reported along a schematic network layout. Each solid line indicates two trains running per hour per direction on a specific line. Light green lines are local services and dark blue lines are intercity services. The dotted line represents an international service scheduled once per hour.

Figure 8 shows the line frequency for both timetables. However, the shuttle timetable requires inherently more train and crew units in order to keep the same frequency as in the regular timetable. For each line, one train/crew unit is always standing at a side of each shuttle base station between two shuttle zones, waiting to operate the next service. Specifically, there is an average turnaround time considered for the crew and rolling stock plans of around 15 minutes. For the whole network considered, four additional train/crew units are required at Utrecht Central Station, 3 units at Den Bosch, and 3 units at Arnhem. For shuttle services, the schedule includes circulation of train/crew units within the stations at the borders of the shuttle zones, where trains are turned back according

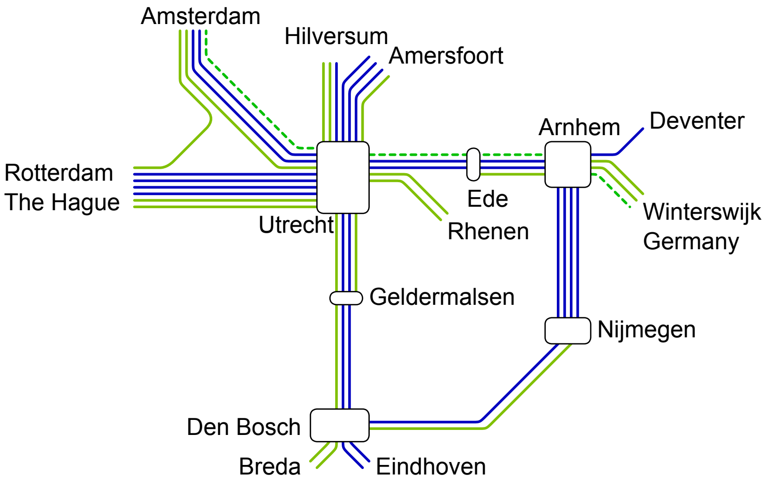

Figure 8: Lines frequency for both regular and shuttle timetables.

to a detailed shunting plan.

Alternative graphs and border graphs

Table 1 describes the characteristics of the instances for the overall network composed of 3 local areas. Each row reports information on 90-minute traffic prediction horizons. Column 1 reports the timetable type, Column 2 the number of trains in the overall network, Column 3 the average number of trains in each local area, Columns 4-6 the average number of nodes, fixed arcs and alternative arcs of the alternative graphs of each local area, Columns 7-8 the number of nodes and arcs of the border graph coordinating the traffic of the overall network.

Table 1: Characteristics of the mathematical models.

Timetable	Number of Trains		G_A			G_B	
Type	All Network	Avg per Area	$\|N\|$	$\|F\|$	$\|A\|$	$\|V\|$	$\|W\|$
Regular	206	89	3141	3577	11346	128	852
Shuttle	221	94	3051	3493	11773	128	852

Disturbance scenarios

A time horizon of traffic prediction of 90 minutes is considered, after a warm-up period of 60 minutes. We assess the timetables over a stochastic set of 50 delay cases, consisting in random variations of the entrance time of all trains in the network. For the proposed instances, the maximum and average entrance delays are respectively 740 and 21 seconds. Around 13% of the running trains are delayed by more than 3 minutes. Those delays are generated according to Weibull distributions fitted to the historical data of real-life operations provided by ProRail, the Dutch Infrastructure manager.

