D4.1: Impacts of Smart Transfer Schemes under Various Scenarios

Project acronym: TRANS-FORM

Project title: Smart transfers through unravelling urban form and travel flow dynamics

Funding Scheme: ERA-NET call on Smart Cities and Communities (ENSCC)

Authors

Menno Yap m.d.yap@tudelft.nl
Johanna Törnquist Krasemann johanna.tornquist.krasemann@bth.se
Nicholas Molyneaux nicholas.molyneaux@epfl.ch
Clas Rydergren clas.rydergren@liu.se
Oded Cats o.cats@tudelft.nl

Internal Reviewer

Patricia Bellver Muñoz pbellver.etraid@grupoetra.com

State: Draft
Distribution: [Confidential]

Deliverable History

Date	Author	Changes
20-9-2018	Oded Cats, TUD	Draft table of contents
15-11-2018	Menno Yap, TUD	Draft urban case study description
16-11-2018	Johanna Törnquist Krasemann, BTH Nicholas Molyneaux, EPFL	Draft regional and intercity layer (2.2) and incomplete draft of section 5.1
28-11-2018		Draft of sections 2.4 and 6.1
10-01-2019	Oded Cats, TUD	Document structure
17-04-2019	Nicholas Molyneaux, EPFL	Draft of hub results (section 6)
29-04-2019	Clas Rydergren, LiU	Added to Section 5.1 and 5.2
29-04-2019	Johanna Törnquist Krasemann, BTH Johanna Törnquist Krasemann, BTH	Added to 5.2 and included the final MIP model in Appendix A.
30-04-2019	Johanna Törnquist Krasemann, BTH Menno Yap, TUD	Expanded and concluded 5.2, 5.3 and 5.4.
03-05-2019	Oded Cats, TUD	Updated and concluded section 2.2 and 4.2.
19-05-2019		Updating section 4.3
20-05-2019		Editing throughout, writing Summary, Introduction and Closing remarks

Contents

Summary

The main objective of this deliverable is to demonstrate the modelling capabilities developed in the course of the TRANS-FORM project by means of a series of applications for diverse case studies and scenarios. The development of the multi-layer integration modelling tool columinates in this deliverable where it is applied to the flagship case study of the Hague in the Netherlands using a sequence of models: train traffic management model, pedestrian flow hub model and dynamic public transport assignment model. The models exchange information about vehicle and passenger flows and delays, allowing the modelling of propagation and spill-over effects as well as potential mitigation measures. Additional case studies at the hub and regional transit networks level further assess the impacts of related flow control and re-scheudling strategies, respecitvely. This delvierable reports the work performed in tasks 4.1 and 4.2 of the TRANS-FORM project.

1. Introduction

The multi-layer passenger distribution and delay propagation model developed in WP2 and WP3 as well as the control and rescheduling strategies are applied and tested for a series of case studies in Sweden, Switzerland and the Netherlands. The pedestrian hub model, the dyanmic public transport assignment model and the train traffic management model detailed in D2.2 are for the first time used in sequence using the integration tool developed in this project and described in D3.3. The flagship application of the TRANS-FORM project centred around the city of The Hague in the Netherlands is used to demonstrate and test the infromation flow between the three models and related functionalities. The application allows to capture the propagation of passenger flows and related delays from the regional train level through a key central station hub to the urban public transport network and thus better quantify the impacts of disruption scenarios varying in their severity. Furthermore, control interventions at the hub and train traffic levels are applied and tested for the case studies of the train station in Lausanne, Switzerland and the regional train network in the Blekinge region, Sweden, respectively.

This delvierable reports the work performed in tasks 4.1 and 4.2 of the TRANS-FORM project. Task 4.1 involved with the set-up of both three local case studies and the joint case study in order to evaluate the impacts of the disruptions and the transfer strategies developed in the previous work packages. The task also operationalizes the control tehcniques and the integrated modelling tool developed in WP3. The work invovled verifying the required data for the case study, focusing on the interactions among the levels. We then define the scenarios evaluated in the joint case study which includes detailed network representation and model testing. Task 4.2 pertained to implementing the case studies in the respective models, model application and the compilation of model outputs, scenario comparisons and reporting model results.

The results of these activites are reported in this deliverable as follows. First, the flagship multi-layer case study is described in detail in Section 2 for each of the modelling levels. The set of sceanrios for which the multi-layer modelling has been applied is described in Section 3. The results in terms of the hub-urban passenger flow equilbrium, the train traffic optimization and the overall impacts of disruptions on passenger delays are presented and discussed in Section 4. Section 5 is devoted to the appliaction of various rescheduling measures for regional trains whereas Section 6 presents the application of pedestrian flow control strategies for interchange stations. Conclusing remarks are provided in Section 7.

