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A microscopic model for optimal train short-turnings during complete blockages

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Abstract

Currently railway traffic controllers use predefined solutions (contingency plans) to deal with a disruption. These plans are manually designed by expert traffic controllers and are specific to a certain location and timetable. With a slight change in the timetable or infrastructure, these plans might not be feasible and have to be updated. Instead traffic controllers can benefit from algorithms that can quickly compute an optimal solution given a disruption specification. This paper presents a Mixed Integer Linear Programming model to compute a disruption timetable when there is a complete blockage and no train can use part of the track for several hours. The model computes the optimal short-turning stations, routes and platform tracks. In this approach short-turning as a common practice in case of complete blockages is modelled at a microscopic level of operational and infrastructural detail to guarantee feasibility of the solution. To demonstrate the functionality and applicability of the model two case studies are performed on two Dutch railway corridors. In the first case, four experiments are presented to show how different priorities can change the optimal solution including the order of services and the choice of short-turning station. In the second case the performance of the model on a big station is investigated. It is shown that the model can compute the optimal solution in a short time.

Keywords: Microscopic optimization, Railway disruption, Rescheduling, Short-turning

1. Introduction

Railway operations are prone to unplanned events such as infrastructure failure or incidents. A timetable is designed to recover from small delays. However, in case of events that can lead to the blockage of a track section for several hours, the resources need to be rescheduled. Trains approaching the blockage cannot proceed with their original plans and have to short-turn at a station close to the disruption. Simultaneously, trains from the opposite direction are not able to pass the blockage and provide services further.

A common practice in case of complete blockages in railway operation is to short-turn trains. Short-turning is a measure that uses the arriving trains at a station before a disruption area to perform services in the opposite direction for which the trains could not reach the station from the other side of the disruption. The short-turning measure prevents the congestion of trains in the stations close to the disrupted area by maintaining the rolling stock circulation in the network. Providing services in the opposite direction can isolate the disrupted area by reducing delay propagation to the neighbouring stations.

To provide support for the traffic controllers, predefined solutions are generally used. These solutions which are called contingency plans are common practice in many countries such as the Netherlands, Germany, Switzerland, Denmark and Japan as pointed out by Chu and Oetting (2013). The solution provided by a contingency plan consists of cancelled, rerouted or short-turned services including the arrival and departure times and platform tracks. Obviously each contingency plan is designed for a specific location and a specific timetable.

The contingency plans are designed manually, therefore the suggested solution might not be optimal. For example the suggested solution does not always consider the operational constraints such as minimum short-turning time which

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eventually would result in an infeasible solution. Moreover they are not sufficiently detailed on the infrastructure allocation and they cannot cover all possible disruption scenarios throughout the entire network. Changes in the timetable or the infrastructure require an updated contingency plan. In case there is no relevant contingency plan, the traffic controllers have to deal with the disruption without any support. Therefore there is a need to develop an algorithm that is able to compute an optimal rescheduling solution in real-time.

There are several macroscopic rescheduling approaches proposed by Louwerse et al. (2014), Zhan et al. (2015) and Veelenturf et al. (2016). However providing a feasible solution requires a microscopic representation of the infrastructure and operation. Ghaemi et al. (2017) show the importance of employing microscopic models for rescheduling in case of disruptions. As Cacchiani et al. (2014) and Ghaemi et al. (2017) conclude, there are very few references that model disruptions at the microscopic level. The existing microscopic models can also be classified based on the covered level of detail. By doing so it is observed that none of the existing models such as Hirai et al. (2009) and Corman et al. (2011) provide a comprehensive solution with a sufficient level of detail for the entire disruption period. Pellegrini et al. (2014) developed a microscopic optimization model that provides rescheduling and rerouting solutions for railway disturbance management. The model computes the optimal route choice for each service by calculating the track section occupation based on the blocking time model (Hansen and Pachl (2008)). The advantage of this model is that the simultaneous occupation of each track section is avoided by defining an order variable. Unlike other microscopic rescheduling models such as Caimi et al. (2011) and Lusby et al. (2011) there is no need for pre-processing the track occupation for detecting any conflict.

To deal with disruptions of a complete blockage Ghaemi et al. (2016) propose a short-turning optimization model in which the arriving trains at the final station (before disruption) are assigned to the scheduled departures in the opposite direction. The final station before disruption is referred to as the primary short-turning station. The model allows the possibility for short-turning not only at the primary short-turning station, but also at a preceding station which represents the secondary short-turning station. Two main limitations of this model are that it excludes the possibility of reordering services and the infrastructure and operation are not considered at the microscopic level of detail. Fixed order can impose unnecessary restriction on the solution. For example by fixing the operation order of two train services from local and intercity lines might result in a situation where the intercity train is delayed because the preceding local train is delayed. While this can be avoided by considering a flexible order. The model proposed by Ghaemi et al. (2016) does not include the infrastructure and operation details and only computes the arrivals and departures. Thus based on these arrivals and departures the position of the trains along the routes can be roughly estimated. However in order to detect possible conflicts, it is necessary to know the precise running of the trains on track section level. Formulating the infrastructure and operation with a fine level of detail is essential to understand the real capacity. To give an example, in case of short-turnings, knowing the number of platform tracks in the station is not sufficient to compute a feasible solution. Although each platform track can be assigned to one short-turning at a time, but there might be conflicts with other trains in the inbound and outbound routes to and from the station. A conflict can be resolved by either rerouting or rescheduling the operation. Thus it is important to carefully take into account the movements of the trains specially in the short-turning stations.

The contribution of this study is a rescheduling model that selects the optimal short-turning stations, in/out bound routes and platform sections for all the services including the short-turning trains. In this paper we adopt the microscopic rescheduling model by Pellegrini et al. (2014) and extend it with the short-turning possibility introduced by Ghaemi et al. (2016) for the case of a complete blockage. In this way the limitations of the model by Ghaemi et al. (2016) are removed as the microscopic model takes into account the reordering possibility and represents the infrastructure and operation with fine level of detail. The extended MILP model computes optimal rerouting and rescheduling solutions for cases of complete blockages where all the approaching trains towards the blockage need to short-turn. Moreover some services might need to be cancelled. A key assumption of this extension is that a reliable disruption length estimate is available. There are different approaches to estimate the disruption length such as the one developed by Zilko et al. (2016) using Copula Bayesian Network. Within the disruption period, the arriving trains should be short-turned and assigned to the departing schedules in the opposite direction. The extended part includes the choice of short-turning taking into account the operational constraints such as minimum short-turning time. In other words, the model determines which scheduled departing service in the opposite direction is being performed by each approaching train. Since all the approaching trains to the disrupted area need to short-turn, there might not be enough capacity in the primary short-turning station. For this reason the possibility of short-turning at a secondary station is included. Although an early short-turning implies more service cancellations, it can result in less total delay.

The remaining of the paper is structured as follow: in Section 2, first the macro short-turning model and the micro rescheduling model are described briefly and then the formulation of the integrated model is presented. Section 3 shows the application of the model on two Dutch railway corridors and finally Section 4 discusses the conclusions.

2. Microscopic short-turning formulation

In this section, the mathematical formulation of the microscopic short-turning model is presented. As addressed previously, the microscopic short-turning model is partly based on the short-turning model introduced by Ghaemi et al. (2016) and partly based on the microscopic rescheduling model developed by Pellegrini et al. (2014). Before describing each model it is necessary to define the notation used in this model. The notation is listed in Table 1.

2.1. Short-turning decisions

The main task of the short-turning model is to assign the arriving trains to the scheduled departures in the opposite direction. It is common to short-turn the arriving services as the scheduled departure services from the same line. So there should be a distinction between services from different lines. In addition to the line indicator it is also required to know the time of the operation and the order of the service within the line. Thus within the short-turning model each service v is defined with three indicators $v^i_{l,n}$ where l represents the line number, n represents the operation time and i indicates the sequence of the service within the line l. To give an example, Figure 1 shows a time-distance diagram for a disruption scenario between stations a and b. The services running downwards to the disrupted area cannot operate further than station a. Thus, they can either short-turn at the primary short-turning station a or at the secondary short-turning station a'. As shown with red arcs, the short-turning possibilities for the approaching service $v^i_{l,n}$ in station a' are the three scheduled departures $v^j_{l,m}$,$v^j_{l,o}$ or $v^j_{l,r}$ in the opposite direction. In case service $v^i_{l,n}$ short-turns in station a', it is called an early short-turning. Each early short-turning leads to cancellation of two services. In this example if service $v^i_{l,n}$ short-turns as $v^j_{l,m}$, then services $v^{i+1}_{l,n}$ and $v^{j-1}_{l,m}$ need to be cancelled. Alternatively service $v^i_{l,n}$ can continue as service $v^{i+1}_{l,n}$ and short-turn as either services $v^{j-1}_{l,m}$, $v^{j-1}_{l,o}$ or $v^{j-1}_{l,r}$. Obviously in this example one of the scheduled departures needs to be cancelled as there are two arriving trains and three scheduled departures. In case service $v^{i+1}_{l,n}$ short-turns as service $v^{j-1}_{l,m}$, the departure of this service will be delayed as the arrival of service $v^{i+1}_{l,n}$ is taking place after the scheduled departure of service $v^{j-1}_{l,m}$.