Figure 9 presents the probability density functions of the Weibull distributions used to generate the set of entrance delays. The x-axis shows the variation (in seconds) to the

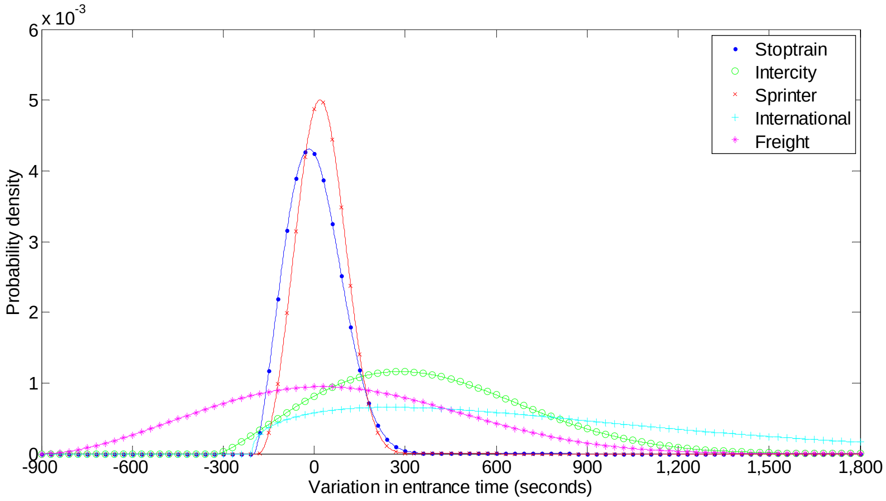

Figure 9: Variations of the entrance times for all trains in the network.

scheduled entrance times of trains in the network, while the y-axis the probability density function for each specific train category. In total, we analyze different characteristic distributions for 5 train categories divided per type of service: 'Stoptrain' and 'Sprinter' are local services, 'International' and 'Intercity' are long-distance services, and freight trains.

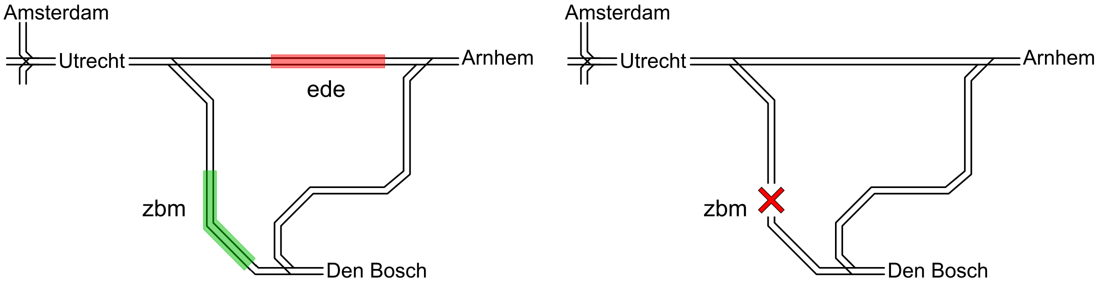

Figure 10: Location and extent of the speed reduction (left) and the track blockage (right).

In addition to entrance delays, we also study disrupted traffic conditions. Figure 10 presents light and heavily disruptions. A light disruption is a train speed reductions enforced, due e.g. to adverse weather conditions, on the corridors near Zaltbommel (zbm) or near Ede (ede), for a length of about 10 km of railway line. The new reduced speed limit is 120 km/h for all trains. A heavy disruption refers to a blockage near Zaltbommel, such that both tracks are completely blocked for traffic between the stations of Geldermalsen and Den Bosch.

Dispatching measures

For each scenario resulting from the combination of entrance delays and disrupted traffic conditions, we consider two types of dispatching measures: retiming and rescheduling. Both measures are used to compute a feasible train schedule for the whole network in presence of disturbances. An off-line timetable is taken as reference and is adapted to deal with perturbed or even disrupted traffic.

The retiming measure keeps the train orders as scheduled in the timetable and updates only passing times of trains at meeting points according to the delay experienced. The trains exploit their running time supplements and buffer times at planned stops, when possible. On the one hand, the implementation of the retiming strategy is straightforward and easy since it does not require to take additional decisions other than those already available in the timetable. On the other hand, it is quite inefficient to keep the off-line order in case of large delays. In our implementation, the computation time of the retiming measure is up to 15 seconds.

