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Macroscopic multiple-station short-turning model in case of complete railway blockages

Nadjla Ghaemi*, Oded Cats, Rob M.P. Goverde

Department of Transport and Planning, Delft University of Technology, The Netherlands

A R T I C L E I N F O

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A B S T R A C T

In case of railway disruptions, traffic controllers are responsible for dealing with disrupted traffic and reduce the negative impact for the rest of the network. In case of a complete blockage when no train can use an entire track, a common practice is to short-turn trains. Trains approaching the blockage cannot proceed according to their original plans and have to short-turn at a station close to the disruption on both sides. This paper presents a Mixed Integer Linear Program that computes the optimal station and times for short-turning the affected train services during the three phases of a disruption. The proposed solution approach takes into account the interaction of the traffic between both sides of the blockage before and after the disruption. The model is applied to a busy corridor of the Dutch railway network. The computation time meets the real-time solution requirement. The case study gives insight into the importance of the disruption period in computing the optimal solution. It is concluded that different optimal short-turning solutions may exist depending on the start time of the disruption and the disruption length. For periodic timetables, the optimal short-turning choices repeat due to the periodicity of the timetable. In addition, it is observed that a minor extension of the disruption length may result in less delay propagation at the cost of more cancellations.

1. Introduction

In railway operation unplanned events such as infrastructure failures, rolling stock breakdown, and incidents are recurrent and unavoidable. As a result, a part of a railway track might be unavailable for several hours. In such cases, the traffic controllers have to deal with the disrupted traffic. Short-turning is a common practice to isolate the disrupted area. This measure suggests that those train services that are heading towards the disrupted area, short-turn in an earlier station and provide service in the opposite direction. In this way, some services can still be offered in the opposite direction and the trains do not queue up in the stations close to the disrupted area. Consequently, the disrupted area can be isolated from the rest of the network.

To improve the performance during the disruption, traffic controllers commonly use pre-defined solutions called contingency plans. Each contingency plan is manually designed for a specific disrupted area given a specific timetable. These plans resemble if-then scenarios: if a certain part of the infrastructure is out of service, then specific disruption measures should be pursued. The main input for designing contingency plans are the original timetable (basic hourly pattern) and the infrastructure layout around the disrupted location. The contingency plan then provides the disruption timetable structure that includes the cancelled services, operating services, and short-turned services. For each short-turned service, the arrival, departure, platform track and the train line numbers are indicated. The advantage of these contingency plans is that they provide some guidelines and consensus when there is a

* Corresponding author.
E-mail address: N.Ghaemi@tudelft.nl (N. Ghaemi).

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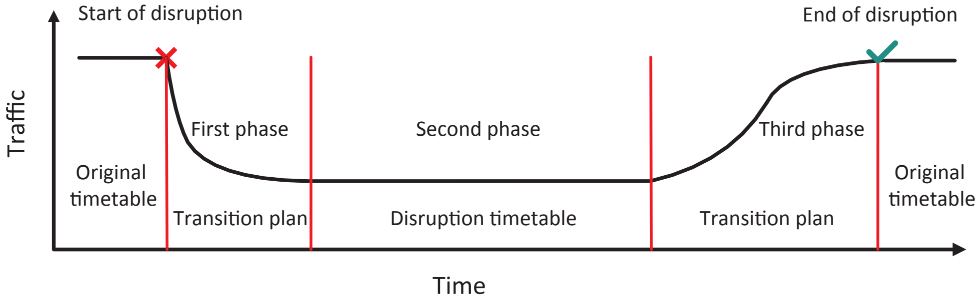

Fig. 1. The service level during disruptions (Ghaemi et al., 2017b).

need for a fast action to deal with the disruption Ghaemi et al. (2017b).

During disruptions the level of service decreases and remains so until the cause of disruption is solved and the original operation can be resumed. From this perspective the traffic level during a disruption resembles a bathtub as shown in Fig. 1. Corresponding to the bathtub, the disruption period is divided into three phases. The first and third phases are called transition phases as they represent the transition of operation from the original timetable to the disruption timetable in the second phase and vice versa. The first phase starts as soon as the blockage starts. Usually there are some irregularities (e.g. different short-turnings) before a stable and reduced timetable (disruption timetable) can be observed.

There are several processes during the first phase including receiving the disruption notification, announcing the disruption in the online system, identifying the exact disrupted location, selecting the relevant contingency plan and finally executing the plan. A study by Zon and Wink (2014) on 452 disruption cases of the Dutch railway network reports that the first phase can take on average around 40 min. In this study it is also shown that the longest process relates to selecting the relevant contingency plan and adjusting it which can take on average around 16 min. The third phase starts when it is known that the blockage is going to be resolved shortly and the train services can resume operating in the previously disrupted area. However it might take some time to recover from the disruption timetable to the original timetable as is shown in Fig. 1. For detailed processes during each phase see Ghaemi et al. (2017b).

Besides being static and inflexible, the main drawback of the contingency plans is that they do not provide any support for handling the transition phases. Having fast and smooth transition plans is essential for quickly resuming the disruption timetable in the second phase and recovering the original timetable in the third phase. The existing contingency plans are not able to provide any support for the execution of the transition phases, since they do not take into account the disruption period. After all, different causes of disruption can lead to different disruption lengths (Zilko et al., 2016). This leaves the traffic controllers without any support for making decisions in the transition phases. Besides the fact that the existing contingency plans do not suggest the optimal solution, with each update in the infrastructure or operation, the contingency plans need to be manually updated. Moreover, certain disruption may not have a corresponding contingency plan. A slight difference between the timetable in operation and the one used for designing the contingency plan may make the latter invalid.

The rescheduling domain in case of disruptions specially at the microscopic level is relatively unexplored, as Cacchiani et al. (2014) and Ghaemi et al. (2017b) conclude. Since disruptions of complete blockages can have a huge impact on the network it is necessary to consider bigger areas as opposed to the disturbances that perturb a timetable locally. The microscopic approaches, such as Pellegrini et al. (2014) or Caimi et al. (2012), can only include relatively small areas due to the magnitude of the modelled details. Despite techniques such as the one developed by Samá et al. (2017) to reduce the number of route choices, considering several stations at the microscopic level can lead to long computation times. Thus the focus of this literature is on the macroscopic rescheduling models that can handle disruptions. Zhan et al. (2016) apply a rolling horizon approach to take into account the uncertainty of disruption length for rescheduling in case of the partial blockage. Xu et al. (2017) developed a rescheduling model for disruptions caused by temporary speed restrictions. Since there is no blockages short-turning is not considered as a rescheduling measure. Coor (1997) investigates the impact of the short-turning strategy on the passenger waiting time on a high-frequency single transit line and concludes that in case of severe delays it is more beneficial than in case of small delays. In another study by Shen and Wilson (2001) different strategies such as short-turning, holding and stop skipping are examined. It is concluded that the combination of short-turning and holding strategies can reduce the mean passenger waiting time considerably. Ghaemi et al. (2016) model short-turning exclusively as a main measure to handle disruptions during the second phase. Only one side of the disruption is considered and the impact of the transitions are discarded. Its focus is on the trade-off between cancellation and delays by selecting different cancellation and delay penalties. Ghaemi et al. (2017a) extend the microscopic rescheduling model developed by Pellegrini et al. (2014) with the short-turning model presented in Ghaemi et al. (2016). Louwerse and Huisman (2014) develop a MILP model to compute the disruption timetable by maximizing the service level. Similarly Binder et al. (2017) develop an ILP model to compute a disruption timetable with three objectives of passenger satisfaction, operational costs and deviation from the original timetable. Veelenturf et al. (2017) developed a heuristic to adapt the timetable during disruption. To find the best adaptation, a list of alternative timetables are evaluated in terms of rolling stock and passenger flow and the one with the least consequences is selected. These references focus on the second phase of the disruption and neglect the transition phases. There are a few models that address the recovery from a disruption such as Jespersen-groth et al. (2009), Meng and Zhou (2011), Narayanaswami and Rangaraj (2013), Zhan et al. (2015). However, they do not provide any support for the second phase of the disruption. There are a few references such as

Nakamura et al. (2011) and Veelenturf et al. (2016) that provide a disruption timetable and implicitly take into account the recovery phase. The model developed by Nakamura et al. (2011) does not optimize the timetable but instead the solution is provided by performing specific steps. These steps identifying the cancelled and short-turned services, assigning rolling stock to each scheduled departure and finally resolving the mismatch for scheduled departures that need rolling stock to operate. Veelenturf et al. (2016) extends the model by Louwerse and Huisman (2014) which maximizes the service level taking into account three resources; open track, station track and rolling stock. However this model only allows short-turning in the final station before the disruption and the possibility of short-turning in the preceding station due to the limited capacity is not included. In their approach services from the affected lines are divided into three parts from which the second part are those that are scheduled to operate in the disrupted area. In case these services are cancelled, then the first part or third part might also be cancelled. Moreover it is assumed that the third phase takes a specific amount of time. The research on the first phase is indeed limited. Chu and Oetting (2013) provide insight into the processes during the first phase and recommend to take into account the extra time while designing the contingency plans. Hirai et al. (2006) also focus on the first phase by proposing an algorithm to compute the stopping stations for the disturbed train lines.

In case of disruptions the rolling stock circulation is rescheduled based on the rescheduled timetable, as Jespersen-groth et al. (2009) highlight. Thus many rolling stock rescheduling models such as those proposed by Nielsen et al. (2012), Cacchiani et al. (2012) and Wagenaar et al. (2017) assume a predefined timetable.

To the best of our knowledge, the existing literature on optimal rescheduling and short-turning does not concretely address the three phases of disruption and specially the traffic interaction from both sides of the blockage upon the disruption resolution while accounting for rolling stock. For a review of the related literature see Ghaemi et al. (2017b).

This paper presents a macroscopic rescheduling model which is an extension of the model introduced by Ghaemi et al. (2016). The macroscopic rescheduling model computes a three-phase disruption timetable, including the recovery plan for the case of a complete blockage given a certain disruption length. The main contributions of the paper are as follows:

- A macroscopic MILP model is developed to compute the disruption timetable and the transition plans given a certain disruption period.
- Allowing for short-turning at multiple stations while taking the platform track occupation into consideration.
- Accounting for the traffic on both sides of the disrupted location during the three phases.
- Demonstrating how the disruption length affects the optimal periodic short-turning solution of the second phase.

The structure of the paper is as follows. The three-phase rescheduling problem is elaborated in Section 2. Section 3 presents the mathematical formulation of the MILP model. In Section 4 the results of the application of the model on a Dutch railway corridor are discussed. Finally, the conclusions are given in Section 5.

2. Problem description

In case of large disruptions, the rescheduling decisions are usually made by the traffic controllers located in the centralized traffic control center who monitor and control the entire network. If there is no relevant contingency plan, the traffic controllers have to quickly respond and devise a feasible plan for short-turning train services that are heading towards the disrupted location. The train services that are running towards the disrupted location are referred to as approaching train services throughout this study. The traffic controllers have to decide how to assign the approaching train services to the scheduled departures in the opposite direction. Having multiple train services that need to be short-turned on both sides of the disrupted location and communicating the plan with other traffic controllers to reach a consensus would take a long time and might postpone the recovery. Hence an algorithm that can quickly compute the optimal short-turning solution on both sides of the blockage as well as the transition to the original timetable can speed up the process. Before defining the problem, it is necessary to explain how a service is defined in this study. Fig. 2 illustrates the time-distance diagram for two opposite trains from station a to station d (downwards) and from station d to station a (upwards). Each service $v_{l,n}^{i}$ is characterized with three indicators: l identifies the line number that determines the stopping stations, n represents the operation time of the service and i indicates the sequence of the service within line l. In this way each service is recognized as a trip

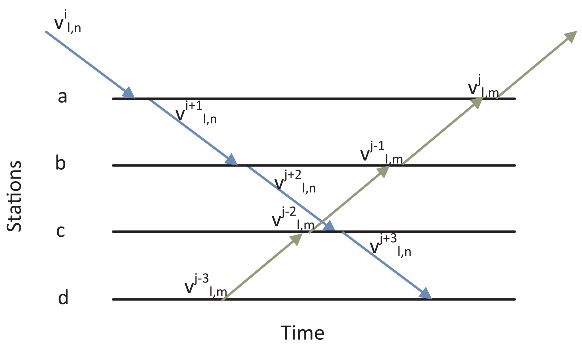

Fig. 2. Service definition.