The short-turning model requires a preprocessing phase to make a distinction between the arriving services and scheduled departures in the opposite direction. In this phase the approaching services towards the disruption area that are arriving at station h within the disruption period are identified as V'_h. Note that station h is either the primary short-turning station which is noted as h_a or it can be the secondary short-turning station noted as $h_{a'}$. These two stations are called short-turning stations and are referred as H_{sht}. The scheduled departures in the opposite direction that depart from station h within the disruption period are identified as V''_h. Similarly station h can either represent the primary or the secondary short-turning station. The short-turning possibilities for each approaching service $v^i_{l,n}$ are identified as $Pair_{v^i_{l,n},*}$ where $*$ represents several possibilities for scheduled departures. And $Pair_{*,v^j_{l,m}}$ represents all the arriving services possibilities for the scheduled departure $v^j_{l,m}$.

2.2. Microscopic rescheduling model

Here a brief review of the microscopic rescheduling model is given as it has been extensively described by Pellegrini et al. (2014). In this model, each service has a set of alternative routes between its departure and arrival stations to select from. Each route might consist of several block sections and each block section might consist of several track sections. The input of the model contains the running time of each service on each track section and the original timetable. The objective of the model is to minimize the deviation of the computed timetable from the original timetable. The blocking time model mentioned by Hansen and Pachl (2008) is used to formulate the capacity consumption. In this approach the conflicts are avoided by computing an order variable that prevents simultaneous track utilization.

Table 1: The notation used in the microscopic model

H	The set of stations h.
S	The set of track sections s.
P	The set of platform tracks p.
B	The set of block sections b.
R	The set of routes r.
L	The set of lines l.
V	The set of scheduled services.
SI	The set of track sections in the interlocking area.
SO	The set of track sections in the open track.
S_v	The set of all track sections that can be used by service v.
R_v	The set of all routes that can be used by service v.
$R_{v,s}$	The set of all routes that can be used by v and contain section s.
H_v	The set of departure and arrival stations of service v.
τ_v^d	The scheduled departure time of service v.
τ_v^a	The scheduled arrival time of service v.
h_v^a	The arrival station of service v.
h_v^d	The departure station of service v.
s_O	The virtual track section that represents the start of each route.
s_D	The virtual track section that represents the end of each route.
$p_{r,s}$	The previous track section of s along the route r.
$f_{r,s}$	The following track section of s along the route r.
$u_{r,s}$	The last track section of the block including track section s along route r
$t_{v,r,s}^{run}$	The running time of train v on the track section s along the route r.
S^r	The ordered set of all track sections of route r.
B_r	The ordered set of all block sections composing route r.
$S_{r,b}$	The ordered set of all track sections composing block section b along route r.
$\theta_{v',v''}^{min}$	The minimum short-turning time needed for service v'.
$\delta_{v,\hat{v}}$	The dwell time between the arrival of v and departure of $\hat{v}$.
$q_{r,s}$	The first track section of the previous block of section s along the route r.
t^r	The time needed for signal sight and reaction.
t^s	The switching time needed for release and setup the track section.
t^c	The clearing time.
ω_v^c	The penalty for cancelling service v.
ω_v^d	The penalty for delaying the arrival of service v.
$f(v, \hat{v})$	Indicator: 1 if $\hat{v}$ uses the same rolling stock as v after v in the same direction.
M	A sufficiently large constant.
$V_l \subset V$	The set of services in line l in both directions.
$V_{l,n} \subset V$	The n^{th} set of ordered services in line l.
$v_{l,n}^i$	The i^{th} service in set $V_{l,n}$.
h_a	The primary short-turning station.
$h_{a'}$	The secondary short-turning station.
H_{sht}	The short-turning stations (h_a and $h_{a'}$).
L_{Dist}	The lines that are affected by the disruption.
V_h'	The services approaching the disruption with arrival station at h.
V_h''	The services moving away from the disruption with departure at h.
$Pair_{v_{l,n}^i,*}$	The set of all possible scheduled departures that can be performed by $v_{l,n}^i$.
$Pair_{*,v_{l,m}^j}$	The set of all possible arriving services that can be short-turned to $v_{l,m}^j$.
$Pair_{l,h}$	The short-turning pairs for line l in station h.
$Pair_h$	All the short-turning pairs in station h.

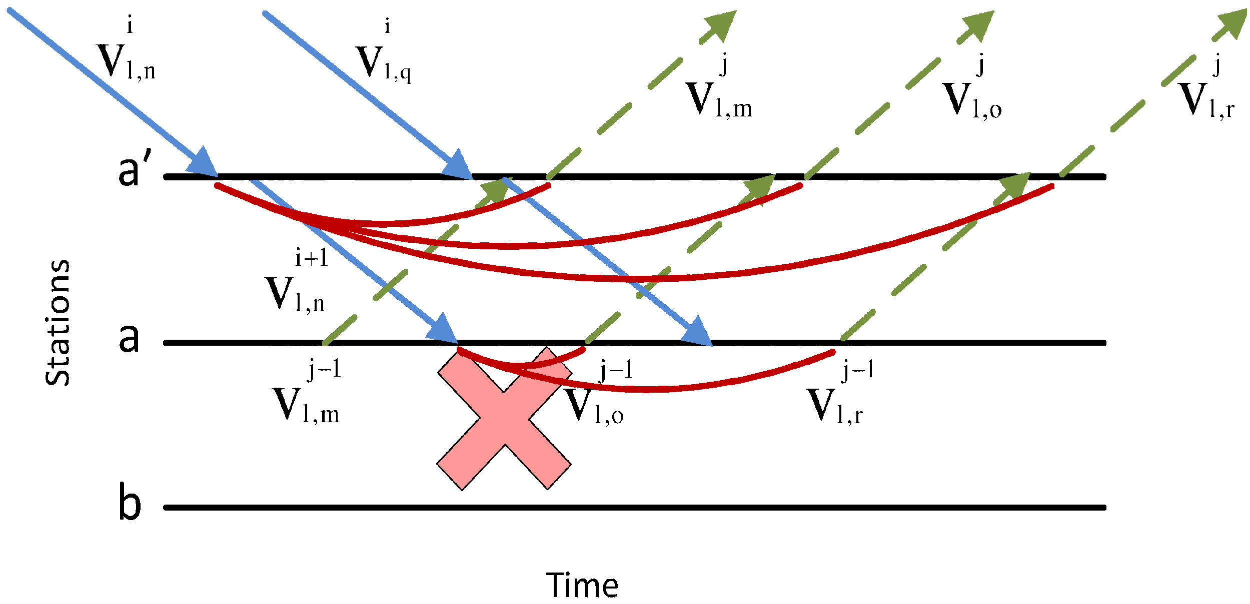

Figure 1: The possible short-turnings either at the primary or at the secondary short-turning station.

2.3. Mathematical formulation of the microscopic short-turning model

In this section, the mathematical formulation of the extended model is presented. The aim of the extended model is to compute a disruption timetable that is feasible at the microscopic level of detail. The disruption timetable is developed based on short-turning decisions. Thus, the short-turning of services is microscopically formulated. In addition to minimizing delay, the second objective is to minimize the number of cancelled services. The output of the model provides the optimal inbound and outbound routes for each short-turning in either of the short-turning stations. The decision variables are introduced in Table 2. The extended parts that are mostly described in Section 2.3.1 can be distinguished by the short-turning ($\lambda_{v',v''}$) and cancellation (c_v) decisions.

Table 2: The decision variables

$x_{r,v}$	If route r is selected for service v then $x_{r,v} = 1$, otherwise $x_{r,v} = 0$
$y_{v,\bar{v},s}$	If service v uses section s before service $\bar{v}$, then $y_{v,\bar{v},s} = 1$, otherwise $y_{v,\bar{v},s} = 0$.
$e_{v,r,s}$	The time when service v enters track section s along the route r.
$b^s_{v,s}$	The start of the blocking time of track section s for service v.
$b^e_{v,s}$	The end of the blocking time of track section s for service v.
d_v	The arrival delay of service v.
c_v	If service v is cancelled, then $c_v = 1$, otherwise $c_v = 0$
$\lambda_{v',v''}$	If service v' short-turns as v'' then $\lambda_{v',v''} = 1$, otherwise $\lambda_{v',v''} = 0$.