Regarding the train rescheduling measure, we use the distributed algorithm of [8] to compute a feasible schedule for each disturbed traffic situations, by potential conflicts and deadlocks for a given timetable. This algorithm is based on the bilevel rescheduling methodology described in Section 3. For the set of experiments in this section, the computation time of the rescheduling measure is up to 3 minutes.

Assessment of train delays and travel times

We next evaluate the two timetables (regular and shuttle) and the two dispatching measures (retiming and rescheduling), considering the different disturbance scenarios previously described. In this section we refer to the speed reduction only, while the complete track blockage is evaluated in full in a later section. The schedule robustness is studied in terms of the impact of the stochasticity in input towards key performance indicators in output. Specifically, we investigate train delays and travel times since these are typical objectives of infrastructure managers and dispatchers that are interested in limiting delay propagation as much as possible.

Figure 11 presents three plots regarding the average total delay (top, in seconds) the average consecutive delay (middle, in seconds) and the Travel Time Spent (TTS, in hours) over all trains running in the network. Each plot shows the results for the ideal traffic situation (labeled Normal) and the two speed reduction situations (labeled respectively 120 Ede and 120 Zbm), averaging over the 50 delay cases.

For this set of experiments, Figure 11 shows that the rescheduling measure allows around 50% (25%) consecutive (total) delay reduction compared to the retiming measure. The TTS is also considerably reduced by the rescheduling measure.

The timetable structure has some influence as well. Overall, the shuttle timetable results in worse delay figures. When using the retiming measure, the average consecutive delay of this timetable is 2% larger than the regular one. On the other hand, when rescheduling is applied an improvement of up to 3% is reached. This reduction is more evident for the shuttle timetable compared to the regular one when dealing with the TTS, specially in large station areas.

Light disruptions result in slightly larger delays, while preserving similar relations between combinations of timetable structure and dispatching actions.