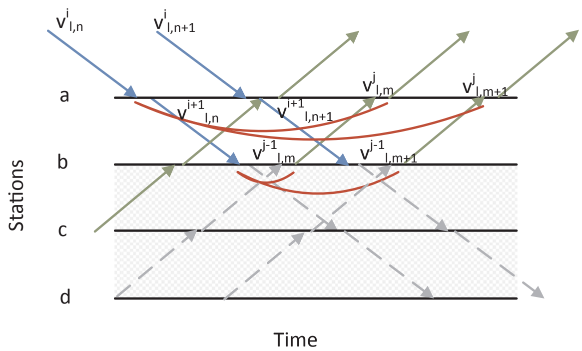

Fig. 3. Different short-turning possibilities.

between two consecutive stations. Hence the following service from station a to b that is performed by the rolling stock of service $v^{i}_{l,n}$ from the same line is denoted by $v^{i+1}_{l,n}$. As shown in Fig. 3 the next service of the same line from station a to b is denoted by $v^{i+1}_{l,n+1}$ where $n+1$ indicates that this service operates in the following cycle.

In case there is a disruption in station c, the approaching trains cannot proceed further and they have to short-turn before the disrupted area. In Fig. 3 an approaching train $v^{i}_{l,n}$ has to short-turn the latest at station b. The blockage results in cancellation of the services from station d to c and from c to b. Thus the services from b to a and from a upwards have to be performed by the short-turning trains. As is illustrated with the red short-turning arcs, there are two scheduled departures possible from station b to a;$v^{j-1}_{l,m}$ and $v^{j-1}_{l,m+1}$. If the capacity is not sufficient for short-turning all approaching trains, then the trains can also short-turn a station earlier to scheduled departures $v^{j}_{l,m}$ or $v^{j}_{l,m+1}$. Thus each approaching train has multiple short-turning possibilities in different stations. The optimal choice of short-turning is the main problem in the second phase of the disruption. The traffic scheduling decisions during the first and third phases directly depend on the start and end times of the disruption period. Note that the optimal short-turning choice in the second phase is dependent of the disruption period. The first phase deals with the services that depart towards the disrupted location before the start of the disruption. Logically these services need to short-turn in the next stations even if the initial schedule did not include this stop. The third phase starts when train services can start again using the previously blocked section and lasts until the original timetable can be resumed. In order to plan for the third phase, it is assumed that the end of the disruption is known in advance.

Figs. 4 and 5 show two time-distance diagrams for a disruption with same start time and two different disruption lengths. In this example, station c is disrupted. The train services need to short-turn either at stations b and d or those preceding them, namely stations a and e.

The two vertical lines represent the start and end times of the disruption. Note that each short-turning is the assignment of an arriving train to a scheduled departure in the opposite direction. Consequently, the short-turning trains on one side of the disrupted

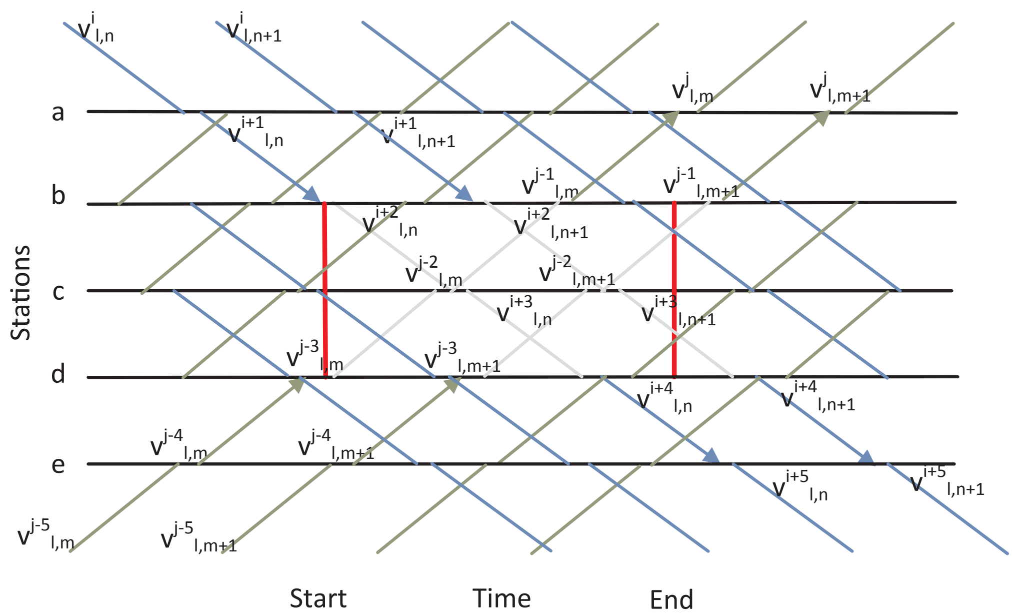

Fig. 4. Disruption scenario with symmetrical condition.

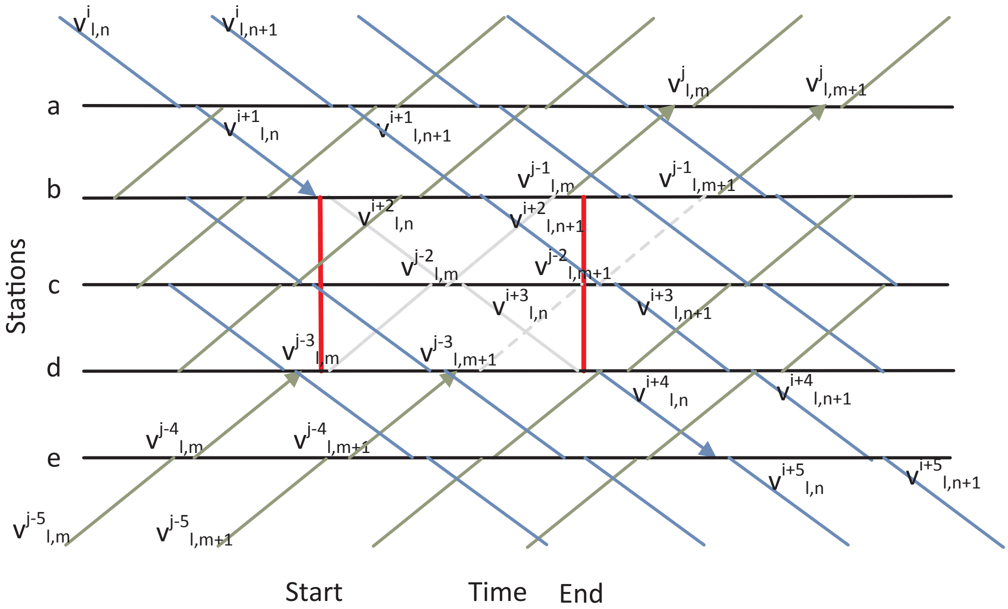

Fig. 5. Disruption scenario with asymmetrical condition.

location correspond to the scheduled departures of the short-turnings on the other side of the disrupted location. For example, if the train service $v_{l,n}^{i}$ (or $v_{l,n}^{i+1}$) short-turns in station a (or b), then $v_{l,n}^{i+4}$ (or $v_{l,n}^{i+5}$) needs to be performed by a short-turning in station d (or e).

The train services that are affected by the blockage are those that run towards disruption with the scheduled arrival at station c and those that are scheduled to depart from station c within the disruption period. In Figs. 4 and 5, the approaching train services are shown by arrows. Moreover, the scheduled departures on the other side of the disruption corresponding to the approaching train services are also depicted by arrows.

The number of approaching train services for short-turnings on each side of the disruption may either be equal or unequal. Thus, depending on the disruption period there can be either symmetrical (equal) or asymmetrical (unequal) condition. Figs. 4 and 5 show disruption scenarios with symmetrical and asymmetrical conditions, respectively.

In a symmetrical condition, an equal number of approaching train services on both sides of the disrupted location also implies equal approaching train services and scheduled departures on each side. As is shown in Fig. 4 there are two approaching train services on each side. In this case, the train services $v_{l,n}^{i+1}$ and $v_{l,n+1}^{i+1}$ from one side and train services $v_{l,m}^{j-4}$ and $v_{l,m+1}^{j-4}$ from the other side are approaching stations b and d. These train services need to short-turn at or prior to stations b and d. Note that the model can also suggest early short-turnings of the corresponding services ($v_{l,n}^{i}$,$v_{l,n+1}^{i}$ and $v_{l,m}^{j-5}$,$v_{l,m+1}^{j-5}$) in stations a and e. By short-turning the train services $v_{l,n}^{i+1}$ and $v_{l,m}^{j-4}$, the services $v_{l,n}^{i+2}$ and $v_{l,m}^{j-3}$ need to be cancelled. These cancelled services are represented using solid grey lines. Similarly, the train services $v_{l,n+1}^{i+1}$ and $v_{l,m+1}^{j-4}$ short-turn.

In an asymmetrical condition, an unequal number of approaching train services implies that on one side of the disruption, there are more approaching train services than scheduled departures in the opposite direction and vice versa on the other side. Fig. 5 is an example where there are two approaching train services $v_{l,m}^{j-4}$ and $v_{l,m+1}^{j-4}$ in station d (or $v_{l,m}^{j-5}$ and $v_{l,m+1}^{j-5}$ in station e) and one approaching train service $v_{l,n}^{i+1}$ in station b (or $v_{l,n}^{i}$ a). Since there are two approaching train services in station d and only one possible scheduled departure in the opposite direction, only one short-turning can take place and the second approaching train has to wait until the disruption is over and it can continue towards station a. In case of an asymmetrical condition, the recovery service is the successive service corresponding to the final approaching train service on the side with more approaching train services. In this case the recovery services $v_{l,m+1}^{j-3}$ can only depart with some delay.

In the third phase, there might be congestion resulting from the train services that are waiting for the end of the disruption period until they can start running towards the other side of the previously blocked section.

3. Mixed-integer linear programming formulation

Before defining the variables and constraints of the Mixed Integer Linear Programming model, it is necessary to introduce the assumptions and construct the relevant sets. Section 3.1 lists the underlying assumptions. The sets are defined in Section 3.2 followed by the MILP model in Sections 3.3 and 3.4. Finally Section 3.5 describes how different phases of disruption are measured.

3.1. Model assumptions

The model in its current formulation addresses the disruption cases where a station is completely blocked for a certain disruption

Table 1
The notation of the input used in the macroscopic model.