The objective is to minimize the weighted sum of delays and cancelled services:

$$\min \sum_{v \in V} \omega^c_v \cdot c_v + \sum_{v \in V} \omega^d_v \cdot d_v. \tag{1}$$

2.3.1. Short-turning constraints

The short-turning constraints are given as follows.

$$\sum_{(v',v'')\in Pair^h_{v^i_{l,n},*} \cup Pair^h_{v^{i+1}_{l,n},*}} \lambda_{v',v''} = 1, \qquad \forall v^i_{l,n} \in V'_{h_{a'}}, \tag{2}$$

$$\sum_{(v',v'')\in Pair_{*,v^j_{l,m}} \cup Pair_{*,v^{j-1}_{l,m}}} \lambda_{v',v''} + c_{v^j_{l,m}} = 1, \qquad \forall v^j_{l,m} \in V''_{h_{a'}}, \tag{3}$$

$$c_{v^j_{l,m}} \leqslant c_{v^{k+1}_{l,m}}, \qquad \forall v^j_{l,m} \in V''_{h_{a'}}, k \in [j, |l| - 1], \tag{4}$$

$$\sum_{(v',v'')\in Pair_{v^i_{l,n},*}} \lambda_{v',v''} = c_{v^{i+1}_{l,n}}, \qquad \forall v^i_{l,n} \in V'_{h_{a'}}, \tag{5}$$

$$\sum_{(v',v'')\in Pair^h_{*,v^j_{l,m}}} \lambda_{v',v''} + c_{v^j_{l,m}} = c_{v^{j-1}_{l,m}}, \qquad \forall v^j_{l,m} \in V''_{h_{a'}}, \tag{6}$$

$$(1 - \lambda_{v',v''}) \cdot M + \sum_{r\in R_{v''}} e_{v'',r,s_0} \geqslant \sum_{r\in R_{v'}} e_{v',r,s_D} + \theta^{min}_{v,v'} \cdot x_{r,v'}, \qquad \forall (v', v'') \in Pair_h, h \in H_{sht}, \tag{7}$$

$$\sum_{r\in R_{v',s}} x_{r,v'} \leqslant \sum_{r\in R_{v'',s}} x_{r,v''} + (1 - \lambda_{v',v''}) \cdot M, \qquad \forall (v', v'') \in Pair_h, h \in H_{sht}, s \in P, \tag{8}$$

$$\sum_{r\in R_{v'',s}} x_{r,v''} \leqslant \sum_{r\in R_{v',s}} x_{r,v'} + (1 - \lambda_{v',v''}) \cdot M, \qquad \forall (v', v'') \in Pair_h, h \in H_{sht}, s \in P, \tag{9}$$

$$\sum_{r\in R_{v'',s}:p_{r,s}=s_O} b^s_{v'',s} < \sum_{r\in R_{v',s}:f_{r,s}=s_D} b^e_{v',s} + (1 - \lambda_{v',v''}) \cdot M, \qquad \forall (v', v'') \in Pair_h, h \in H_{sht}. \tag{10}$$

Constraints (2) ensure that all the services that approach the disruption area, should short-turn in either short-turning stations. Each scheduled departure $v^j_{l,m}$ in the opposite direction can take place if there is an arriving service assigned to it in either station of H_{sht}. Otherwise, as shown in constraints (3) the scheduled service $v^j_{l,m}$ needs to be cancelled. If a scheduled departure $v^j_{l,m}$ is cancelled, all the following services $v^{j+1}_{l,m}$, $v^{j+2}_{l,m}$,...etc. need to be cancelled. This is ensured by constraints (4). In case service $v^i_{l,n}$ is short-turned in the secondary short-turning station, the following service $v^{i+1}_{l,n}$ that was planned to continue in the same direction, has to be cancelled, $c_{v^{i+1}_{l,n}} = 1$. Short-turning in the secondary short-turning station also means that there should be another cancelled service. If service $v^j_{l,m}$ is the result of short-turning service $v^i_{l,n}$, then service $v^{j-1}_{l,m}$ should be cancelled. Constraints (5) and (6) formulate these cancellations. The departure times of the short-turned trains should respect the minimum short-turning time. Constraints (7) ensure the minimum short-turning time. Here the big M method is used to model the different possibilities of short-turning. Constraints (8) and (9) guarantee that the short-turned trains are departing from the same platform that is used for the arrival. To model the capacity, the blocking time for each track section is considered. The start and end time of each blocking time are represented by $b^s_{v,s}$ and $b^e_{v,s}$. In case of a short-turning the relevant track section of the platform track should be kept occupied. Hence, the start of the blocking time of the block section for the departing train should take place before the end of the blocking time for the arriving train. This is formulated by constraints (10).

2.3.2. Extended microscopic rescheduling constraints

The rest of the constraints are extended to incorporate the trains short-turnings.

$$\sum_{r\in R_v} x_{r,v} + c_v = 1, \qquad \forall v \in V, \tag{11}$$

$$e_{v,r,s} \leqslant M \cdot x_{r,v}, \qquad \forall v \in V, r \in R_v, s \in S_r, \tag{12}$$

$$e_{v,r,s} \geqslant \tau_v^d \cdot x_{r,v}, \qquad \forall v \in V, r \in R_v, s \in S_r, \tag{13}$$

$$e_{v,r,s} = e_{v,r,p_{r,s}} + t^{run}_{v,r,p_{r,s}} \cdot x_{r,v}, \qquad \forall v \in V, r \in R_v, s \in S_r, \tag{14}$$

$$d_v = \sum_{r\in R_v} e_{v,r,s_D} - \tau_v^a \cdot (1 - c_v), \qquad \forall v \in V, \tag{15}$$

$$c_{\hat{v}} \cdot M + \sum_{r\in R_{\hat{v}}} e_{\hat{v},r,s_O} \geqslant \sum_{r\in R_v} e_{v,r,s_D} + \delta_{v,\hat{v}} \cdot x_{r,v}, \qquad \forall v, \hat{v} \in V : f(v,\hat{v}) = 1, \tag{16}$$

$$\sum_{r\in R_{\hat{v},s}:p_{r,s}=s_O} b^s_{\hat{v},s} - c_{\hat{v}} \cdot M \leqslant \sum_{r\in R_{v,s}:f_{r,s}=s_D} b^e_{v,s} + c_v \cdot M, \qquad \forall v, \hat{v} \in V : f(v,\hat{v}) = 1, \tag{17}$$

$$\sum_{r\in R_{v,s}} x_{r,v} - c_v \cdot M \leqslant \sum_{r\in R_{\hat{v},s}} x_{r,\hat{v}} + c_{\hat{v}} \cdot M, \qquad \forall v, \hat{v} \in V : f(v,\hat{v}) = 1, s \in P, \tag{18}$$

$$\sum_{r\in R_{\hat{v},s}} x_{r,\hat{v}} - c_{\hat{v}} \cdot M \leqslant \sum_{r\in R_{v,s}} x_{r,v} + c_v \cdot M, \qquad \forall v, \hat{v} \in V : f(v,\hat{v}) = 1, s \in P. \tag{19}$$

For each running service, exactly one route should be assigned as formulated by constraints (11). Constraints (12) make sure that the entrance time for all the track sections related to the unselected routes are zero. The entrance time of train v on track section s along the selected route r should at least be equal to the scheduled departure time τ_v^d. This is taken into account by constraints (13). The entrance time for each track section along the route can be computed by the sum of the entrance time of the previous track section and the running time on the previous track section. For this reason the constraints (14) are considered. The arrival delay of each service is formulated by constraints (15) which measure the difference between the actual arrival time $e_{v,r,s_{D,r}}$ and the scheduled arrival time τ_v^a.

If service $\hat{v}$ uses the same rolling stock as service v after service v has been completed in the same direction, then the dwell time, platform occupation and the platform choice consistency should be taken into account for the pair $(v, \hat{v})$. Constraints (16) make sure that the entrance time of the departing service $\hat{v}$ in the first track section of its selected route should respect the dwell time after the arrival of service v. During the dwell time, the selected platform track should be occupied. Thus, constraints (17) extend the start time of the selected platform track blocking time of the departing service $\hat{v}$, in order to block this platform track section during the dwell time. Each platform track can be the first track section of several outbound routes and the final track section of several inbound routes. The selected outbound route for the departing service $\hat{v}$ should correspond to the selected inbound route for the arriving service v. This platform choice consistency is modelled through constraints (18) and (19).

$$b^s_{v,s} = \sum_{r\in R_{v,s}} (e_{v,r,q_{r,s}} - t^r x_{r,v}),$$

$$\forall v \in V,\ s \in S_v : (v \notin V''_h, h \in H_{sht}), (\nexists \hat{v} \in V : f(v,\hat{v}) = 1) \vee (\forall r \in R_v : q_{r,s} \neq f_{r,s_O}), \tag{20}$$

$$b^s_{v,s} \leqslant \sum_{r\in R_{v,s}} (e_{v,r,q_{r,s}} - t^r x_{r,v}),$$

$$\forall v \in V, s \in S_v, : (v \in V''_h, h \in H_{sht}), (\exists \hat{v} \in V : f(v,\hat{v}) = 1), (\forall r \in R_v : q_{r,s} = f_{r,s_O}), \tag{21}$$

$$b^e_{v,s} = \sum_{r \in R_{v,s}} (e_{v,r,s} + (t^{run}_{v,r,s} + t^c + t^s) x_{r,v}), \qquad \forall v \in V, s \in SI, \tag{22}$$

$$b^e_{v,s} \geqslant \sum_{r \in R_{v,s}} (e_{v,r,f_{r,ur,s}} + (t^c + t^s) x_{r,v}), \qquad \forall v \in V, s \in SO, \tag{23}$$

$$y_{v,\bar{v},s} + y_{\bar{v},v,s} = 1, \qquad \forall (v, \bar{v}) \in V, s \in S_v \cap S_{\bar{v}}, \tag{24}$$

$$b^e_{\bar{v},s} \leqslant b^s_{v,s} + M \cdot y_{v,\bar{v},s}, \qquad \forall (v, \bar{v}) \in V : s \in S_v \cap S_{\bar{v}}. \tag{25}$$