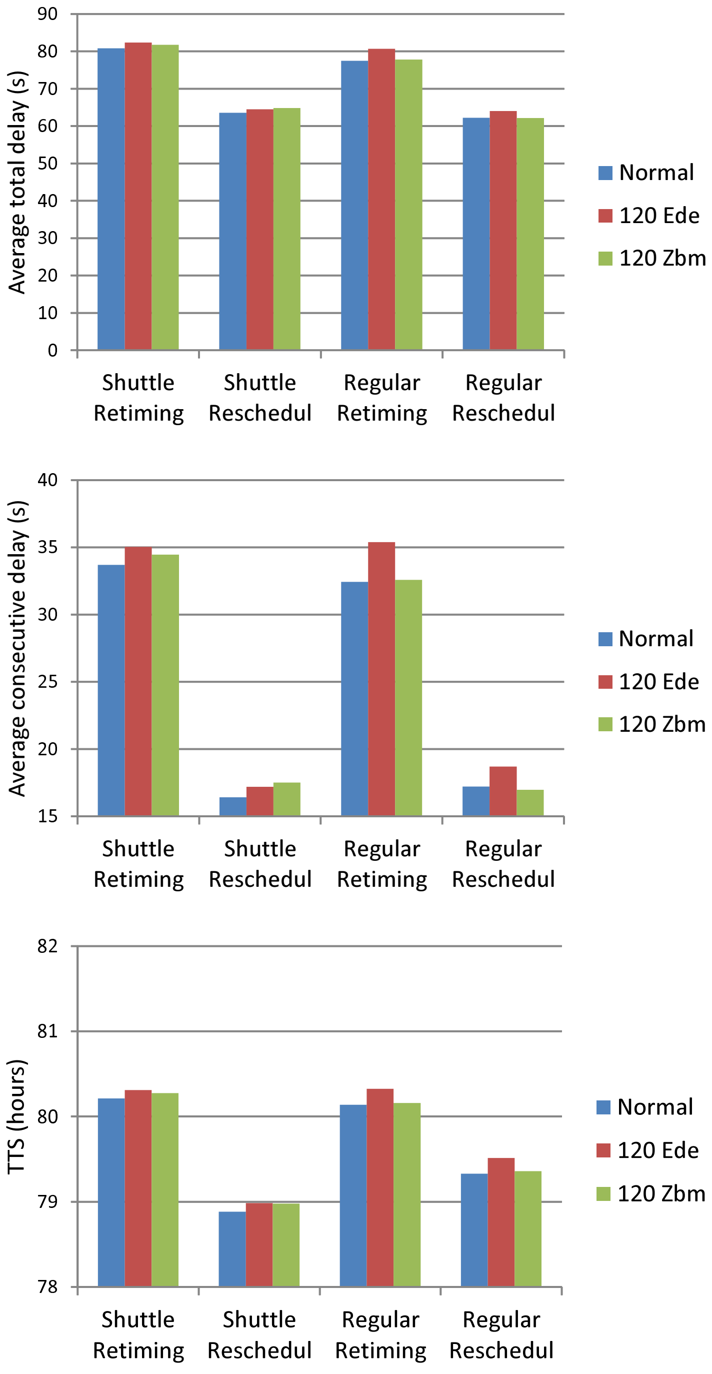

Figure 11: Train delay and travel time spent for each pair of timetable and dispatching measure.

Assessment of passenger travel times

A "generalized travel time" is investigated for passengers traveling on the network, along few relevant OD pairs. The generalized travel time is a weighted sum of the following times: (i) the waiting time at a station before the first leg of the trip (i.e., at this time the traveler can still opt for using another service or another mode), (ii) the in-vehicle travel time, (iii) the waiting time for transfers between successive trains. The three times are weighted, respectively, 1.5, 1 and 4. A long waiting time at a station is therefore penalized more than a long travel time on train. The shuttle timetable does not include passenger connections, generally resulting in additional waiting times at stations.

Figure 12 refers to average results (in seconds) over the 50 delay cases for the undisrupted traffic situation. We do not report explicitly the detailed evaluation of the two light disrupted traffic situations, as they have a limited effect on the generalized travel time. In fact, the whole travel time is about 20 minutes for short OD pairs and 50 minutes for long OD pairs, while the consecutive delays account on average for about 20 seconds. Regarding the heavy disruption, we postpone the discussion to the next subsection.

In our assessment of the generalized travel time, we consider the five OD pairs with the majority of passengers: Utrecht (Ut) to Den Bosch (Ht), Utrecht to Arnhem (Ah), Amsterdam (Ams) to Utrecht, Amsterdam to Den Bosch, Amsterdam to Arnhem. Specifically, each row of Figure 12 presents two plots for a single OD pair. The plots on the first column refer to the generalized travel time for a fixed passenger trip departure time: the time published in the timetable regarding the departure of the intercity service connecting the origin and destination stations of the specific trip. In this case, we assume that passengers are aware of the timetable. Based on that knowledge, they minimize their waiting time before the first leg of the trip, while they are still directly affected from dispunctuality of train services.

The plots on the second column of Figure 12 refer to the average over all possible choices of departure times within the studied time horizon. In other words, the traveler enters into an origin station and takes the first train service available to reach the destination station. A uniform distribution of departure times of travelers at the first station is assumed, thus the generalized travel time does not depend on the precise departure times of trains but rather on the service frequency and delays experienced during the specific trip.

The first three rows of the plots of Figure 12 give results on the OD pairs for which passengers are not required to change train in both timetables. For the first two OD pairs, the shuttle timetable presents smaller travel times compared to the regular timetable. The gap is more evident in the main station area of Utrecht and when considering the average over all departure times over the time horizon (see the two top-most plots in the right column of Figure 12), since in the shuttle timetable trains are more evenly distributed, there are less potential conflicts in the interlocking area, and the waiting time of passengers is significantly reduced. Differently, for the third OD pair (connecting Amsterdam to Utrecht), there is a very small difference between the two timetables. This is due to the high frequency of services and the large amount of direct trips (without transfer connections).