S	The set of all stations s
L	The set of all lines l
V	The set of all scheduled services
$V_{l,n} \subset V$	The n^{th} set of ordered services in line l
$v_{l,n}^{i} \subset V_{l,n}$	The i^{th} service in set $V_{l,n}$
$P_{s,v_{l,n}^{i}}$	The set of platform tracks for service $v_{l,n}^{i}$ in station s
$S_{v_{l,n}^{i}} \subset S$	The departure and arrival stations ($s_{v_{l,n}^{i}}^{d}$, $s_{v_{l,n}^{i}}^{a}$) of $v_{l,n}^{i}$
$S_0 \subset S$	The disrupted station (x)
$S_1 \subset S$	The first surrounding stations (b and d) around the disrupted station x
$S_2 \subset S$	The secondary surrounding stations (a and e) around stations in S_1
$S^{l} \subset S$	The set of possible short-turning stations for line l
$d_{l,n}^{i}$	The scheduled departure time of service $v_{l,n}^{i}$
$a_{l,n}^{i}$	The scheduled arrival time of service $v_{l,n}^{i}$
$\theta_{v_{l,n}^{i}}^{min}$	The minimum short-turning time needed for service $v_{l,n}^{i}$
$\tau_{v_{l,n}^{i}}^{run}$	The running time of service $v_{l,n}^{i}$ between two stations
$\tau_{v_{l,n}^{i},v_{l,n}^{i+1}}^{dwell}$	The dwell time between service $v_{l,n}^{i}$ and service $v_{l,n}^{i+1}$ in the station
$\tau_{v_{l,n}^{i},v_{w,z}^{u}}^{h}$	The minimum headway time between two train services $v_{l,n}^{i}$ and $v_{w,z}^{u}$
$\omega_{v_{l,n}^{i}}^{c}$	The penalty for cancelling service $v_{l,n}^{i}$
$\omega_{v_{l,n}^{i}}^{z}$	The penalty for delaying the arrival of service $v_{l,n}^{i}$
t^{s}	The start time of disruption
t^{e}	The end time of disruption
M	A large constant

period. However with some minor adjustments, the model can be applied for complete blockages of open track sections. The main assumptions of this model are that the disruption length is known upon occurrence and the original timetable is cyclic. Literature proposes several models to predict the disruption length from which we refer to the model by Zilko et al. (2016) that is based on Copula Bayesian Network. It is also assumed that each service can only short-turn to replace a service from the same line. Thus the possibility of short-turning an intercity train and replacing a service from the local line is excluded to avoid complications in rolling stock circulation. The proposed MILP problem is a macroscopic model and does not provide microscopic solution that determines the utilization of every track detection section. Instead a minimum headway is considered to avoid any conflict between the operating services. In addition, the running, dwell and short-turning times are assumed as input.

3.2. Preprocessed sets based on the disruption period

The notation is listed in Table 1. For notation simplification, the approaching train services are shown as v' and those services that are scheduled to approach the disrupted station are denoted by v''. Finally, those services that are scheduled to move away from the disrupted area are denoted as v''' regardless of their line specifications. Before formally defining these sets, an example is used to make a better distinction between them.

This example shows three operating lines (k,l,m) in one direction. Thus the approaching services to station a,b, and c each consist of three sets that are shown distinctively in each column,

$$V'_{a,k} = \{v_{k,n}^{z},v_{k,n+1}^{z}\},\quad V'_{b,k} = \{v_{k,n}^{z+1},v_{k,n+1}^{z+1}\},\quad V''_{c,k} = \{v_{k,n}^{z+2},v_{k,n+1}^{z+2}\},$$
$$V'_{a,l} = \{v_{l,n}^{i},v_{l,n+1}^{i}\},\quad V'_{b,l} = \{v_{l,n}^{i+1},v_{l,n+1}^{i+1}\},\quad V''_{c,l} = \{v_{l,n}^{i+2},v_{l,n+1}^{i+2}\},$$
$$V'_{a,m} = \{v_{m,n}^{p},v_{m,n+1}^{p}\}.\quad V'_{b,m} = \{v_{m,n}^{p+1},v_{m,n+1}^{p+1}\}.\quad V''_{c,m} = \{v_{m,n}^{p+2},v_{m,n+1}^{p+2}\}.$$

Similarly the services that move away from the disruption and depart from station d and e each consist of three sets that are shown distinctively in each column,

$$V'''_{d,k} = \{v_{k,n}^{z+4},v_{k,n+1}^{z+4}\},\quad V'''_{e,k} = \{v_{k,n}^{z+5},v_{k,n+1}^{z+5}\},$$
$$V'''_{d,l} = \{v_{l,n}^{i+4},v_{l,n+1}^{i+4}\},\quad V'''_{e,l} = \{v_{l,n}^{i+5},v_{l,n+1}^{i+5}\},$$
$$V'''_{d,m} = \{v_{m,n}^{p+4},v_{m,n+1}^{p+4}\}.\quad V'''_{e,m} = \{v_{m,n}^{p+5},v_{m,n+1}^{p+5}\}.$$

In the preprocessing step, the following sets are defined.

- The set of lines l that are planned to operate in the disrupted area during the disruption,

$$L_{Dist} = \{l \in L|\ \exists\ i,n,S_{v^i_{l,n}} \subseteq \{S_1,S_0\},t^s \leqslant a^i_{l,n} \leqslant t^e\}.$$

- The set of all approaching services $v^i_{l,n}$ to station $s \in S_1 \cup S_2$ from line l for which the service $v^{i+1}_{l,n}$ (or $v^{i+2}_{l,n}$) is scheduled to arrive at S_0 within the disruption period,

$$V'_{s,l} = \{v^i_{l,n} \in V|s = s^a_{v^i_{l,n}},s^d_{v^i_{l,n}} \notin \{S_1,x\},\exists\ z \in \{i+1,i+2\},t^s < a^z_{l,n} < t^e,\},\quad \forall\ s \in S_1 \cup S_2,l \in L_{Dist}.$$

- The set of all services $v^i_{l,n}$ from line l that are scheduled to depart from station $s \in S_1$ and arrive at station x within the disruption period,

$$V''_{s,l} = \{v^i_{l,n} \in V|s = s^d_{v^i_{l,n}},s^a_{v^i_{l,n}} = x,v^{i-1}_{l,n} \in V'_{s,l}\},\quad \forall\ s \in S_1,l \in L_{Dist}.$$

- The set of services that are scheduled to depart from station $s \in S_1 \cup S_2$ from line $l \in L_{Dist}$ and run away from station x,

$$V'''_{s,l} = \{v^j_{l,m} \in V|s^d_{v^j_{l,m}} = s,v^{j-2}_{l,m},v^{j-3}_{l,m} \in V''_{\bar{s},l},\bar{s} \in S_1,l \in L_{Dist}\},\quad \forall\ s \in S_1 \cup S_2.$$

- To compute the optimal short-turnings, all the possible pairs of approaching train services and scheduled departures in the opposite direction in the relevant stations are defined by the following sets,

$$Out_{v^i_{l,n}} = \{(v^i_{l,n},v^j_{l,m})|v^j_{l,m} \in V'''_{s,l}\},\quad \forall\ v^i_{l,n} \in V'_{s,l},s \in S_1 \cup S_2,l \in L_{Dist},$$

$$In_{v^j_{l,m}} = \{(v^i_{l,n},v^j_{l,m})|v^i_{l,n} \in V'_{s,l}\},\quad \forall\ v^j_{l,m} \in V'''_{s,l},s \in S_1 \cup S_2,l \in L_{Dist}.$$

- Since the disruption period is assumed to be known in advance, in the preprocessing step the services in the first phase can be predetermined. Considering the first phase starting with a reduction in the traffic level, the approaching services in the first phase are denoted as $V'_{s,l,red}$. This set consists of the approaching services to station s from line l that depart before the start of the disruption and arrive within the disruption period. They are a subset of the approaching services $V'_{s,l}$ that already departed from their possible short-turning station and they have to short-turn in the final station before the disruption. They are defined by the following set,

$$V'_{s,l,red} = \{v^i_{l,n} \in V'_{s,l}|d^i_{l,n} \leqslant t^s,s \notin S^l\},\quad \forall\ l \in L_{Dist}.$$

- Similarly the scheduled departures in the opposite direction in the first phase are denoted as $V'''_{s,l,red}$. This set consists of the first scheduled departures from station s and line l in the opposite direction for which there is no rolling stock available and thus can be performed by short-turning the approaching train in the first phase. The scheduled departures in the opposite direction in the first phase are defined by the following set,

$$V'''_{s,l,red} = \{v^j_{l,m} \in V'''_{s,l}|d^j_{l,m} < d^j_{l,w},s \notin S^l\},\quad \forall\ v^j_{l,w} \in V'''_{s,l},l \in L_{Dist}.$$

- Based on the defined sets in the first phase, the short-turning couples of the first phase are denoted as sht_{red} and defined by the following set,

$$sht_{red} = \{(v^i_{l,n},v^j_{l,m})|v^i_{l,n} \in V'_{s,l,red},v^j_{l,m} \in V'''_{s,l,red}\},\quad \forall\ l \in L_{Dist}.$$

- Likewise, the services of the third phase can be predetermined. The services that may use the blocked section after the disruption is over, are called recovery services and are denoted as $V''_{s,l,rec}$. The recovery service is defined as the last service on those lines which have a greater number of approaching services than scheduled departures in the opposite direction:

$$V''_{s,l,rec} = \begin{cases} \{v^i_{l,n} \in V''_{s,l}|a^i_{l,w} < a^i_{l,n}\},\quad \forall\ v^i_{l,w} \in V''_{s,l},s \in S_1,l \in L_{Dist} & \text{if } |V'_{s,l}| > |V'''_{s,l}| \\ \varnothing, & \text{otherwise.} \end{cases}$$

3.3. Decision variables

The decision variables are formulated as either continuous or binary variables. The continuous decision variables represent time and are non-negative:

$t^a_{v^i_{l,n}}$ The arrival time of service $v^i_{l,n}$.
$t^d_{v^i_{l,n}}$ The departure time of service $v^i_{l,n}$.
$z_{v^i_{l,n}}$ The arrival delay of service $v^i_{l,n}$.

The decisions regarding occupying a platform track, cancelling a service, and the choice of short-turning are represented by binary decision variables:

$$p_{v^i_{l,n},q} = \begin{cases} 1 & \text{if } v^i_{l,n} \text{ arrives at platform track } q, \\ 0 & \text{otherwise;} \end{cases}$$

$$c^i_{l,n} = \begin{cases} 1 & \text{if } v^i_{l,n} \text{ is cancelled,} \\ 0 & \text{otherwise;} \end{cases}$$

$$\lambda_{v',v'''} = \begin{cases} 1 & \text{if } v' \text{ short–turns to } v''', \\ 0 & \text{otherwise.} \end{cases}$$

3.4. Objective function and constraints

The objective function includes two terms, penalized cancellations and delay,

$$\min \sum_{v^i_{l,n} \in V} (\omega^c_{v^i_{l,n}} \cdot c^i_{l,n} + \omega^z_{v^i_{l,n}} \cdot z_{v^i_{l,n}}), \tag{1}$$

where $\omega^c_{v^i_{l,n}}$ and $\omega^z_{v^i_{l,n}}$ are penalties for cancellation and arrival delay of service $v^i_{l,n}$.

3.4.1. Running, dwell, delay and departure time constraints

$$t^a_{v^i_{l,n}} - t^d_{v^i_{l,n}} = \tau^{run}_{v^i_{l,n}}, \qquad \forall\, v^i_{l,n} \in V, \tag{2}$$

$$t^d_{v^{i+1}_{l,n}} - t^a_{v^i_{l,n}} + M \cdot (c^i_{l,n} + c^{i+1}_{l,n}) \geqslant \tau^{dwell}_{v^i_{l,n},v^{i+1}_{l,n}}, \qquad \forall\, v^i_{l,n}, v^{i+1}_{l,n} \in V, \tag{3}$$

$$t^d_{v^i_{l,n}} - d^i_{l,n} \geqslant 0, \qquad \forall\, v^i_{l,n} \in V, \tag{4}$$

$$t^d_{v^i_{l,n}} - d^i_{l,n} \leqslant (1 - c^i_{l,n}) \cdot M, \qquad \forall\, v^i_{l,n} \in V, \tag{5}$$

$$z_{v^i_{l,n}} = t^a_{v^i_{l,n}} - a^i_{l,n} \qquad \forall\, v^i_{l,n} \in V, \tag{6}$$

$$t^d_{v^i_{l,n}} \geqslant t^e \qquad \forall\, v^i_{l,n} \in V''_{s,l,rec}, s \in S_1, l \in L_{Dist} \tag{7}$$

Minimum running and dwell times are considered by constraints (2) and (3). The departures should respect the schedule. Constraints (4) enforce this restriction. To avoid double penalties for cancelled services, their operations are modelled on time. Constraints (5) make sure that the departures of cancelled services are the same as the schedule. Constraints (6) measure the arrival delays. The recovery services can only operate after the end of the disruption. Constraints (7) ensure this restriction.