Each blocking time starts t^r before the train enters the reservation track section $q_{r,s}$ of track section s. Constraints (20) represent the start of a blocking time for all the trains and track sections, except when they start after short-turning or dwelling. The start of the block for those services that depart after a dwell or short-turn are formulated by constraints (21). In an interlocking area each blocking time ends after the train has passed all track sections from the reservation track section $q_{r,s}$ to the end of the considered track section s plus the time needed for clearance and release. On an open track the blocking times end when the train exits the last track section of the block. The reason for this difference is that in the interlocking area, there are switches that can belong to multiple block sections. Keeping the switches occupied until the train leaves the block section would consume unnecessary capacity. Thus, in interlocking areas the sectional-release route-locking principle is modelled where the subsequent track sections on the route are released one by one or in groups after specific release points, whereas for open track blocks all track sections in the block are released simultaneously. The end of the blocking time for the interlocking sections are represented by constraints (22) and for the open track sections are shown by constraints (23). To exclude the possibility of blocking a track section by more than one train, an order is defined for each track section that may be used by each pair of trains. This relation is shown by constraints (24). To avoid conflict, constraints (25) ensure that the start blocking time of the second train occurs after the end blocking time of the first train.

3. Case study

The model is applied on two corridors of the Dutch railway network. In both cases there are two short-turning stations. In the first case two small stations are selected so that the functionality of the microscopic short-turning model and the impacts of its parameters can be shown in more details. In the second case the performance of the model on larger stations is investigated where there are multiple platforms and several switches offering more routes within the short-turning stations. The model is implemented in MATLAB R2016b and solved by Gurobi. The toolbox YALMIP by Löfberg, J. (2012) is used to construct the MILP model.

3.1. First case: Parameter analysis

The model is applied on a railway corridor in the middle of The Netherlands. Figure 2 shows the corridor from station Nijmegen through Nijmegen Dukenburg (Nmd), Wijchen (Wc), Ravenstein (Rvs), Oss (O) and further towards Den Bosch Oost (Hto). This corridor for the most part has double tracks, except between stations Wijchen and Ravenstein there is a single track serving trains in both directions. The disruption occurs between station Oss and Den Bosch Oost, thus all the arriving trains from Nijmegen have to short-turn latest at station Oss back to Nijmegen.

The timetable and disruption location are the same as presented in Ghaemi et al. (2017). In the original timetable, two train lines operate between stations Nijmegen and Den Bosch: an intercity (IC) and local train line (called sprinters (SP) in Dutch). To make a distinction between opposite services of the same line odd and even numbers are used depending on the travel direction. For example the services of the lines IC3600 and SP4400 run from station Den Bosch to Nijmegen, and services of the lines IC3601 and SP4401 run in the opposite direction. The last two digits of the train line numbers indicate the operation time of that line during the day. For instance IC3617 departs at 06:18:00 from Nijmegen. The next IC train in the same direction departs half an hour later at 06:48:00 as IC3619. Both lines IC3600 and SP4400 operate with a frequency of two services per hour in each direction. The IC services can only short-turn in station O as they have a planned stop at this station. However the SP services have planned stops at all the stations. Thus, early short-turnings are considered for SP services at station Rvs.

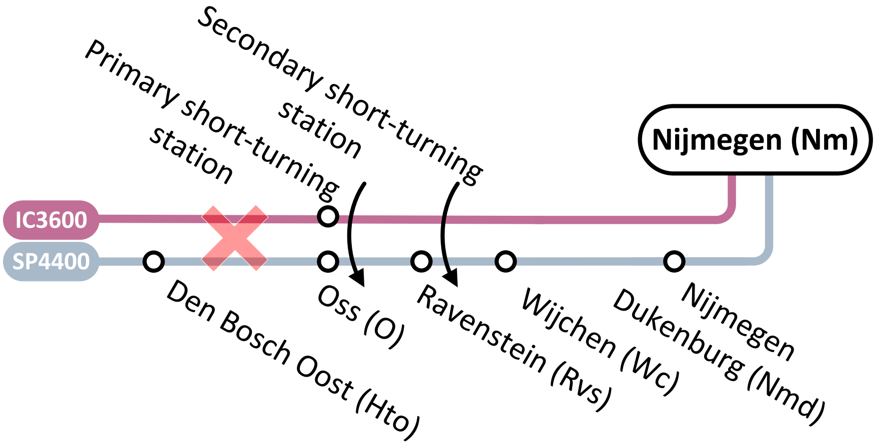

Figure 2: The affected lines in the first case study.

Figure 3 shows the track layout for the short-turning stations O and Rvs. The SP services can short-turn on the upper or lower track of either stations and IC services can only short-turn on the upper or lower track of station O. The routes r_1 and r_2 are the routes for short-turning for both IC and SP services in station O. Later, the results are visualized based on these routes.

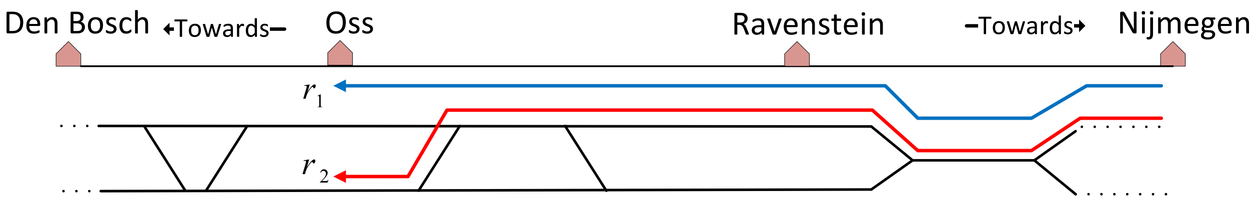

Figure 3: The track layout of short-turning stations O and Rvs.

Table 3 shows the hourly pattern of the original timetable for the two lines SP4400 and IC3600. The actual service numbers are represented by ** as they vary for each hour. The departures and arrivals are indicated by the minutes in the hour. For instance the first row can represent the service IC3617 that departs from Nm at 06:18 and arrives at O at 06:32. The parameters used in the model are listed in Table 4.

Table 3: Original timetable

Train lines	Dep from Nm	Arr to O
IC36**	18	32
SP44**	23	43
IC36**	48	02
SP44**	53	13
Train lines	**Dep from O**	**Arr to Nm**
SP44**	14	35
IC36**	26	44
SP44**	44	05
IC36**	56	14

The disruption starts around 6:00 and it is assumed that it lasts until 8:00. Within this period three IC services

Table 4: Parameters

Parameters	Value (s)
Min short-turning time ($\theta^{min}_{v',v''}$)	360
Signal reaction time (t^r)	10
Release and setup time (t^s)	2
Clearing time (t^c)	3

IC3617, IC3619, IC3621 arrive at station O and cannot operate further due to the disruption and have to short-turn in station O. There are four IC services IC3618, IC3620, IC3622, IC3624 scheduled from station O to Nm within the disruption period. Thus, three of these services can be operated by the three arriving services resulting in an IC service cancellation from O to Nm. The model decides which IC service is better to be cancelled. The service IC3623 is the first service that arrives at O slightly after the end of disruption and can operate on the planned route further than station O. Within the disruption period, there are four SP services SP4417, SP4419, SP4421, SP4423, that arrive at station O and they have to short-turn as four SP services SP4418, SP4420, SP4422, SP4424 scheduled in the opposite direction. As mentioned, the short-turning of the SP services can either be at the final station (O) or at the preceding station (Rvs). Since each early short-turning results in two service cancellations, the optimal solution highly depends on the considered cancellation penalty. Besides penalized cancellations, the objective function includes penalized arrival delay. The choice of penalties can be decided based on the priority of the services. To show the impact of the cancellation and arrival penalties on the optimal short-turning solution, four experiments are performed. In the first and second experiments the impacts of small and large cancellation penalties on the optimal solution are shown. In the third and forth experiments the arrival delay of IC services are penalized to illustrate the impacts of the different delay penalties on the optimal solution. To make the disruption timetable stable against delays, one minute buffer time is considered between trains at the single track.

In experiment 1 small cancellation penalties ($\omega^c_v = 100$) and arrival delay penalty ($\omega^d_v = 1$) are considered for all services. As concluded by the macroscopic short-turning model (Ghaemi et al. (2016)), the result with small cancellation penalty might suggest early short-turnings. The same result can be observed from the microscopic short-turning model with small cancellation penalty. This result for route r_2 is visualized in the blocking time diagram shown in Figure 4. The red dashed lines represent the original timetable and the solid blue lines represent the computed timetable. As shown in this diagram, SP4417 short-turns as SP4418, SP4419 as SP4420, SP4421 as SP4422, and SP4423 as SP4424 in station Rvs. The microscopic short-turning model also computes the optimal inbound and outbound routes (platform track) for short-turnings. The SP short-turnings in Rvs are shown by the long blocks. The IC services can only short-turn at station O where IC3617 short-turns as IC3620, IC3619 as IC3622, IC3621 as IC3624, and the cancelled IC service is IC3618. The solution suggests that the optimal platform track for IC short-turnings is the lower track in station O.