The last two rows of the plots of Figure 12 show two OD pairs for which passengers need to change train in the shuttle timetable, and have the choice of direct or indirect trips in the regular timetable. In this case, the shuttle timetable results less attractive than the

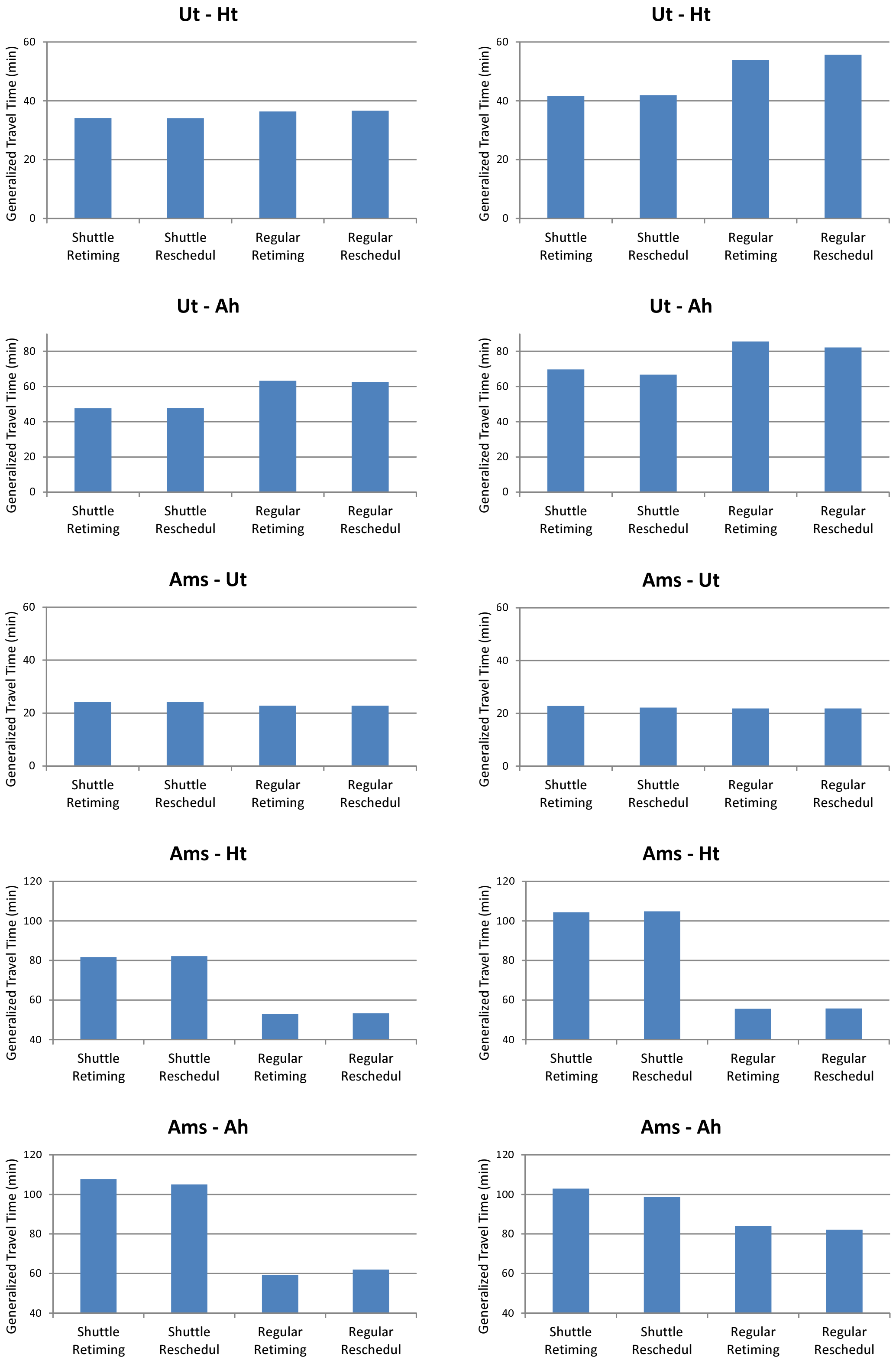

Figure 12: Generalized travel times for the main OD pairs, for the published departure times (left) and for the departure times spread over all time horizon considered (right).