2. Multi-layer case study

2.1. Overview

We apply our methodology to the multi-level public transport (PT) network of The Hague, the Netherlands. The Hague is the third largest city in the Netherlands, located in the main economic area of the Netherlands called the Randstad in the western part of the country. The population size of the city is over 500,000 inhabitants. The agglomeration of The Hague including its surrounding cities covers an area of 405 km2 with more than 1 million inhabitants.

The case study multi-level PT network entails the complete urban PT network of The Hague consisting of 12 tram lines and 8 bus lines, and all train services serving The Hague. The latter means all train services from/to the directions Leiden, Gouda and Delft starting at, terminating from, or serving one of the train stations of The Hague are incorporated in our case study (Figure 1). Intercity train services, serving only larger cities, and local train services stopping at all stations are both simulated. The train network is cordoned at the stations Leiden, Gouda and Delft Zuid, meaning these stations are modelled as portals where train services start and end. The *cordoned train network consists of 16 stations, of which 10 stations allow passengers to transfer between the (inter)regional train network level and the urban tram and bus network level.*

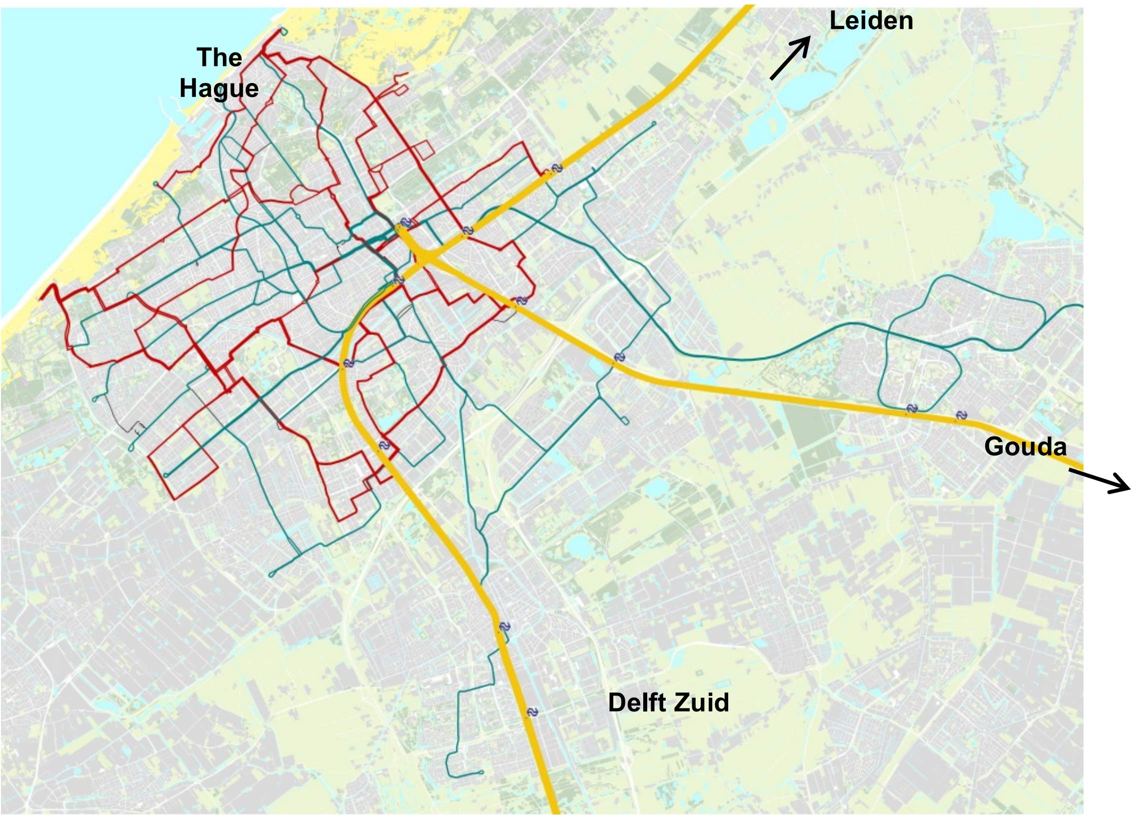


Figure 1. *Case study public transport network (yellow: train services / green: tram services / red: bus services)*

2.2. Regional and intercity layer

In the regional and intercity layer, we include the part of the railway network depicted in Figure 2 below. It includes the train traffic between:

- *The Hague Central - Leiden Central (Schiphol airport / Haarlem)*
- *The Hague Central - Delft Zuid (Rotterdam)*
- *The Hague Central- Gouda (Utrecht)*

We include the train traffic in the morning time period between 06:00 am and 10:00 am. In line with the categorization suggested in (Törnquist Krasemann, 2012) we consider a number of different disturbance categories:

- *Category 1 refers to that a train that suffers from a temporary delay at one particular section and it can occur due to e.g. delayed train staff, or crowding at platforms resulting in increasing dwell times at stations.*
- *Category 2 refers to that a train has a permanent malfunction resulting in increased running times on all line sections it is planned to occupy.*
- *Category 3 refers to an infrastructure failure causing, e.g., a speed reduction on a particular section, which results in increased running times for all trains running through that section.*
- *Category 4 refers to a complete line blockage, where no trains can pass. A partial cancellation is consequently required by short-turning affected trains in both ends of the blocked link according to a pre-defined plan.*

The specific settings of those disturbance scenarios are outlined in Table 1 in section 3 below, where "Disruption 1 – Local delay" refers to a disturbance of category 3 and "Disruption 2 – Moving delay" refers to a disturbance of category 2.

We evaluate and compare two alternative train traffic management policies. The first is more train-oriented and where train delays are primarily minimized while the second policy is more passenger-oriented and where we minimize passenger delays using weighted train delays based on number of alighting passengers at each stop.

The permitted re-scheduling and control strategies are mainly:

- *Re-timing (i.e. changing the departure and arrival times, while respecting the initial earliest departure time and minimum dwell times at commercial stops and running times of the trains).*
- *Reordering (i.e. permitting shift of train meets and overtaking to neighboring stations, while respecting the safety constraints in the network).*
- *Local re-routing (i.e. allowing change of track and platform assignment) for all stations except for The Hague Central.*

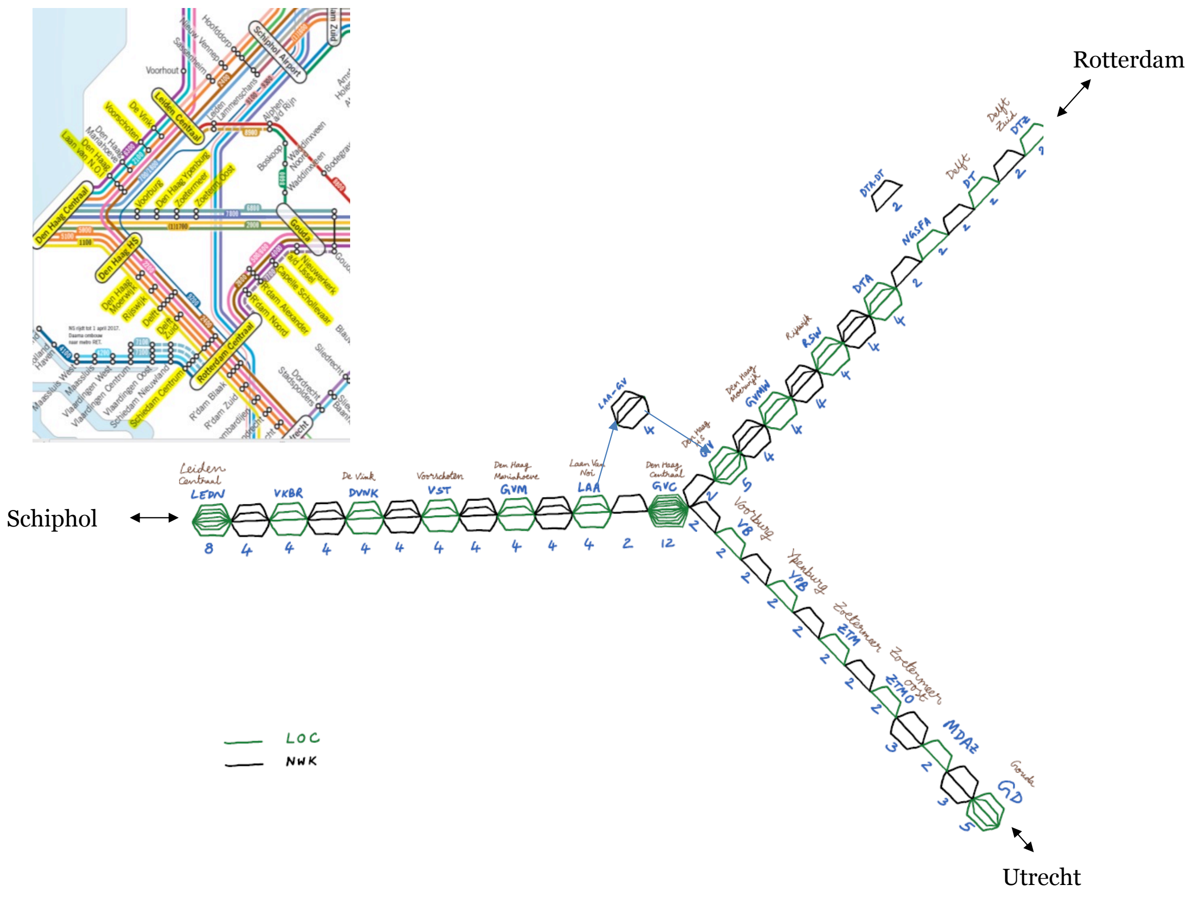


Figure 2 *Illustration of the selected railway sub-network for the joint case study.*