In experiment 2 the cancellation penalty is increased ($\omega^c_v = 1000$) while the arrival delay ($\omega^d_v = 1$) is the same. It is observed that the choice of short-turning station changes around $\omega^c_v = 365$. In case the cancellation penalty is large, the optimal solution suggests to short-turn all the services at the final station O. Figure 5 shows the blocking time diagram of the optimal solution with large cancellation penalty for route r_2. The reason that the SP short-turnings are not visualized in this figure is that they short-turn on the upper track of station O which belongs to route r_1. For each short-turn a minimum short-turning time should be respected. From the original timetable, it is observed that in station O there is just one minute between the arrival of SP services and the departures in the opposite direction. Thus, there is not enough short-turning time inbetween arrival and departure of SP services. This would result in a delayed departure of SP services from O to Nm. This delay will cause a conflict on the single track between Rvs and Wc, with the IC services from station Nm towards O. To avoid the conflict, the microscopic short-turning model suggests a departure delay of around ninety three seconds for IC services from Nm. This of course is the result of considering the same punctuality preference for both IC and SP services. In case the IC services have a higher punctuality priority, this can be considered by setting a large IC arrival delay penalty.

In experiment 3, besides the large cancellation penalty for all services ($\omega^c_v = 1000$), delayed arrivals of IC services are largely penalized ($\omega^d_v = 1000$) whereas in experiments 1 and 2, this penalty was 1. Figure 6 shows the optimal result. Since the IC arrival delays are penalized, it is observed that SP4418 is delayed more so that IC3617 uses the

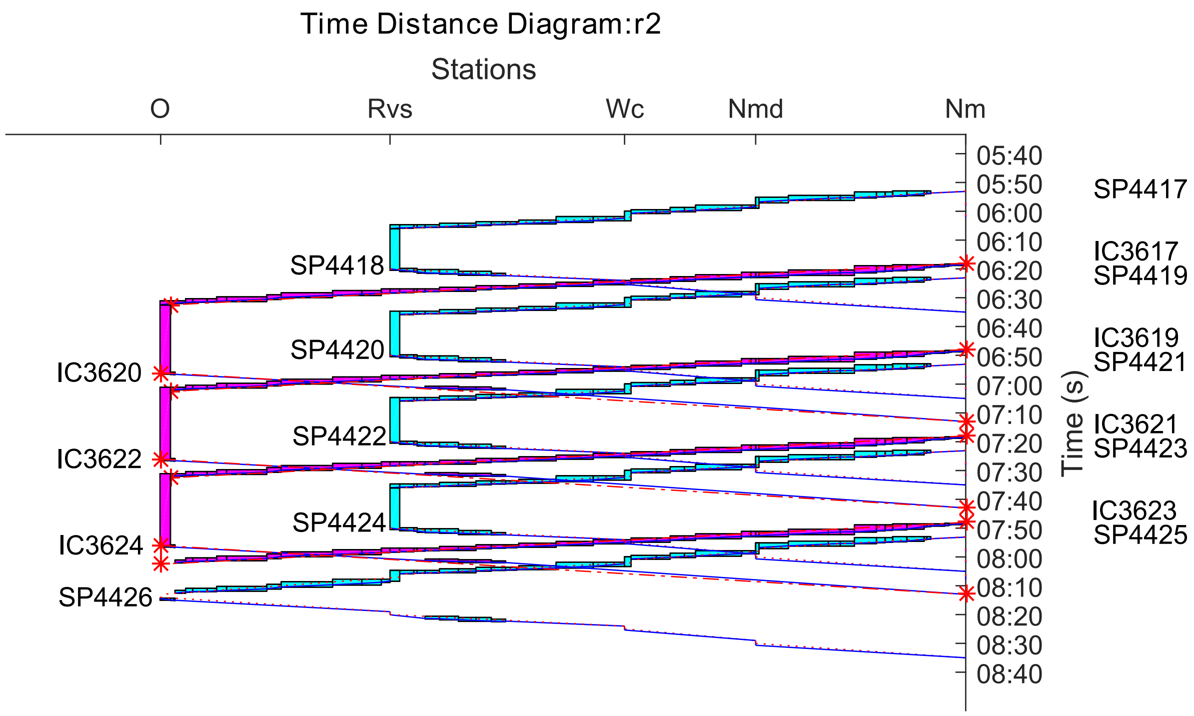

Figure 4: The blocking time result of the microscopic short-turning model with small cancellation penalty from experiment 1.

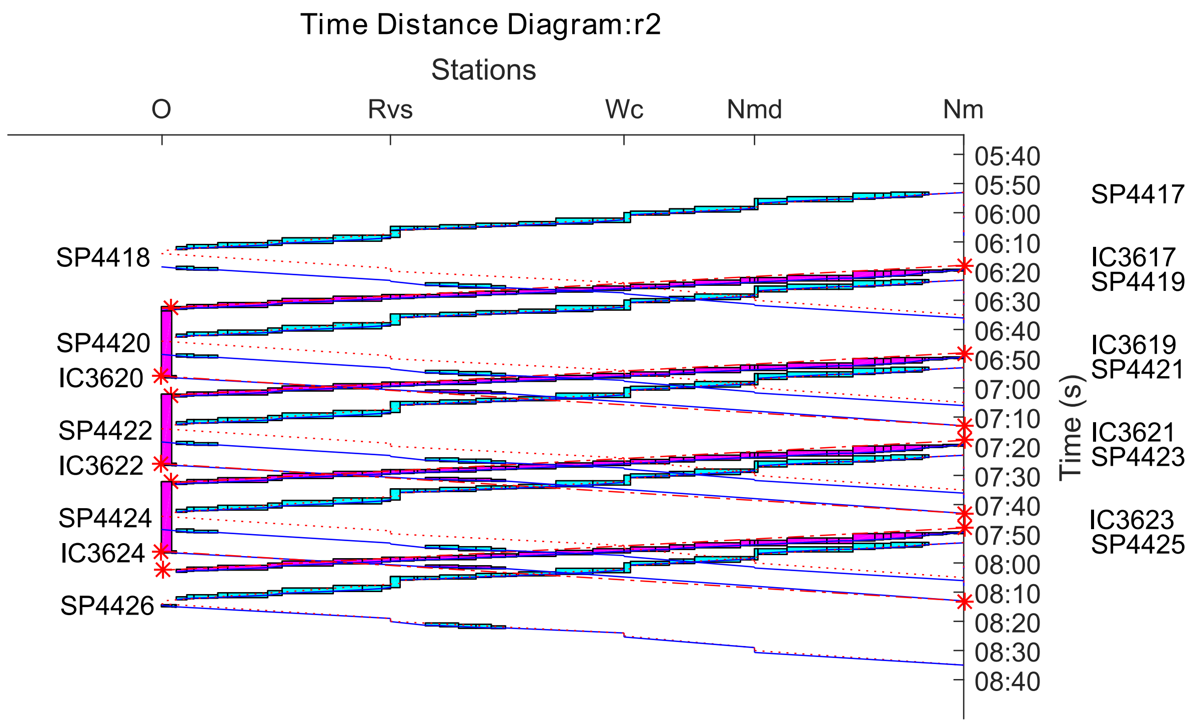

Figure 5: The blocking time result of the microscopic short-turning model with large cancellation penalty from experiment 2.