regular timetable. In fact, changes and transfers result in discomfort for passengers and are penalized by a larger generalized travel time. The different gap between the fourth and fifth OD pairs depends on the particular setup of the railway lines. For the OD pair Amsterdam-Arnhem, the gap between the regular and shuttle timetables is limited. The motivation is that in the regular timetable there are two services per hour offering a direct trip Amsterdam-Arnhem, plus other two services per hour requiring a transfer in Utrecht. Differently, the OD pair Amsterdam-Den Bosch is served by direct intercity services in the regular timetable, resulting in a stronger advantage compared to shuttle services.

Assessment of a temporarily blocked track

This subsection presents the computational results obtained for the heavy disruption of Figure 10. We recall that we consider a track blockage near Zaltbommel that is a double track. Consequently, no train can be operated between Geldermalsen and Den Bosch, in both directions. For the analysis of this traffic situation, we focus our attention on the generalized travel time for specific OD pairs, that are the same of Figure 12. Train delays and travel times are not shown since we found less significant differences between the timetables for these two performance indicators.

Figure 13 presents three time periods of traffic prediction. Each period has a duration of 90 minutes. For each OD pair, a plot for each time period is depicted:

- The left-side plot shows the stage of complete track blockage, i.e., all services through the blocked area are canceled for all 90 minutes.
- The middle plot shows the transition stage between the track blockage situation and its resolution at time T, i.e., the track is unavailable until time T when traffic returns to normality. We assume perfect information regarding the track blockage that last from time 0 min ($T - 60$) to time 60 min (T).
- The right-side plot shows the normal traffic situation after the disruption.

This set of computational experiments is focused on studying the effects of the track blockage, so no other traffic disturbance is added, such as train delays or light disruptions. We study the transition from the track blockage situation back to the regular timetable, since there is a reasonably sufficient time for computing optimal train rescheduling solutions and much less uncertainty is involved compared to the transition from the regular timetable to the track blockage situation. In the latter stage, different dispatching measures have also to be considered such as rerouting trains and/or reversing trains running in the direction of the blocked track.

The plots of Figure 13 present the generalized travel time (in minutes) in the y-axis and the train departure times related to a specified time period in the x-axis. Shuttle timetables are reported as solid red lines, while regular timetables as dotted blue lines. Regarding the dispatching measures, we only show the rescheduling measure, since retiming did not produce feasible schedules.

From the results in Figure 13, each plot has a distinctive saw-tooth pattern, showing valleys and peaks for a specific OD pair and time period; valleys correspond to the time at which a train is leaving the origin station, and the generalized travel time is the value at the bottom of the valley. Just after each valley there is a peak, i.e., passengers just missed the latest train leaving their origin station and have to wait for the next one. For some departure times, the generalized travel time is not reported, since the arrival time at the destination station exceeds the time period.

We next discuss the results obtained for each OD pair in Figure 13:

- **Ut − Ht** is the shortest OD pair affected by the heavy disruption. During the track blockage period, the only option for both timetables is a long detour via Arnhem and Nijmegen. Due to the long duration of this detour, departures after 40 min are not shown in the left plot, since passengers cannot reach the destination station within the considered time period. During the transition period from track blockage back to normal traffic (middle plot), the travel time of passengers decreases with the increase of the departure time. However, there is a peak around $T + 15$ since Utrecht station becomes more dense of traffic just after the resolution of the disruption. Between $T - 10$ and $T + 10$, the shuttle timetable shows smaller travel times than the regular one, since the transition requires less additional rolling stock in the former timetable. In normal traffic condition (right plot), the timetables have only minor differences.