3.4.2. Short-turning constraints

$$\sum_{(v',v''') \in Out_{v^i_{l,n}} \cup Out_{v^{i+1}_{l,n}}} \lambda_{v',v'''} = c^{i+2}_{l,n}, \qquad \forall\, v^i_{l,n} \in V'_{s,l}, s \in S_2, l \in L_{Dist}, \tag{8}$$

$$\sum_{(v',v''') \in In_{v^j_{l,m}} \cup In_{v^{j-1}_{l,m}}} \lambda_{v',v'''} + c^j_{l,m} = c^{j-2}_{l,m}, \qquad \forall\, v^j_{l,m} \in V'''_{s,l}, s \in S_2, l \in L_{Dist}, \tag{9}$$

$$\sum_{(v',v''') \in Out_{v^i_{l,n}}} \lambda_{v',v'''} = c^{i+1}_{l,n}, \qquad \forall\, v^i_{l,n} \in V'_{s,l}, s \in S_2, l \in L_{Dist}, \tag{10}$$

$$\sum_{(v',v''') \in In_{v^j_{l,m}}} \lambda_{v',v'''} + c^j_{l,m} = c^{j-1}_{l,m}, \qquad \forall\, v^j_{l,m} \in V'''_{s,l}, s \in S_2, l \in L_{Dist}, \tag{11}$$

$$\sum_{(v',v''') \in Out_{v^{i+1}_{l,n}}} \lambda_{v',v'''} + c^{i+1}_{l,n} \leqslant 1, \qquad \forall\, v^i_{l,n} \in V'_{s,l}, s \in S_2, l \in L_{Dist}, \tag{12}$$

$$(1-\lambda_{v',v'''})\cdot M + t^{d}_{v'''} \geqslant t^{a}_{v'} + \theta^{min}_{v'}, \qquad \forall\ (v',v''') \in Out_{v'}, \tag{13}$$

$$c^{j}_{l,m} \leqslant c^{k+1}_{l,m}, \qquad \forall\ v^{j}_{l,m} \in V'''_{s,l}, s \in S_2, l \in L_{Dist}, k \in [j,|S|-1], \tag{14}$$

$$\lambda_{v',v'''} = 1, \qquad \forall\ (v',v''') \in sht_{red}. \tag{15}$$

The short-turning constraints are better explained by the time distance diagram shown in Fig. 3. Every approaching service to the disrupted area has to short-turn in a station preceding the blockage. Assuming the arrival station of $v^{i}_{l,n}$ to be station $a \in S_2$, then it implies that service $v^{i+2}_{l,n}$ has to be cancelled due to the blockage unless $v^{i+2}_{l,n}$ can wait in the final station and then arrives at station c which was disrupted. In case service $v^{i+2}_{l,n} \in V''_{s,l}$ is cancelled then $v^{i}_{l,n}$ or $v^{i+1}_{l,n}$ has to short-turn. Otherwise the approaching train can continue as the recovery service. Constraints (8) enforce this relation. There should be a train assigned to each scheduled departure in the opposite direction. Thus, there are three options for each scheduled departure in the opposite direction. If there is no available train that can operate this service, it needs to be cancelled. Otherwise either an approaching train service or the recovery train service from the other side of disruption is assigned. This possibility is present through Constraints (9). Each early short-turning leads to two cancelled services. To give an example, if service $v^{i}_{l,n}$ is short-turned as service $v^{j}_{l,m}$ in a station upstream of the closest station to the blockage, then the following service $v^{i+1}_{l,n}$ will be cancelled. Likewise the preceding service of $v^{j}_{l,m}, v^{j-1}_{l,m}$, will be cancelled. These cancellations are considered in constraints (10) and (11). Constraints (12) make sure that if service $v^{i+1}_{l,n}$ is cancelled due to a short-turning in an earlier station a (or e), the relevant pairs should not be selected in the last station b (or d). For each short-turning there should be a minimum short-turning time between the arrival of the approaching train service and the scheduled departure in the opposite direction. Constraints (13) ensure the minimum short-turning time. If a departing service from stations a (or e) that runs away from the disruption is cancelled, then the following services need to be cancelled. Constraints (14) guarantee these cancellations for the remaining services of the line. The short-turning couples of the first phase that are defined in the preprocessing step are realized by imposing their short-turning variables through Constraints (15). (see Fig. 6)

3.4.3. Platform constraints

$$\sum_{q \in P_{s,v^{i}_{l,n}}} p_{v^{i}_{l,n},q} + c^{i}_{l,n} = 1 \qquad \forall\ v^{i}_{l,n} \in V'_{s,l} \cup V'''_{s,l}, s \in S_1 \cup S_2, l \in L_{Dist}, \tag{16}$$

$$\begin{gathered}(3-(p_{v',q} + p_{v^{u}_{w,z},q})-\lambda_{v',v'''})\cdot M + t^{a}_{v^{u}_{w,z}} \geqslant t^{d}_{v'''} + \tau^{h}_{v^{i}_{l,n},v^{u}_{w,z}},\\ \forall\ (v',v''') \in Out_{v'}, v' \in V'_{s,l}, s \in S_1 \cup S_2, l \in L_{Dist}, \forall\ v^{u}_{w,z} \in V\colon s^{a}_{v^{u}_{w,z}} = s, a^{u}_{w,z} \geqslant a^{v'}, \qquad \forall\ q \in P_{s,v'} \cap P_{s,v^{u}_{w,z}},\end{gathered} \tag{17}$$

$$\begin{gathered}(c^{i+1}_{l,n} + 2-(p_{v^{i}_{l,n},q} + p_{v^{u}_{w,z},q}))\cdot M + t^{a}_{v^{u}_{w,z}} \geqslant t^{d}_{v^{i+1}_{l,n}} + \tau^{h}_{v^{i}_{l,n},v^{u}_{w,z}},\\ \forall\ v^{i}_{l,n} \in V'_{s,l}, s \in S_2, l \in L_{Dist}, \forall\ v^{u}_{w,z} \in V\colon s^{a}_{v^{u}_{w,z}} = s, a^{u}_{w,z} \geqslant a^{i}_{l,n}\ \forall\ q \in P_{s,v^{i}_{l,n}} \cap P_{s,v^{u}_{w,z}}.\end{gathered} \tag{18}$$

Constraints (16) guarantee a platform assignment for each arriving service. Figs. 7 and 8 visualize the constraints (17) and (18). Constraints (17) make sure that in case train service v' is being short-turned as service v''' using platform track q then any next arriving service $v^{u}_{w,z}$ should wait until the minimum headway time after the departure of v''' if it uses the same platform track q. Similarly, constraints (18) ensure the platform occupation is unique to only one train service at a time for those services that do not short-turn.

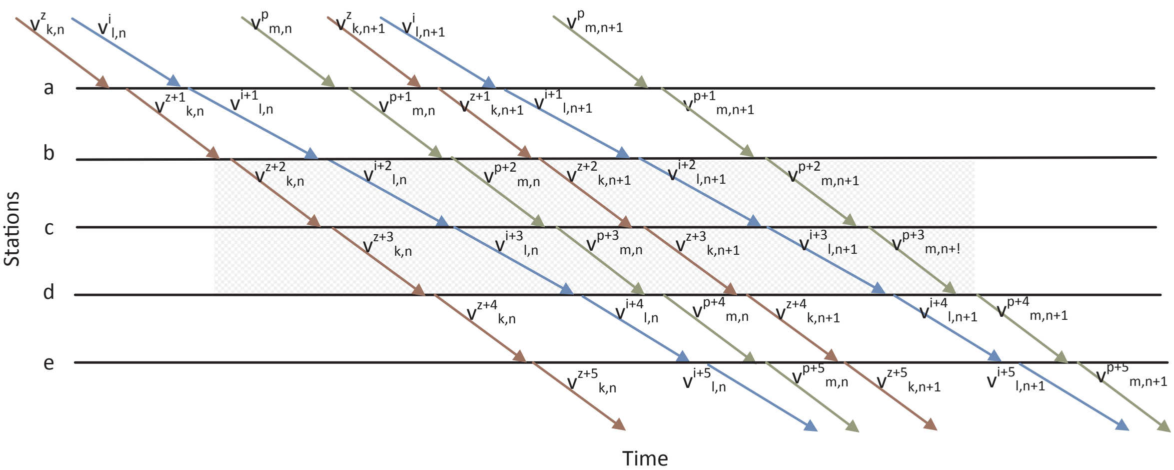

Fig. 6. Different lines operating in one direction.

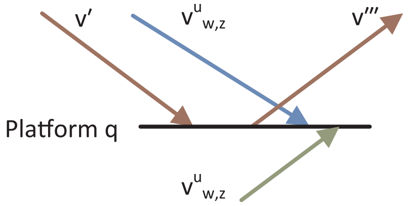

Fig. 7. The platform occupation constraint for short-turning services.

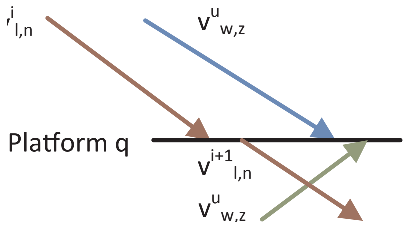

Fig. 8. The platform occupation constraint for the non short-turning services.

3.5. Postprocessed measures of disruption phases

To measure the lengths of each phase of disruption, there should be a distinction between phases. The phases are measured within the short-turning stations. In this approach the first phase starts as soon as the disruption starts. It is acknowledged that in practice the first phase may take longer due to the time needed for communication and reaching an agreement on how to proceed with the decisions made by the traffic controllers. The end of the first phase, which is also the start of the second phase, is defined as the time that (fewer) trains operate regularly again and no more irregularities caused by the first phase are observed. The regular operation includes short-turnings that repeat every cycle. If the services of the first phase can short-turn on time, then the first phase ends as soon as the latest service of the first phase departs after short-turning. In case the short-turnings of the first phase cause delay, then the end of the first phase is measured at the latest arrival at the short-turning stations. The second phase lasts until the earliest departure of the recovery services from the short-turning stations. This time point is the beginning of the third phase which lasts until the latest arrival of the recovery services at the short-turning stations.

4. Case study

The model is applied to a mainly double-track railway corridor from Utrecht (Ut) to ’s-Hertogenbosch (Ht) in the middle of the Netherlands. The model is implemented in MATLAB R2016b and solved by Gurobi. The toolbox YALMIP (Löfberg, 2004) is used to construct the MILP model. The optimal solutions are achieved with zero gaps. The corridor is illustrated in Fig. 9 and includes 13 stations and 7 lines with each a frequency of two services per hour in each direction. So 14 trains per hour per direction operate in this corridor. The case study considers a disruption that takes place at station Geldermalsen (Gdm). There are different intercity and local train lines operating in this corridor. These lines are colored differently in Fig. 9. The original timetable for this corridor is illustrated in Fig. 10. Two intercity lines IC800 (in light green[1]) and IC3500 (in dark green) and two local lines (called sprinters (SPR) in Dutch) SPR16000 (in orange) and SPR6000 (in blue) run through Geldermalsen. The local line SPR36700 (in purple) provide services to Geldermalsen. The intercity lines have scheduled stops only at stations Utrecht (Ut) and ’s-Hertogenbosch (Ht). Thus, in case of a disruption in Geldermalsen, the IC train services need to short-turn in these stations. The SPR train services SPR16000 and SPR6000 have scheduled stops at Utrecht Lunetten (Utl), Houten (Htn), Houten Castellum (Htnc), Culemborg (Cl), and Geldermalsen. From Geldermalsen, SPR6000 runs towards the east to station Tiel Passewaaij (Tlpsw) and SPR16000 operates towards the south to Zaltbommel (Zbm) and ’s-Hertogenbosch. The short-turning stations to the south of Geldermalsen for the SPR services are Zbm or Ht, and for IC services only Ht. The short-turning stations to the north of Geldermalsen are Cl or Htnc for SPR services. The two lines IC3600 (in light blue) and SPR4400 (in pink) are not affected by the disruption in Gdm. However since they stop in Ht, they are included in the model. The IC services short-turn in Ut which due to its complexity is not included in this case study. The stations Beesd and Tiel Passewaaij are not frequently served. So the short-turnings in these stations can be performed on schedule without introducing any delay, thus their short-turnings are excluded in the case study. Table 2 lists the stops for each line.