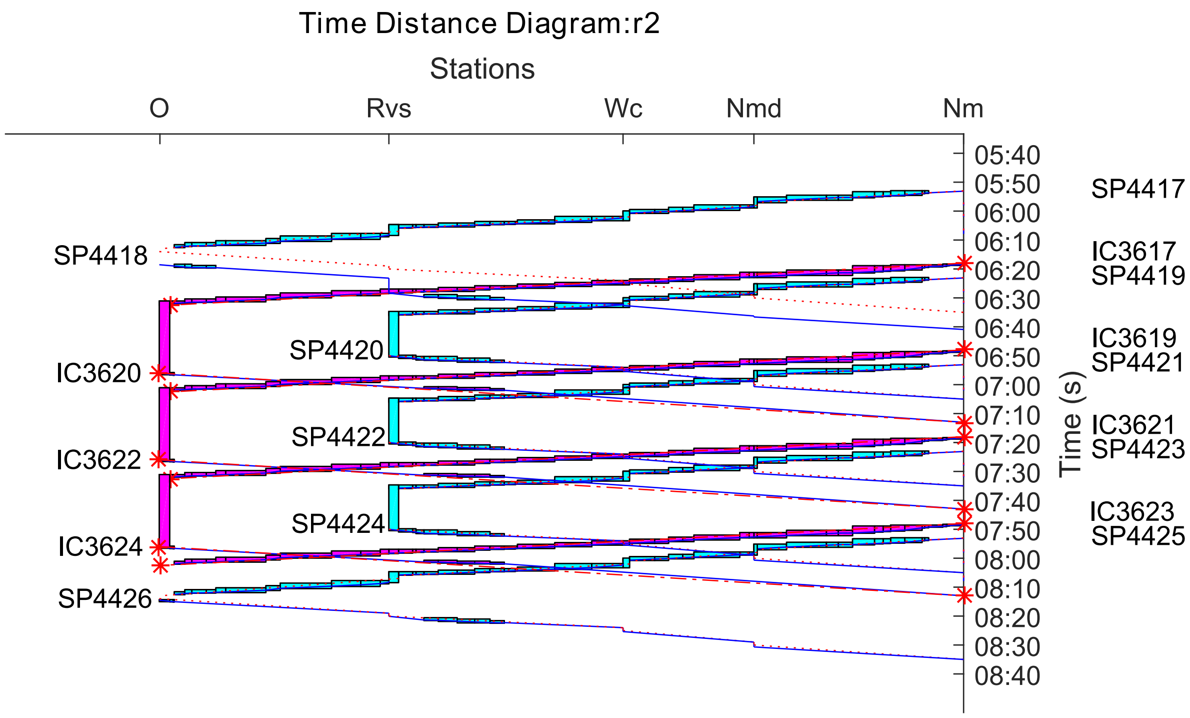

Figure 6: The blocking time result of the microscopic short-turning model with large penalty for cancellation and IC arrival delay from experiment 3.

single track first to avoid arrival delay for IC3617. This solution suggests that short-turning the arriving SP services (SP4419, SP4421, and SP4423) at the secondary short-turning station Rvs is better than short-turning them at station O, although the cancellation penalty is large. The reason is that if the SP services were short-turned in O, then there would be a conflict on the single track with the IC services from Nm as explained in Experiment 2. In this case, changing the order still causes conflicts on the single track with IC services from O. Thus, in case the SP services were short-turned at station O, their departures would largely be delayed. However, since IC3618 is cancelled, SP4418 is not delayed further and with an order change, the IC3617 arrival delay is avoided.

In Experiment 4, both cancellation of all services and delayed arrivals of IC services are extremely penalized (ω_v^c = 10000, ω_v^d = 10000). Figure 7 shows the result where all services are short-turned at the final station. As shown in this figure, the order of SP and IC operation on the single track is changed. For example, service SP4418 runs on the single track after IC3617. SP4420 is delayed as it waits for IC3620 to depart first and then SP4420 departs the station. This delay causes a conflict with SP4421 on the single track. For this reason, the departure of SP4421 from Wc is delayed around three minutes. Since IC3618 is cancelled, SP4418 is able to depart the station with smaller delay than SP4420, SP4422 and SP4424. Service IC3623 is the first service that can again proceed after O. Thus the arrival of this service is planned on the original route. The final SP short-turning takes place very close to the end of the disruption, thus another solution might be to cancel the service SP4424 and wait until the disruption is over and then continue towards Ht. This solution should be assessed considering the traffic from the other side of the disruption.

Table 5 shows the number of cancelled services, the total arrival delays and average arrival delay for both IC and SP services in the four experiments. In experiment 1, 8 SP services are cancelled so that the remaining services can operate on time. In experiment 2, the SP cancellation is avoided by increasing the penalties and it is observed that more services are operating with delay. In experiment 3, 6 SP services are cancelled which are the result of early short-turnings. Due to the large penalty for IC arrival delay, it is observed that none of the IC services are delayed. In experiment 4, the extremely large penalty for cancellation and IC arrival delay results in considerable delay for SP

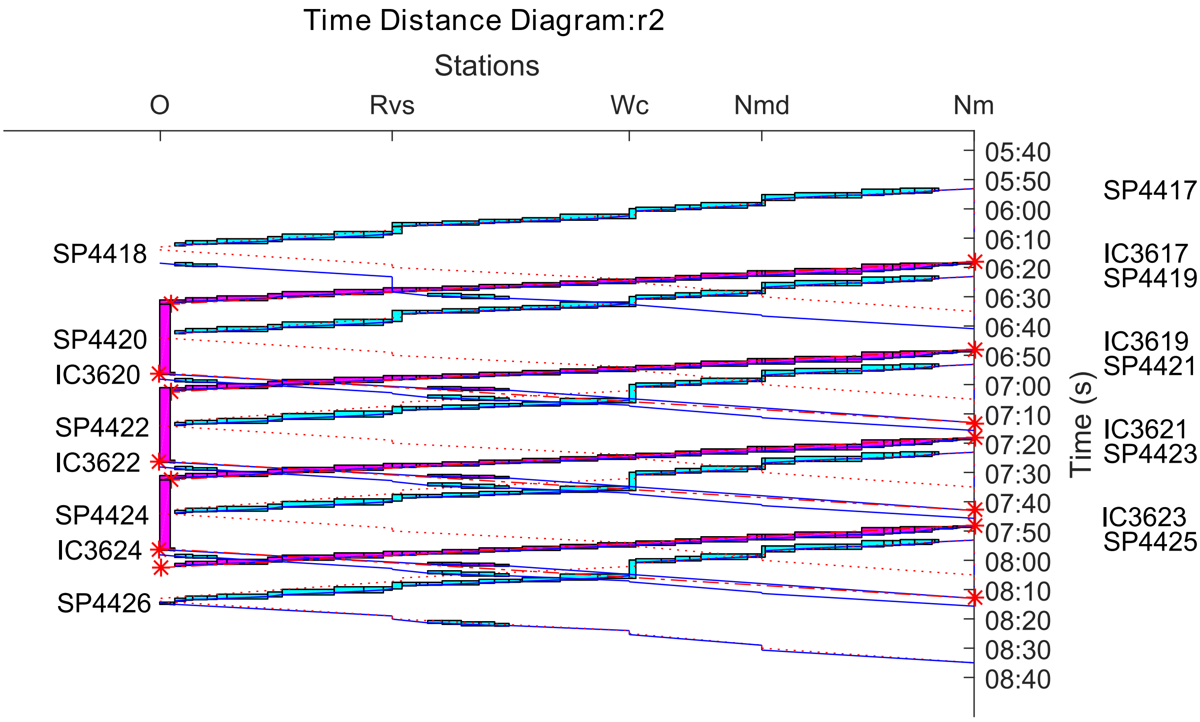

Figure 7: The blocking time result of the microscopic short-turning model with extremely large penalties for cancellation and IC arrival delay from experiment 4.

services.

The different solutions can be shown to professional experts along with their performance indicators. A first check with experts from the infrastructure manager was in favour of the solution in experiment 1 since no delay at Nijmegen would isolate the problem to the corridor between Nijmegen and Oss and thus prevent impact to the rest of the network. However, this argument does not incorporate the inconvenience to passengers of the cancelled services and the costs and effort of running alternative bus services to bring the passengers to Oss. For the railway undertaking these indicators might play a much larger role. Hence, varying the penalties can be used to generate essentially different solutions with their performance indicators that could be evaluated by experts from different perspectives to find an overall best strategy.

Table 5: The results of the microscopic short-turning model for the four experiments

Experiment	# Cancelled SP	SP arr. delay (s)	SP av. delay (s)	# Cancelled IC	IC arr. delay (s)	IC av. delay (s)
1	8	0	0	1	0	0
2	0	2658	66.45	1	261	37.2
3	6	1539	45.26	1	0	0
4	0	11198	279.95	1	0	0

3.2. Second case: Performance analysis

In this case, the model is applied on another Dutch railway corridor, which is shown in Figure 8. The disruption occurs in station Geldermalsen (Gdm) and thus the affected train services have to short-turn in one of the preceding stations: Zaltbommel (Zbm) or Den Bosch (Ht). In this case a disruption of half an hour is assumed between 10:00

and 10:30. The three intercity and two local lines serving station Ht (with a frequency of two per hour per direction) make station Ht an important interchange station in the middle of The Netherlands. Lines IC3500 and IC800 provide services between Vught (Vg) and Zbm and further. Lines SP4400 and IC3600 (which are already introduced in the previous case) operate between Tilburg (Tb) and Hto and beyond towards Nijmegen. Line SP16000 provides services between stations Tb and Zbm and beyond. Since the intercity services from lines IC3500 and IC800 do not have a planned stop at station Zbm, they have to short-turn at station Ht while those from SP16000 can short-turn at both stations Zbm and Ht. The services of lines SP4400 and IC3600 pass through Ht and do not short-turn as they do not traverse the disrupted station Gdm.