- **Ut − Ah** is affected in minor part by the heavy disruption, since the services related to this OD pair are decoupled from those that run through the disrupted area. When comparing the track blockage period (left plot) with the normal traffic period (right plot), no influence of the blockage on the travel time can be detected. During the transition period (middle plot), there are some minor differences with the other two periods, since the track blockage causes delays for the trains departing from Utrecht station. For all time periods, the shuttle timetable performs better than the regular timetable, as the trains are spaced more evenly in the former.

- **Ams − Ut** shows the largest advantage of the shuttle timetable compared to the regular timetable. For this OD pair, the shuttle timetable is not affected by the heavy disruption, since all passengers can be served by shuttle services that have not interaction with the disrupted trains. Differently, the regular timetable is strongly affected by the track blockage, as the trains that should go through the disrupted area serve this OD pair as well. During and after the transition period, traffic is no more affected by the disruption, and the difference between the two timetables is much less relevant.

- **Ams − Ht** is strongly affected by the heavy disruption. During the track blockage period, the only way to run the services related to this OD pair is a long detour via the stations of Utrecht, Arnhem and Den Bosch. As a result, a large generalized travel time is required for the passengers. This detour is only possible for passengers departing from Amsterdam within the first 10 minutes of the considered time period. During and after the transition period, the regular timetable performs better than the shuttle one, since the former timetable offers direct services connecting origin and destination stations, while the latter timetable requires passengers to change train during their trip.

- **Ams − Ah** is affected in minor part by the heavy disruption. When dealing with the transition period, both timetables often offer smaller travel times compared to the normal traffic conditions. This positive effect is due to the cancelation of trains