[1] For interpretation of color in Figs. 9-19, the reader is referred to the web version of this article.

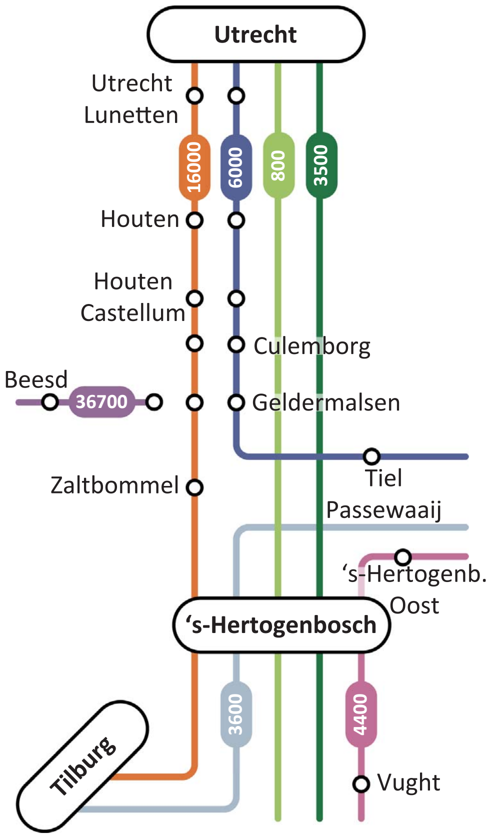

Fig. 9. The disrupted corridor.

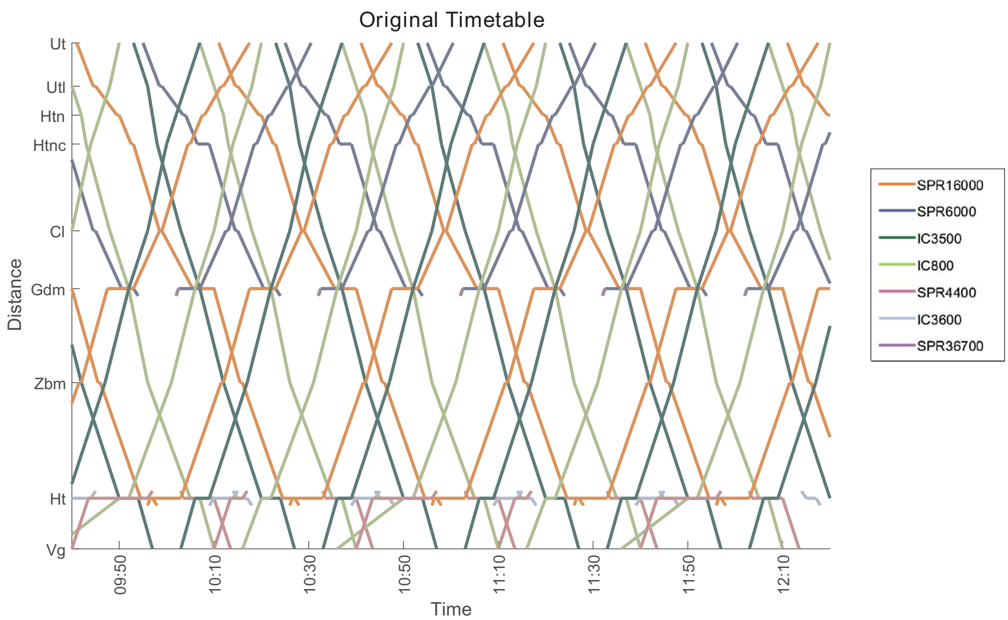

Fig. 10. The time-distance diagram of the original timetable.

Table 2
Lines.

Line	Stops								
IC800	Ut	Ht							
IC3500	Ut	Ht							
IC3600	Hto	Ht	Tb						
SPR36700	Bsd	Gdm							
SPR4400	Hto	Ht	Vg						
SPR6000	Ut	Utl	Htn	Htnc	Cl	Gdm	Tlpsw		
SPR16000	Ut	Utl	Htn	Htnc	Cl	Gdm	Zbm	Ht	Tb

Table 3
Parameters.

Parameter	Notation	Value
Short-turning time	$\theta^{min}_{v^i_{l,n}}$	5 (min)
Headway time	$\tau^h_{v^i_{l,n},v^u_{w,z}}$	3 (min)
Big M	M	50,000
IC cancellation penalty	$\omega^c_{v^i_{l,n}}, \forall v^i_{l,n} \in V, l \in \{$ IC800, IC3500, IC3600$\}$	10000
SPR cancellation penalty	$\omega^c_{v^i_{l,n}}, \forall v^i_{l,n} \in V, l \in \{$ SPR36700, SPR4400, SPR6000, SPR16000$\}$	1000
IC delay penalty	$\omega^{d^a}_{v^i_{l,n}}, \forall v^i_{l,n} \in V, l \in \{$ IC800, IC3500, IC3600$\}$	10
SPR delay penalty	$\omega^{d^a}_{v^i_{l,n}}, \forall v^i_{l,n} \in V, l \in \{$ SPR36700, SPR4400, SPR6000, SPR16000$\}$	1

Table 4
platforms.

Station	Htnc	Cl	Gdm	Zbm	Ht
Number of platform tracks	2	2	4	2	5

4.1. Parameters and experiment settings

To test and demonstrate the impact of the disruption on the optimal short-turning solution, four experiments are performed with different disruption periods. In the first experiment, it is shown that with the same disruption length, there could be different optimal solutions depending on the start time of the disruption. This is the result of the different first phase. In the second experiment, it is shown that with the same disruption start time, the third phase could differ due to different disruption lengths. In the third experiment, the three phases of disruption for two scenarios are measured. In the fourth experiment, the optimal solution and the performance of the model with in particular the relation between the cancellation and delay are investigated under various disruption periods. In the experiments the duration of each phase is measured. The delay and cancellation for intercity services are penalized more than the delay and cancellation of local train services. The exact parameters' values and the number of platform tracks in the short-turning stations are detailed in Tables 3 and 4.

4.2. Experiment one: Different start time of disruption and fixed disruption length

In this experiment, station Gdm is disrupted for 30 min. Two scenarios with respect to different disruption start time are considered. In the first scenario (Fig. 11), the disruption starts at 09:45 and in the second scenario (Fig. 12) it starts at 10:00. In these figures, different train lines are identified by different colors which correspond to those used in Fig. 9. The cancelled services are colored in grey. In this experiment there is an equal number of approaching train services from line SPR16000 (in orange) and SPR6000 (in blue) on both sides of the disruption (one approaching train service and one scheduled departure in the opposite direction). The intercity train services from lines IC3500 (in dark green) and IC800 (in light green) have to short-turn in Ht. However, in Fig. 11 it is shown that the service from IC3500 (in dark green) departs from Ht before the start of disruption. Thus, this service is part of the services within the first phase of the disruption and has to short-turn in the following station which is Zbm although this line does not have any stops until Ut. Similarly on the other side of the disruption, the service from IC800 should have short-turned in Ut. However the disruption starts after the departure of this train from Ut. So this service is short-turned in station Cl. The short-turnings that are part of the first phase are shown by the horizontal green line. The other horizontal lines that connect an arriving train service to a scheduled departure in the opposite direction, are the optimal short-turning solutions within the second phase.

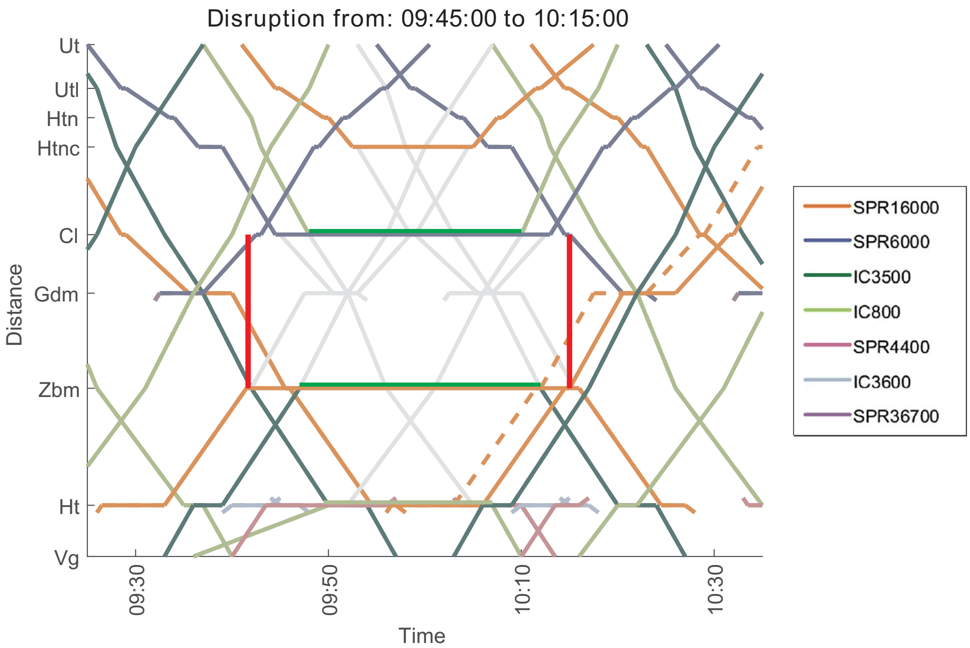

Fig. 11. Optimal short-turning solution for disruption from 9:45 to 10:15.

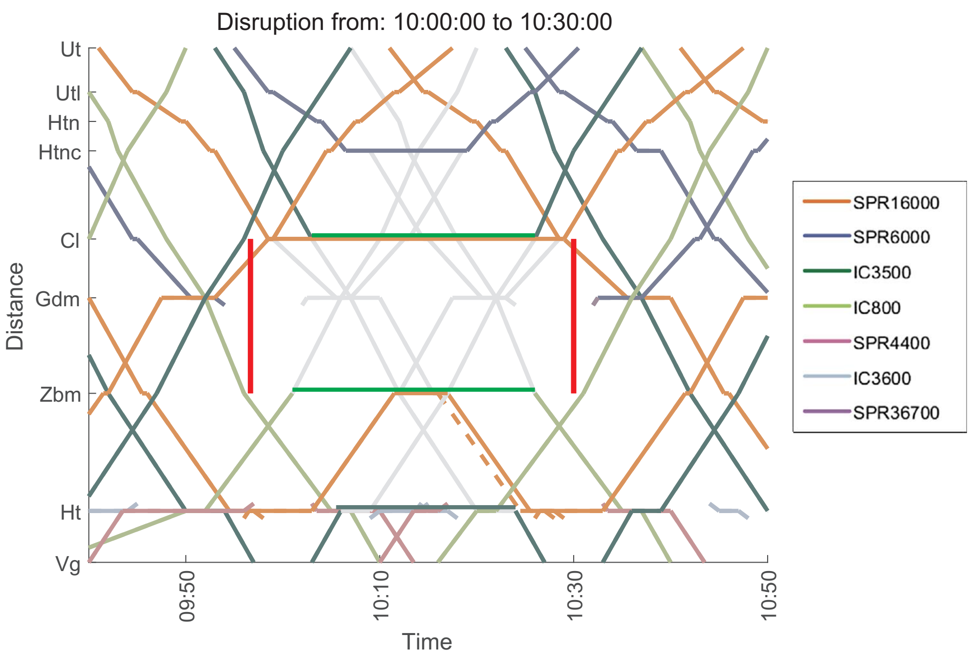

Fig. 12. Optimal short-turning solution for disruption from 10:00 to 10:30.