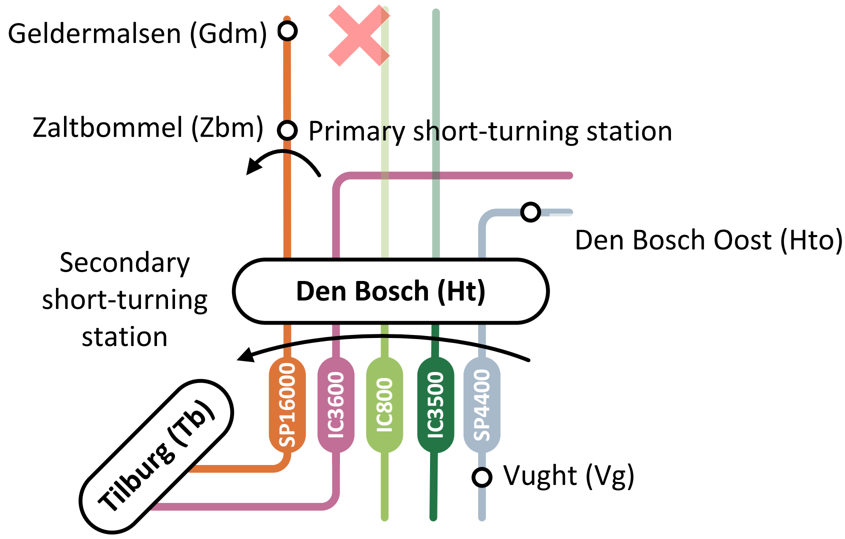

Figure 8: The affected lines in the second case study.

Station Ht has eight tracks five of which have platforms (see Figure 9). The platform tracks are numbered from top to bottom. Tracks that do not have platforms are used by train services (such as freight services) which do not have any stop at Ht. There are several switches in the station that allow the train services to use different platform tracks. Consequently there are many route choices for each train arriving at Ht or departing from each platform. These routes are listed in Table 6.

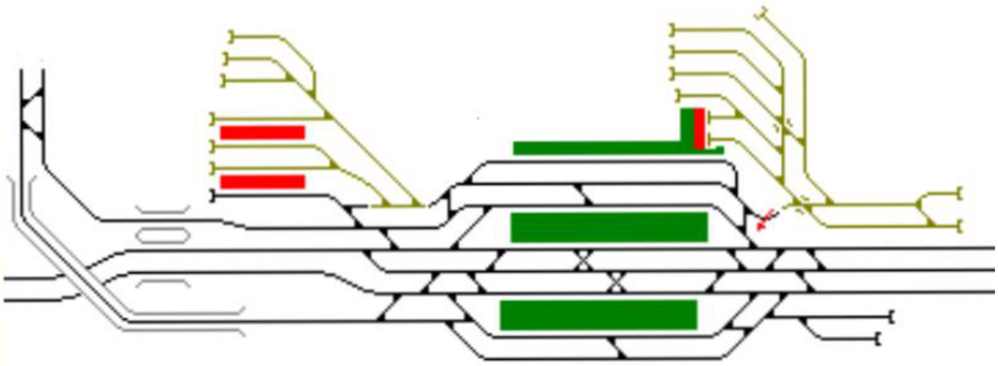

Figure 9: The layout of station Ht. Source: www.sporenplan.nl by Zeegers (2017).

The result for the optimal platform track occupation of the original timetable is shown in Figure 10. Note that this platform track allocation is different from the actual one but used here as a reference to the computations of the disrupted cases. The arrows illustrate the direction of the services that can be either from Tb\Vg towards Hto\Zbm

Table 6: The number of routes and track sections between each OD station pairs.

OD stations	# Routes	# Track sections
Tb-Ht	5	101
Ht-Zbm	7	73
Vg-Ht	5	34
Ht-Hto	12	70
Zbm-Ht	7	66
Ht-Tb	6	120
Hto-Ht	10	50
Ht-Vg	9	42

or vice versa. It is observed that the IC services of line IC3600 from Tb towards Hto dwell on platform track 3 while the opposite services from the same line dwell on platform track 7. The IC services of lines IC800 and IC3500 from Vg towards Zbm dwell on platform track 6 while their opposite services dwell on platform track 4. The local services of line SP4400 use platform track 4 in the direction from Vg to Hto and platform track 7 in the opposite direction. Finally, the local services of line SP16000 from Tb to Zbm dwell on platform track 6 and their opposite services dwell on platform track 7.

The result for the optimal platform track occupation of the disruption is shown in Figure 11. In this case the services IC836, IC3538, and SP16038 need to short-turn. Since cancellation is largely penalized ($\omega_v^c = 1000$) the SP16038 is short-turned at the primary short-turning station Zbm as service SP16039. The optimal solution suggests that IC836 short-turns on platform track 6 and continues as IC839. Note that the train that has to operate as IC839 cannot reach Ht due to the blockage. Meanwhile, IC837 arrives at Ht from Zbm. This is the last service from Zbm before the start of the disruption. The long platform track occupation by the short-turning of service IC836 causes conflicts for those services that are scheduled to dwell on this platform during this short-turning. Consequently they have to be rerouted to other platform tracks. From Figure 10 it is concluded that the services that are scheduled to arrive at platform track 6 between the arrival of IC836 and departure of IC839 should be rerouted to other platform tracks. Thus, services SP16038, IC3538, IC838, SP16040, and IC3540 need to be rerouted. Figure 11 shows that SP16038 and SP16040 are rerouted to platform track 3 and the rest (IC3538, IC838, IC3540) are rerouted to platform track 4.

IC3538 short-turns on platform track 4 and operates as IC3539. Due to this short-turning SP4438 cannot dwell on platform track 4 and thus is rerouted to platform track 3. To avoid a conflict with IC3638, the latter is rerouted to platform track 1. However it is observed that the rescheduled arrival of IC3538 is around 4 minutes later than the scheduled arrival. Moreover, the arrival of IC838 is delayed around 7 minutes. To understand the reason for these delays, the blocking time diagram for a route from Vg to the platform track 4 of Ht is plotted in Figure 12. Similar to the blocking time diagrams of the previous case, the reason that some train paths are partly shown is that those train services run only on parts of the plotted route. The blocks in Ht correspond to the platform track occupation of services IC835, SP4436, IC3537, IC837, IC3538 (short-turning), IC838, IC3540, SP4440, and IC3541. By observing this plot, it is concluded that the order of services between 9:30 and 10:00 resembles the order of services between 10:30 and 11:00. However a different order is observed for the services between 10:00 to 10:30. As mentioned earlier, the difference relates to IC3538 and IC838 which are reordered and thus, delayed. Since the original dwell platform track of IC3538 (platform track 6) is occupied for the short-turning of IC836, this service has to short-turn on platform track 4. This was not the case for the service IC3536 of the previous cycle which was not affected by the disruption and could continue according to the original timetable. From Figure 12 it is observed that platform track 4 is occupied by service IC837 and thus IC3538 cannot arrive at this platform on time. At the same time, the delayed IC3538 causes conflict with IC3638. Since delaying IC3638 from Tb to Ht will cause another delay for the next service from Ht to Hto, the solution suggests a reordering between IC3538 and IC3638 so that this delay cannot propagate and only affect one service (IC3538). Due to this short-turning IC838 is delayed and to avoid any conflict with SP16040, the order is changed. Services IC840 and SP16042 are not affected by the disruption anymore and use their original dwelling platform track (6). The services that dwell on platform track 7 remain unchanged.

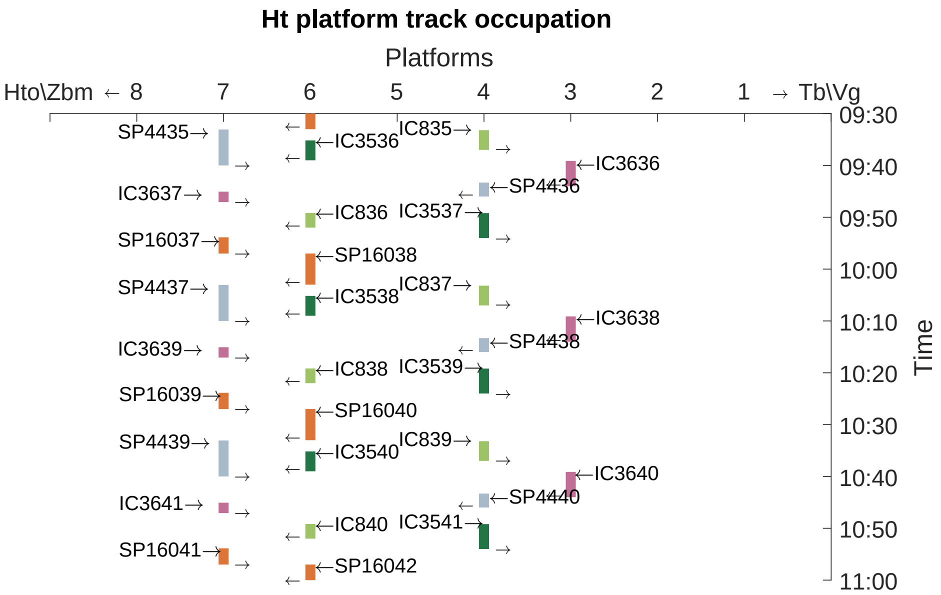

Figure 10: The result for the platform track occupation of the original timetable in the secondary short-turning station, Ht.