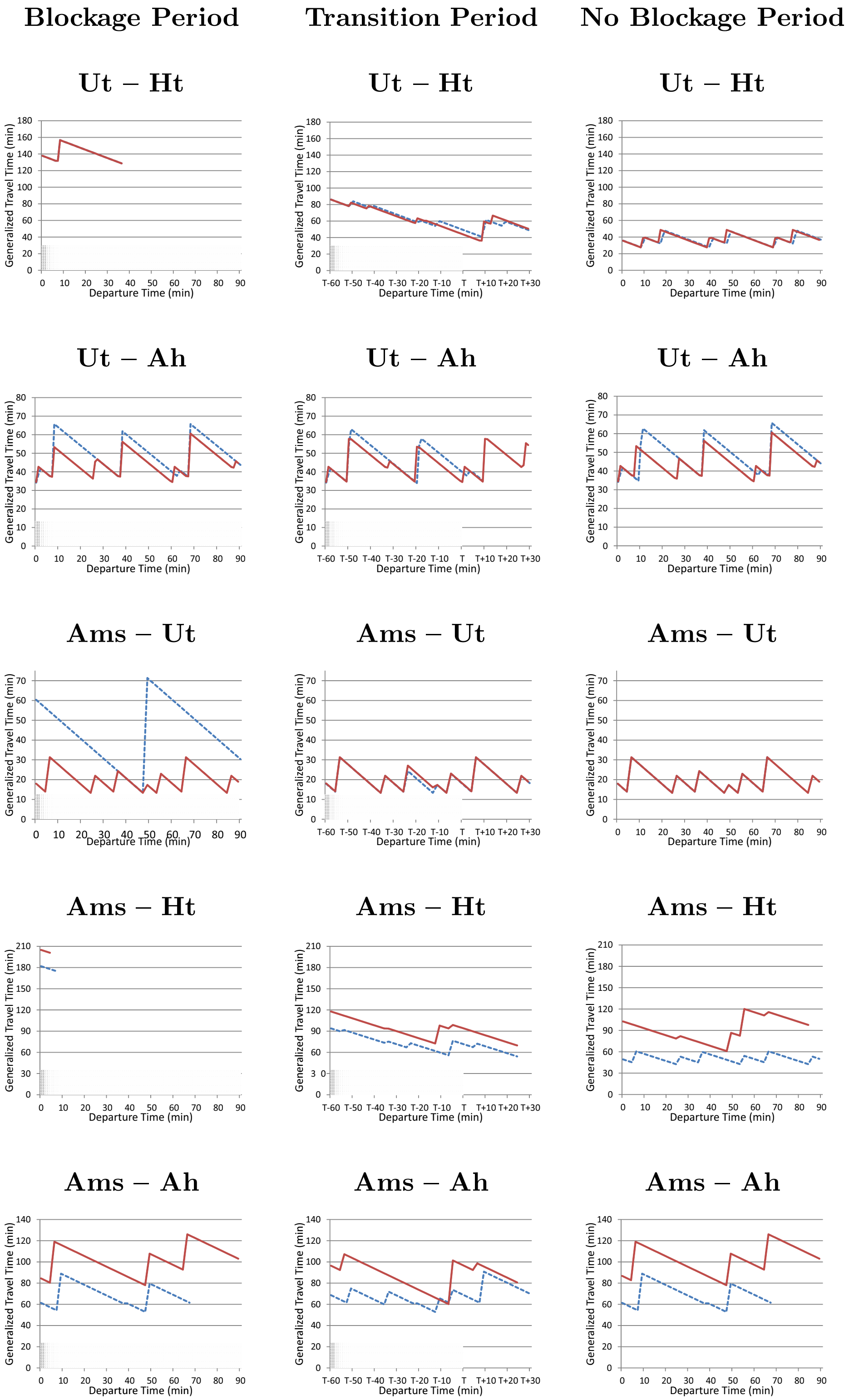

Figure 13: Generalized travel times for the main OD pairs, as function of the departure time and in case of a complete track blockage (left); a partial track blockage and its resolution at time T (middle); no track blockage (right). Each shuttle timetable is reported by a solid red line while each regular timetable by dotted blue line.

serving the disrupted track. Regarding the comparison between the two timetables, the shuttle timetable requires larger generalized travel times since passengers need to change train in Utrecht.

5 CONCLUSIONS AND NEXT RESEARCH

This paper applies an optimization-based framework for the evaluation of railway timetables and dispatching measures over a large network and in case of multiple sources of disturbance, characterized by a shortage of infrastructure capacity. The computational experiments present a detailed disturbance robustness evaluation of the train schedules generated for specific timetables and dispatching measures. Regular and shuttle timetables are investigated; the latter is designed to favorite specific OD pairs. For each timetable, rescheduling and retiming measures are studied. Performance indicators are related to trains and passengers.

We have the following considerations regarding the experiments. In case of light disruptions, the average consecutive delay is by far better minimized by using rescheduling measure when compared to retiming only. Regarding the comparison between different timetables, the shuttle timetable presents slightly better results with respect to the regular timetable. A considerable advantage of shuttle timetables is found when considering the generalized travel time for short trips, i.e., trips that are completely contained within a single shuttle area. On the other hand, shuttle timetables reduce their attractiveness when considering the generalized travel time for long trips, involving at least a passenger connection between different shuttle areas. In case of track blockage, rescheduling is the only measure applicable in order to compute feasible schedules. Also for this set of experiments, the advantage of the shuttle timetable is limited to specific OD pairs.

Our general conclusion from this experimental study is that the shuttle services may be profitable when high priority needs to be assigned to some services, due e.g. to a large number of passengers traveling on a specific OD pair. However, the shuttle services require a significantly higher use of resources, and an increased management cost for the railway companies. Additional dispatcher workload should also be considered since alternative timetables should be evaluated during rescheduling.

Further research could be dedicated to study reliable expectations on the number of passengers per OD pair and their preferred routes, to make detailed assessments regarding passengers' discomfort. Also, the evaluation of combined effects of input variability, alternative timetables and dispatching measures could represent a key aspect for train schedule assessment during early planning stages. Additionally, hybrid macroscopic-microscopic large-scale models could be developed for the computation of train schedules with inclusion of rolling stock and crew circulation in order to quantify robustness against network-wide delay propagation.

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