Station Cl has two platform tracks that are occupied by the services from line SPR6000 (in blue) and IC800 (in light green). Hence, there is no platform track available for the short-turning of service from SPR16000 (in orange) in Cl. So the optimal solution suggests an early short-turning for this line in station Htnc. On the other side of the disruption, the short-turning of the service from line 16000 (in orange) in Zbm, corresponds exactly to those in station Cl. It is also observed that the same occurs to the short-turning of IC800 (in light green) in both stations Cl and Ht. Zbm has two platform tracks, which are occupied by services from line IC3500 (in dark green) and SPR16000 (in orange). So the next service from line SPR16000 (in orange) can arrive with some delay which is the result of the minimum headway. This delay is the difference between the dashed line which is the scheduled train path and the solid line which is the computed path. Obviously, in this scenario, the third phase includes some delays.

Fig. 12 shows the result for the disruption that starts at 10:00, and reveals different optimal short-turning solutions on both sides

Table 5
The results of experiment one.

Disruption period	Affected/total services	# Cancelled services	Delays (s)	Obj. function	Comp. time (s)
9:45 to 10:15	36/210	29	1260	192,260	0.12
10:00 to 10:30	31/210	29	120	191,120	0.08

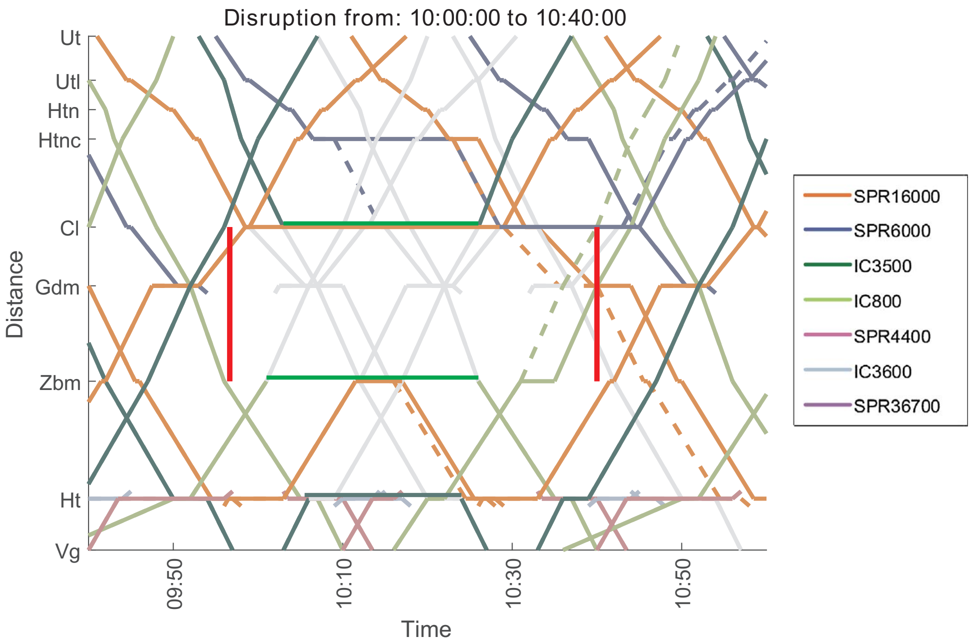

Fig. 13. Optimal short-turning solution for disruption from 10:00 to 10:40.

of the disruption. In this scenario the train service from line SPR6000 (in blue) short-turns in Htnc, due to the fact that both platforms of station Cl are occupied by short-turning services from line SPR16000 (in orange) and IC3500 (in dark green). On the other side of the disruption, a departure delay of one minute is observed after the short-turning of train service SPR16000 (in orange) at station Zbm caused by the minimum short-turning time of 5 min. In this scenario, the third phase is executed smoothly without any delay.

Table 5 shows the results of the first experiment. The second column reports the affected train services (including the cancelled and delayed services) over the total services. In both scenarios, there are 29 cancelled services. Note that each service is defined as a trip between two consecutive stations. There are two cancelled services resulting from early short-turning due to the IC services of the first phase in both scenarios. The remaining 27 cancelled services include the services in the disrupted area (between Cl and Zbm) and those related to the short-turning of the IC services in the first phase. The delay is measured for each arrival while the reported delay is computed by adding all the arrival delays. In the first scenario, there are 7 delayed services of line SPR16000 from Ht to Ut. The large delay for SPR16000 is caused by the limited platform track capacity due to short-turnings. Thus in total there are 36 affected train services in the disruption between 9:45 and 10:15. In the second scenario, there are two delayed services of line SPR16000 which are caused by respecting the minimum short-turning time. So there are 31 affected services in the second scenario. Due to a smaller delay in the second scenario, a lower objective function value is attained. The computation time of both scenarios are less than a second.

Since the disruption lengths of these scenarios are short, only a few short-turnings of the first phase are taking place. This conclusion is made by observing the irregularities of IC short-turnings in station Cl and Zbm. Thus, the first phase is defined from the beginning of the disruption until the latest departures of the IC services (IC800 from Cl and IC3500 from Zbm). On both sides of the disruption these IC services wait for a long time to short-turn to the next scheduled departure. These long short-turnings of the first phase, postpone the second phase. Due to the short disruption period, the third phase starts before a reduced and regular timetable for the second phase can be operated. In the first scenario, the third phase starts with the departure of the recovery service from Ht and lasts until the arrival at station Htnc. In the second scenario, there is no recovery service, so the third phase has a length of zero. This experiment demonstrates that the optimal solutions proposed by the model may differ for the scenarios with the same disruption length but different start times of the disruption. In other words, the impact of disruptions of the same lengths in terms of the delay can differ if they have different start times.

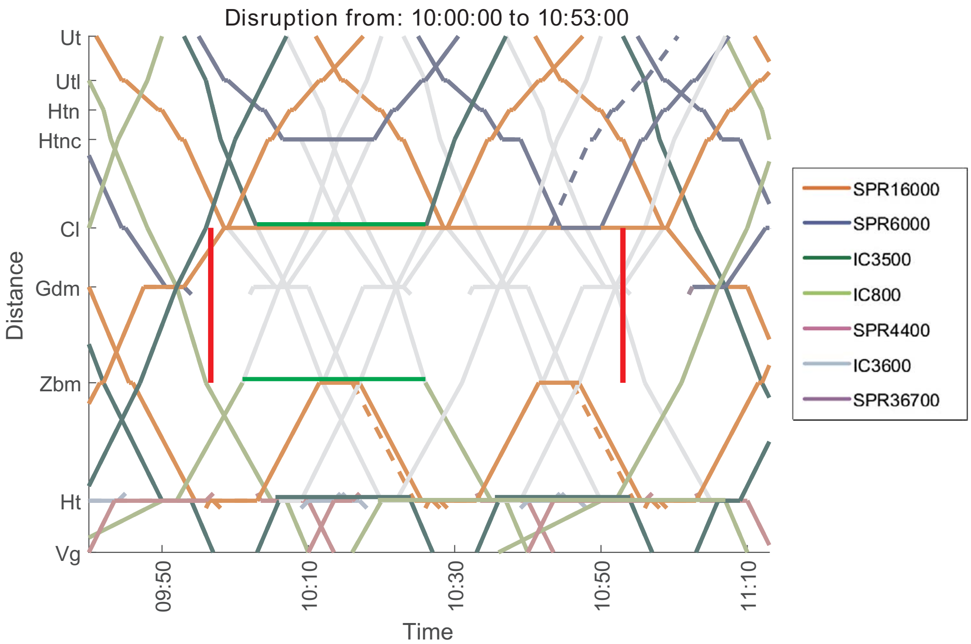

Fig. 14. Optimal short-turning solution for disruption from 10:00 to 10:53.

4.3. Experiment Two: Fixed start time of disruption and different disruption lengths

In this experiment the start time of the disruption is kept fixed whereas different disruption lengths are considered. This experiment is hence devised to explore the role of the disruption length on the optimal solution, specially during the third phase. Fig. 13 shows the optimal short-turning solution for the scenario with a disruption between 10:00 and 10:40. The approaching train service from line SPR6000 (in blue) has to wait for 17 min in station Htnc, until it can proceed and use a platform track in station Cl. The reason that the optimal solution does not suggest the early short-turning for this line is that it would have resulted in more cancelled services. As illustrated, more delay is observed in the third phase in comparison with experiment one. The main reason is that in this scenario, there is an unequal number of approaching train services from line SPR16000 (in orange) and scheduled departures in the opposite direction in station Cl. To be specific, there are two approaching train services and one scheduled departure in the opposite direction. Thus, the second approaching service is recognized as the recovery service and has to wait in Cl until the disruption is over by the time it arrives at Gdm and then it can resume the original train path with some delay. Similarly on the other side of disruption, there are two approaching train services from line IC800 (in light green) and one scheduled departure in the opposite direction in station Zbm. Thus, the second approaching train service has to depart from Zbm with some delay to arrive at Gdm after the disruption is over. In order to improve the third phase, it might be beneficial to resume the original timetable later so that the symmetrical condition is achieved. Fig. 14 shows the optimal short-turning solution for the scenario where resuming the original timetable occurs 13 min after the end of disruption. In this scenario, due to the equality between the number of approaching train services and the number of scheduled departure in the opposite direction, the third phase is rather smooth.

The results of experiment two are listed in Table 6. From the results, it is concluded that by resuming the original timetable later, the number of cancelled services is increased by 57% and the delay is reduced by 52%. Note that the cancelled services are limited to those computed by the model between Cl and Zbm, nonetheless the delay can propagate to stations located outside of the control area. Specially if there are alternative modes of transport in the disrupted area, cancelling a few more services might be more preferred by the train operator than introducing a delay to the network due to the asymmetrical condition. At the same time, different penalties could be considered to provide train operators with alternative solutions. Similar to the previous experiment the model computes the optimal solution quickly.

From this experiment it is concluded that in the proposed model which encompasses the transition phase back to normal operations, the disruption length plays an important role in determining the delay introduced in the final transition phase. The

Table 6
The results of experiment two.

Disruption period	Affected/total services	# Cancelled services	Delays (s) function	Obj.	Comp. time (s)
10:00 to 10:40	59/245	42	4020	292,980	0.19
10:00 to 10:53	74/281	66	1920	481,920	0.31

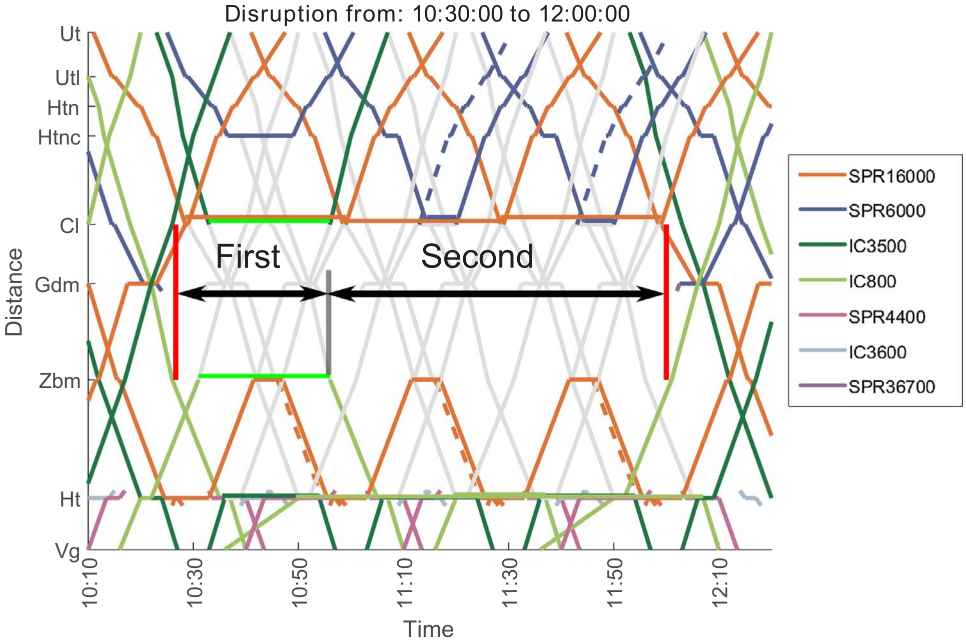

Fig. 15. Optimal short-turning solution for disruption from 10:30 to 12:00.

disruption period can determine whether there is a symmetrical or asymmetrical condition. It is observed that by resuming the original timetable later, it is possible to reach the symmetrical condition and hence the delay can be decreased at the cost of increasing the number of cancellations.