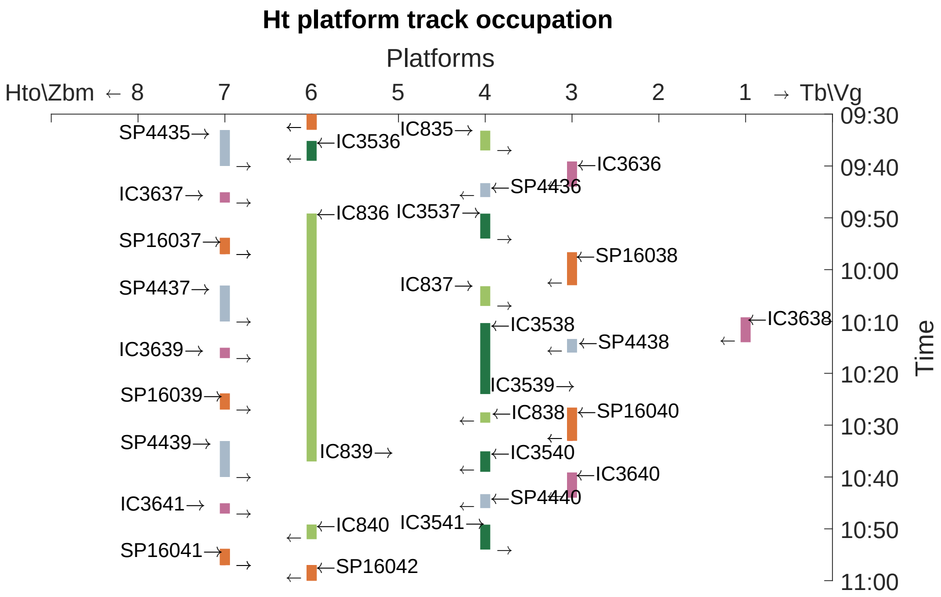

Figure 11: The rescheduled platform track occupation in the secondary short-turning station, Ht.

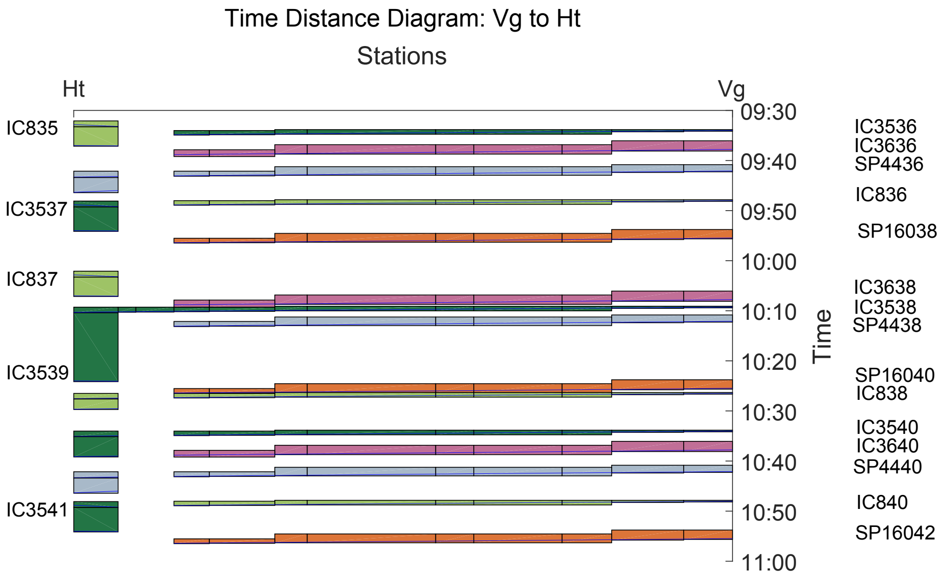

Figure 12: The blocking time result of the microscopic short-turning model for a route between Vg and the platform track 4 in Ht.

Figure 13 shows the corresponding blocking time for a route between platform track 7 in Ht and Tb.

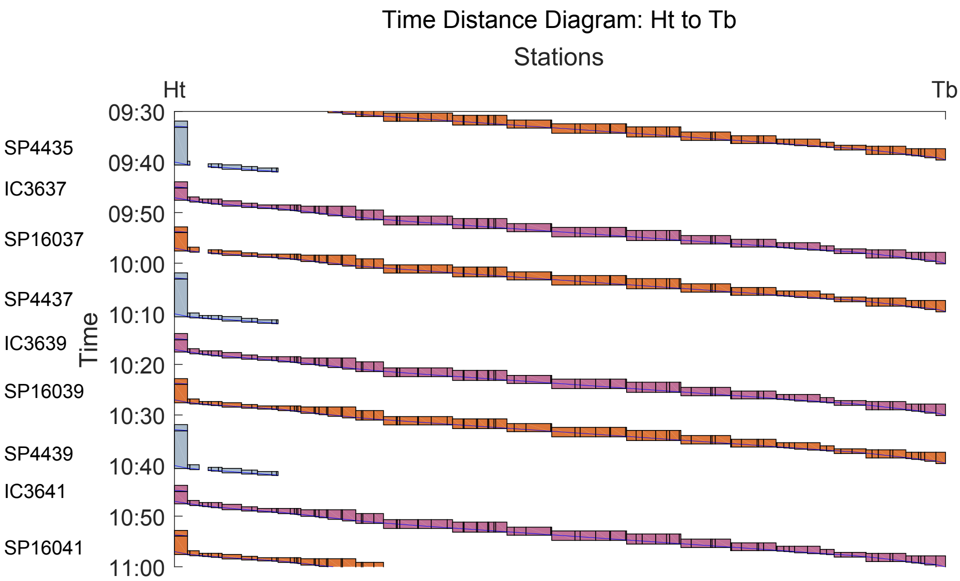

Figure 13: The blocking time result of the microscopic short-turning model for a route between platform track 7 in Ht and Tb.

In order to investigate the performance of the model, the disruption length is increased from 30 to 60 minutes with even intervals of 10 minutes. Table 7 reports the problem size of each disruption in terms of the binary variables, continuous variables, constraints and the computation time. The total number of services, number of cancelled services and total delay for each disruption are listed in the sixth, seventh and eight columns. As expected, with an increase in the disruption length the number of variables and constraints grows. An increased growth is observed in the computation time of longer disruption lengths. The number of cancelled services and total delay increase by longer disruptions. Note that the numbers in the seventh column presents the cancelled services in the network shown in Figure 8 and does not take into account the services beyond Gdm that are also affected by this disruption. From Table 7, it is concluded that the optimal solution for a disruption up to one hour can be computed in 1 minute and 20 seconds. Moreover it is observed that with increased disruption length the short-turning choices and platform tracks repeat. This repetition is due to the cyclic nature of the timetable. Thus the solution for a disruption length of 30 minutes can be similarly applied to a disruption length of 60 minutes by using the same short-turning choices and platform tracks for services during the second period of 30 minutes.

Table 7: The performance of the microscopic short-turning model for different disruption lengths.

Disruption length (min)	# Binary variables	# Continuous variables	# Constraints	Computation time (s)	# Service	# Cancelled IC	Delay (min)
30	10452	15251	78490	11.18	32	10	19
40	14129	17763	94342	20.82	36	15	12
50	18814	19633	108750	36.06	42	17	12
60	24814	23002	132109	80.11	48	20	30

4. Conclusions

In this paper a microscopic short-turning model was presented for disruption management that includes short-turning variables and constraints. The microscopic short-turning model allocates the arriving services to the scheduled departures in the opposite direction taking into account the operational constraints such as running time, minimum short-turning time and dwell time, while computing the optimal conflict-free routes for all services including the short-turning ones. Moreover the model offers the possibility of short-turning in a secondary short-turning station.

The model is applied on two Dutch railway corridors. From the first case study, it is concluded that the optimal short-turning station depends on the penalties considered for cancellation and arrival delays. It was observed that with a small cancellation penalty, the solution proposes short-turnings at the secondary short-turning station. The result of this solution shows the least propagated delays which support the advantage of including a second short-turning station. As the cancellation penalty increases, the model finds optimal short-turnings at the final station to avoid service cancellations. It was also shown that the model proposes to change the order of services in case there is a distinction between the importance of punctuality for different services. As shown in the case study the microscopic visualisation of the optimal solution can provide support to the traffic controllers.

In the second case the performance of the microscopic short-turning model on a big station with multiple routes and platform tracks is investigated. It was shown that there might be platform changes for the lines that are not directly impacted by the disruption and only dwell in the short-turning station. For a disruption length of 1 hour the model is able to compute the optimal solution quickly for a big station such as Ht. The computation time of the optimal solution can grow rapidly with increased disruption length. However it was observed that the short-turning and platform track choices repeat due to the cyclic nature of the timetable. This allows the traffic controllers to apply the optimal solution for the following cycles.

One of the future research directions is exploring different values for delay and cancellation penalties. It is also interesting to model partial blockages where some services are prioritized over the others. In addition, the model can be extended by formulating the interaction of the traffic between both sides of the blockage before and after the disruption. Moreover, the rescheduling model can be extended to include the passenger demand and the impacts of the disruption timetable on the passengers travel times.

Acknowledgement

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