4.4. Experiment three: Measuring the three phases

The three phases of disruption can better be distinguished with longer disruption periods. In this experiment two scenarios (90 min and 100 min) are defined to show how different phases are measured.

The optimal short-turning solutions for the three phases are illustrated in Figs. 15 and 16. In both scenarios, the first phase lasts

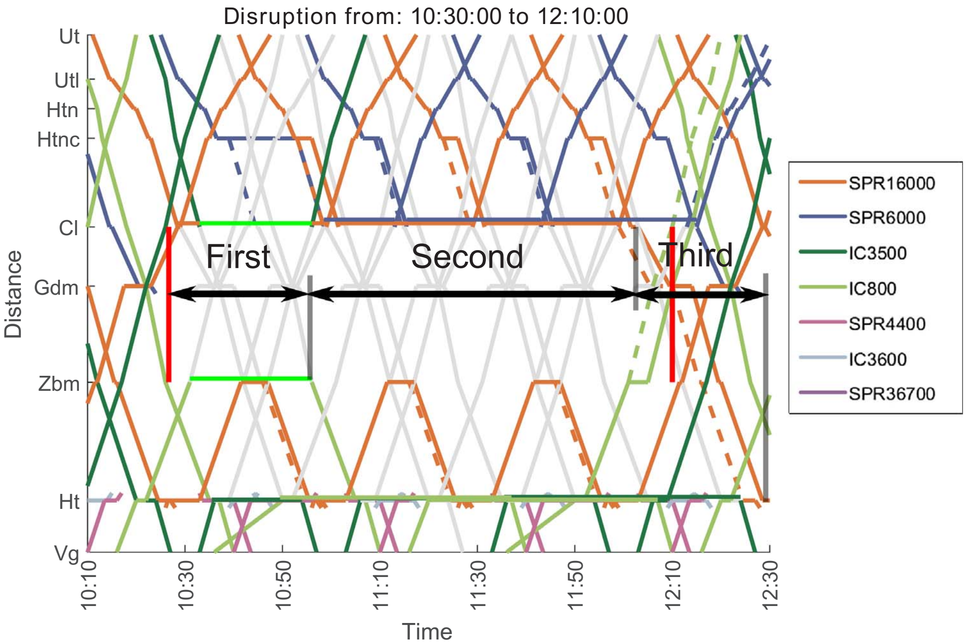

Fig. 16. Optimal short-turning solution for disruption from 10:30 to 12:10.

Table 7
Lengths of the three phases.

Scenario	First phase (s)	Second phase (s)	Third phase (s)
10:30 to 12:00	1560	3840	0
10:30 to 12:10	1560	4020	1560

until the latest departure of the first phase short-turnings. Thus, first phase ends with the departure of a service from line IC800 (in light green) from Zbm to Ht. The second phase starts at the same time point. During the second phase the services from lines SPR16000 (in orange), SPR6000 (in blue), IC3500 (in dark green), and IC800 (in light green) short-turn regularly. The second phase ends with the start of the third phase. Due to the symmetrical condition in the first scenario, there are no recovery services and thus the second phase ends at the end of the disruption. In this scenario the recovery is immediate.

In the second scenario, due to the asymmetrical condition, there are recovery services from both sides of the disruption. The second phase ends at the earliest departure of the recovery services which in this scenario is the departure of the recovery service from line SPR16000 (in orange). As defined in Section 3.5, the third phase lasts until the latest arrival of the recovery services at the short-turning stations. These measurements are listed in Table 7.

4.5. Experiment four: Increasing disruption lengths

In this experiment, the disruption start time is fixed and the disruption length is increased from one to five hours with intervals of 10 min. Figs. 17 and 18 show the optimal short-turning solution for two selected disruption lengths of 180 and 190 min, respectively. It is observed that in the second phase the short-turning of the intercity train services IC800 (in light green) and IC3500 (in dark green) at Ht and the local train service SPR16000 (in orange) in Zbm and Cl remain the same even though the disruption length is increasing. However, the optimal short-turning of the local train services from lines SPR6000 (in blue) changes. The reason this change for line SPR6000 occurs is that the disruption is located at the end of the line and the departures are scheduled slightly earlier than the arrivals. Since there is no train service arriving from the other side after the disruption then some services should be cancelled due to the lack of rolling stock in case there are more scheduled departures than approaching services.

In the symmetrical disruption scenarios, the departures would take place with some delay as the arrivals are after the scheduled departures. In the asymmetrical disruption scenarios, where a scheduled departure should be cancelled, the optimal solution would be to cancel the first scheduled departure so that the rest of departures can take place more on time. This results in alternation of the short-turning choice as the disruption length increases.

With increased disruption length, the short-turnings of line SPR16000 in Cl as shown in Fig. 17 repeats every 30 min (i.e. disruption end times at minutes 0, and 30). In between each half an hour (with disruptions ending at minutes 10, 20, 40, and 50), the short-turning choice shown in Fig. 18 occurs. The optimal solution for the third phase also repeats every half an hour. In other words,

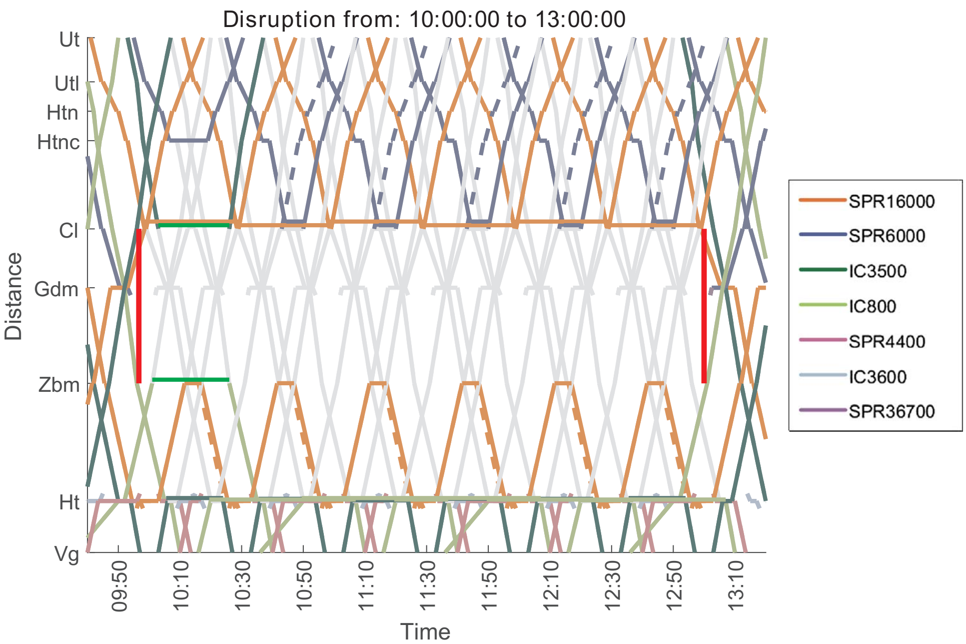

Fig. 17. Optimal short-turning solution for disruption from 10:00 to 13:00.

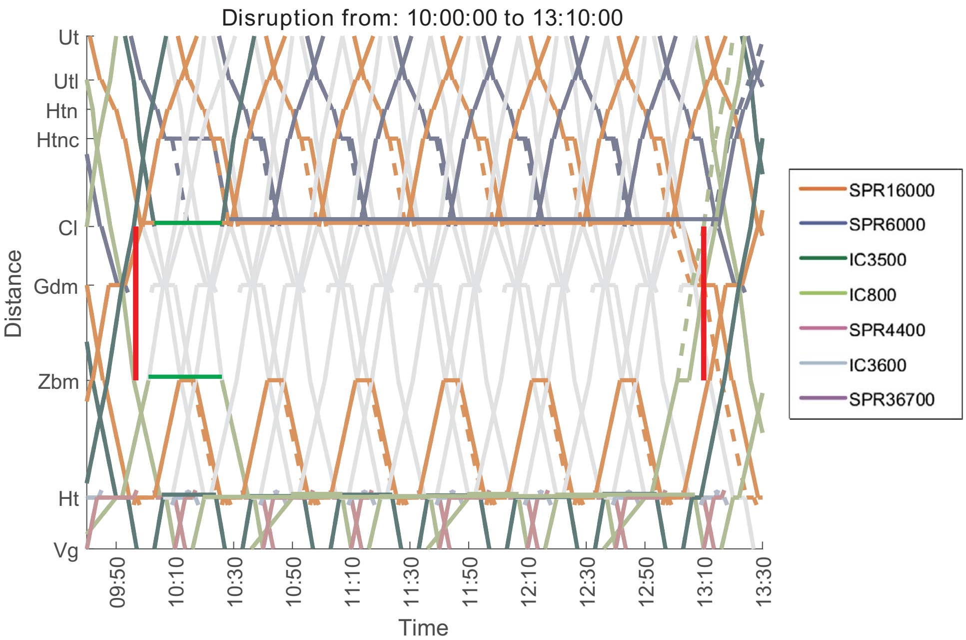

Fig. 18. Optimal short-turning solution for disruption from 10:00 to 13:10.

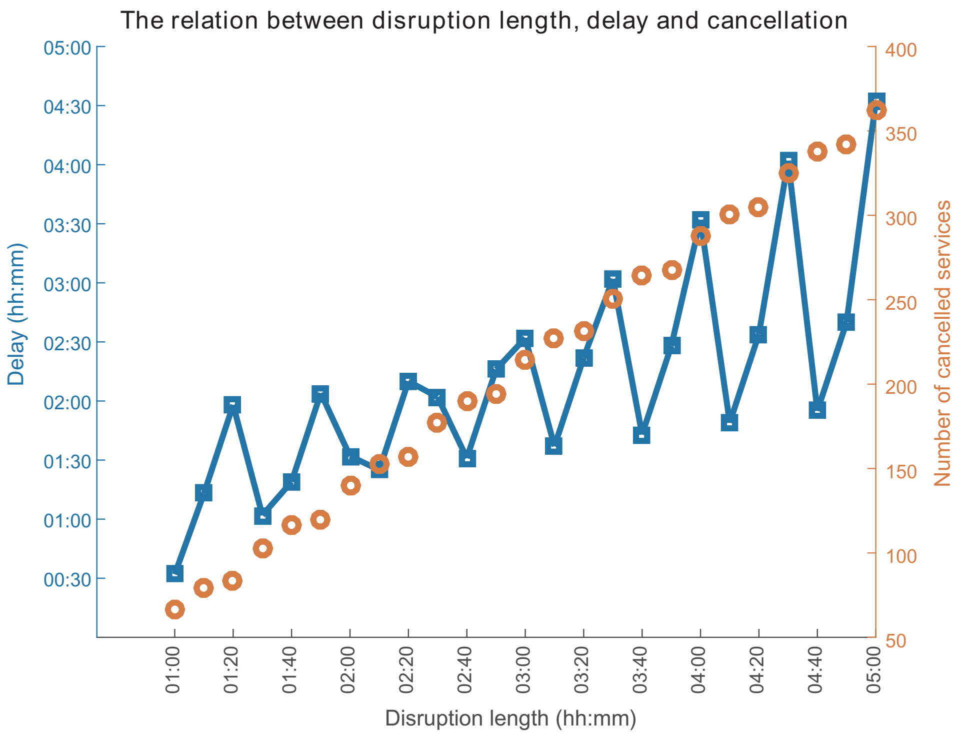

Fig. 19. The relation between the disruption length, delay and number of cancelled services.

the recovery plans for disruptions ending at minutes 10 and 40 are the same. This similarity is also valid for disruption periods ending at minutes 20 and 50 as well as minutes 0 and 30.

The relation between the disruption length, delay and number of cancelled services is illustrated in Fig. 19. As expected, the number of cancelled services (represented by red circles) steadily increases for increasingly longer disruptions. The delay, which is plotted by the blue line, is also increasing with some oscillation. Interestingly, the extent of oscillation grows with disruption length. The peaks in the delay line are the results of waiting for the end of the disruption that occurs in the third phase. It is therefore

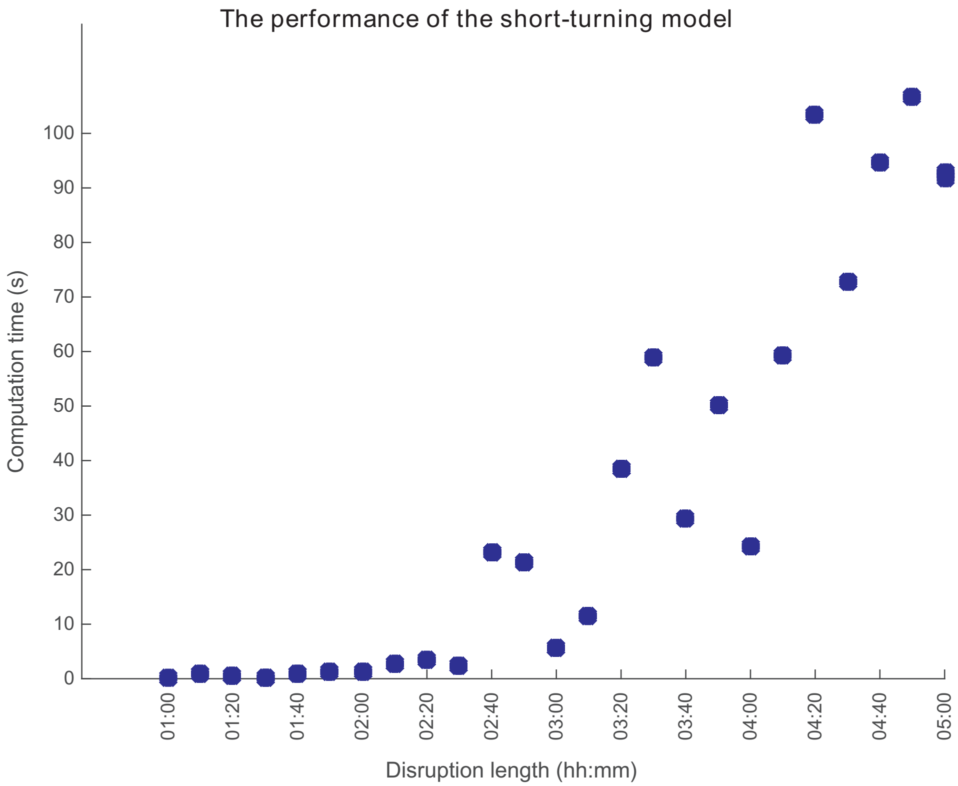

Fig. 20. The computation time of the short-turning model.

concluded that in case of long disruptions corresponding to the peaks, by minor extension of the disruption length, the delay can be reduced considerably at the cost of an increase in the number of cancellations.

The real-time applicability of the model depends on the computation time. Fig. 20 shows the computation time of the short-turning model for given different disruption lengths. It is observed that computing the disruption timetable and the transition plans for a period of three hours for such a busy corridor takes less than 10 s. The computation time of a new timetable for a disruption period up to five hours takes less than two minutes.

5. Conclusion

In this paper, a MILP model is proposed to compute the disruption timetable and the transition plans for complete blockages based on the disruption period. In this formulation, the rescheduling measures of short-turning, partial cancellation, and re-timing are applied on the traffic on both sides of the disrupted location. Depending on the available rolling stock and infrastructure capacity, the short-turnings can take place in multiple stations. Given the disruption period, different services might need to be short-turned on each side of the blockage. The number of short-turning train services on both sides can be either equal (symmetrical) or unequal (asymmetrical) depending on the disruption period. In the asymmetrical scenarios, the extra train services need to wait until the end of the disruption and then proceed and operate on the recently resolved track section. This waiting will postpone the recovery back to the original timetable.

The model is applied to a dense Dutch railway corridor. Several experiments revealed the importance of the disruption period (the start time and the disruption length) in the optimal short-turning solution. The computation time is promising for real-time application. It is concluded that different disruption periods can result in different optimal short-turning choices. Depending on the disruption start time, different services might be affected during the first phase, which would result in different transition plans. Given a certain disruption start time, different disruption lengths can also result in different transition plans for the third phase. The optimal short-turning choice during the second phase can alternate depending on the disruption length. This alternation is due to the symmetrical and asymmetrical conditions for the lines without traffic interaction from both sides of the blockage and those whose scheduled departures are earlier than the arrivals at the short-turning stations. In addition, these choices repeat as the disruption length increases. Since the original timetable is periodic, for a long enough disruption length a periodic pattern will emerge that fits in the periodic timetable of the (undisrupted) rest of the network. The transitions between the three steady-states of the normal (1st and 3rd phase) and disrupted (2nd phase) period timetable will largely determine the periodic pattern during the 2nd phase, which in turn depends on the start and end times of the disruption as shown in the fourth experiment. In asymmetrical scenarios, the delay can be decreased by resuming the original timetable later than the end of disruption to reach the symmetrical condition. However, resuming the original timetable later will lead to more cancelled services. Therefore a rule is necessary to make a trade-off between the number of cancelled services and the delay.

Currently, the model cannot suggest the shortest time required after the end of disruption to reach the symmetrical condition. Finding this time point given the disruption start time would be a next research direction. Another direction is to investigate the optimal short-turning solutions with uncertain disruption lengths. With minor adjustments, the model can be applied on disruption cases of open track blockages. It is also interesting to use a microscopic short-turning model to improve the accuracy of the capacity allocation in the short-turning stations.

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References

Binder, S., Maknoon, Y., Bierlaire, M., 2017. The multi-objective railway timetable rescheduling problem. Transp. Res. Part C: Emerg. Technol. 78, 78–94.
Cacchiani, V., Caprara, A., Galli, L., Kroon, L., Maróti, G., Toth, P., 2012. Railway rolling stock planning: Robustness against large disruptions. Transp. Sci. 46 (2), 217–232.
Cacchiani, V., Huisman, D., Kidd, M., Kroon, L., Toth, P., Veelenturf, L., Wagenaar, J., 2014. An overview of recovery models and algorithms for real-time railway rescheduling. Transp. Res. Part B: Methodol. 63, 15–37.
Caimi, G., Fuchsberger, M., Laumanns, M., Luthi, M., 2012. A model predictive control approach for discrete-time rescheduling in complex central railway station areas. Comput. Oper. Res. 39 (11), 2578–2593.
Chu, F., Oetting, A., 2013. Modeling capacity consumption considering disruption program characteristics and the transition phase to steady operations during disruptions. J. Rail Transp. Plann. Manage. 3, 54–67.
Coor, G.T., 1997. Analysis of the short-turning strategy on high-frequency transit lines by. Tech. rep., Massachusetts Institute of Technology.
Ghaemi, N., Cats, O., Goverde, R.M.P., 2017a. A microscopic model for optimal train short-turnings during complete blockages. Transp. Res. Part B: Methodol. 105, 423–437.
Ghaemi, N., Cats, O., Goverde, R.M.P., 2017b. Railway disruption management challenges and possible solution directions. Public Transp. 9 (1), 343–364.
Ghaemi, N., Goverde, R.M.P., Cats, O., 2016. Railway disruption timetable: Short-turnings in case of complete blockage. In: 2016 IEEE International Conference on Intelligent Rail Transportation (ICIRT). pp. 210–218.
Hirai, C., Tomii, N., Tashiro, Y., Kondou, S., Fujimori, A., 2006. An algorithm for train rescheduling using rescheduling pattern description language R. Comput. Railways X 1, 551–561.
Jespersen-groth, J., Potthoff, D., Clausen, J., Huisman, D., Kroon, L., 2009. Disruption management in passenger railway transportation, pp. 399–421.
Löfberg, J., 2004. Yalmip: A toolbox for modeling and optimization in matlab. In: In Proceedings of the CACSD Conference. Taipei, Taiwan.
Louwerse, I., Huisman, D., 2014. Adjusting a railway timetable in case of partial or complete blockades. Eur. J. Oper. Res. 235 (3), 583–593.
Meng, L., Zhou, X., 2011. Robust single-track train dispatching model under a dynamic and stochastic environment: a scenario-based rolling horizon solution approach. Transp. Res. Part B 45 (7), 1080–1102.
Nakamura, T., Hirai, C., Nishioka, Y., 2011. A practical train rescheduling algorithm using three predetermined factors. Tech. rep.
Narayanaswami, S., Rangaraj, N., 2013. Modelling disruptions and resolving conflicts optimally in a railway schedule. Comput. Indust. Eng. 64 (1), 469–481.
Nielsen, L.K., Kroon, L., Maróti, G., 2012. A rolling horizon approach for disruption management of railway rolling stock. Eur. J. Oper. Res. 220 (2), 496–509.
Pellegrini, P., Marlière, G., Rodriguez, J., 2014. Optimal train routing and scheduling for managing traffic perturbations in complex junctions. Transp. Res. Part B: Methodol. 59, 58–80.
Samá, M., Pellegrini, P., D’Ariano, A., Rodriguez, J., Pacciarelli, D., 2017. On the tactical and operational train routing selection problem. Transp. Res. Part C: Emerg. Technol. 76, 1–15.
Shen, S., Wilson, N.H., 2001. An optimal integrated real-time disruption control model for rail transit systems. In: Computer-aided Scheduling of Public Transport. Springer, Berlin, pp. 335–363.
van Zon, F., Wink, M., 2014. Lean transformation: Communication during disruptions. Tech. rep., ProRail.
Veelenturf, L.P., Kidd, M.P., Cacchiani, V., Kroon, L.G., Toth, P., 2016. A railway timetable rescheduling approach for handling large-scale disruptions. Transp. Sci. 50 (3), 841–862.
Veelenturf, L.P., Kroon, L.G., Maróti, G., 2017. Passenger oriented railway disruption management by adapting timetables and rolling stock schedules. Transp. Res. Part C: Emerg. Technol. 80, 133–147.
Wagenaar, J., Kroon, L., Fragkos, I., 2017. Rolling stock rescheduling in passenger railway transportation using dead-heading trips and adjusted passenger demand. Transp. Res. Part B: Methodol. 101, 140–161.
Xu, P., Corman, F., Peng, Q., Luan, X., 2017. A train rescheduling model integrating speed management during disruptions of high-speed traffic under a quasi-moving block system. Transp. Res. Part B: Methodol. 104, 638–666.
Zhan, S., Kroon, L.G., Veelenturf, L.P., Wagenaar, J.C., 2015. Real-time high-speed train rescheduling in case of a complete blockage. Transp. Res. Part B: Methodol. 78, 182–201.
Zhan, S., Kroon, L.G., Zhao, J., Peng, Q., 2016. A rolling horizon approach to the high speed train rescheduling problem in case of a partial segment blockage. Transp. Res. Part E: Logist. Transp. Rev. 95, 32–61.
Zilko, A.A., Kurowicka, D., Goverde, R.M., 2016. Modeling railway disruption lengths with copula bayesian networks. Transp. Res. Part C: Emerg. Technol. 68, 350–368.