As already mentioned above, we apply two alternative railway re-scheduling policies of which the first is train-oriented and the second passenger-oriented. The model permits e.g. trains to run faster than scheduled and to run ahead of schedule at certain stretches (i.e. to arrive before scheduled arrival time) in order to enable trains to catch-up delays and make way for other trains quicker. The model also permits trains to change tracks and platforms as well as to overtake and meet at other locations than initially planned, if that leds to a reduction of knock-on delays. Hence, in order to ensure that only such beneficial "delay-reducing" re-scheduling decisions are adopted, those need to be associated with a smaller penalty corresponding to e.g. one minute delay. So in *addition to minimizing train delays and passenger delays, respectively, both objectives also minimizes other arrival and departure time deviations and track changes.*

The train-oriented policy adopts the objective function defined by (Eq. 2.1), subject to the constraints defined by (Eq.A1-A8; A10-A22) found in Appendix A (since the trains are here not re-scheduled or coordinated with any bus services, Eq.A9 is omitted). The objective is to minimize transport service delays larger than two minutes, arrival time deviations and track changes. The parameter $\mu_{i,k}^{train}$ *specifies which track or platform that initially is intended to be used by event k belonging to train i. The parameter* α *specifies with which weight track changes are to be penalized. If the time-related variable values are given in e.g. seconds, the value of* α *needs to be set quite high in order to balance the trade-off between reducing train delays and keeping the timetable as intact as possible with respect to the planned routes of the trains through/within the stations. In the experiments reported in this section, we have used* $\alpha = 60$.

$$minimize \sum_{i \in V} \sum_{k \in K_i} (z_{i,k}^{+2} + w_{i,k}) + \sum_{i \in T} \sum_{k \in K_i} \sum_{t \in P_j : t \neq \mu_{i,k}^{train}} \alpha * q_{i,k,t} \quad \text{(Eq. 2.1)}$$

Similarly, the passenger-oriented policy adopts the objective function defined by (Eq. 2.2), subject to the constraints defined by (Eq.A1-A8; A10-A22), where the parameter $n_{i,k}^{aligthing}$ *specifies the number of passengers leaving the corresponding, possibly delayed, train.*

$$minimize \sum_{i \in V} \sum_{k \in K_i} (n_{i,k}^{aligthing} * z_{i,k}^{+2} + w_{i,k}) + \sum_{i \in T} \sum_{k \in K_i} \sum_{t \in P_j : t \neq \mu_{i,k}^{train}} \alpha * q_{i,k,t} \quad \text{(Eq. 2.2)}$$

2.3. Urban public transport layer

Passenger demand is obtained from Automated Fare Collection (AFC) data from 20 working days between 5th March and 30th March 2018. For the urban tram and bus network in The Hague, a distance-based fare system applies where passengers are required to tap-in and tap-out at in-vehicle devices for each journey leg. This means each complete AFC transaction consists of a tap-in time, stop, line and vehicle ID, as well as a tap-out time and stop. The dataset consists of 6.48 million AFC transactions solely for the urban tram and bus network, equating ≈325,000 AFC transactions per average working day made on the urban PT network. 29,271 AFC transactions (0.5%) were incomplete due to an error in the AFC system and deleted from the dataset. Due to the in-vehicle tap-in and tap-out devices, destination inference is not required for complete AFC transactions. In case of an incomplete AFC transaction where a passenger (un)deliberately did not tap-out, the well-known trip chaining algorithm is applied to infer to most plausible tap-out stop (Munizaga and Palma 2012). If there is only one AFC transaction made by a certain card ID on the day of the incomplete transaction, or if no candidate alighting stop is found within a plausible walking distance of 400 Euclidean meter from the next registered boarding stop, no destination inference could be performed. In response, these 43,427 (0.7%) AFC transactions were removed from the dataset. For all remaining 6.39 million AFC transactions on the urban PT network, a transfer inference algorithm is applied to construct stop-to-stop journeys based on Gordon et al. (2013) and Yap et al. (2017).

In our case study we focus on AM peak journeys with starting time between 7-9AM. Besides simulating PT demand and supply between 7-9 AM, demand and supply are also simulated between 6-7AM and 9-10AM as warm-up and cooling-down period. This is necessary to make sure all passengers starting their journey between 7-9AM have PT supply available at all locations to start and finish their journey. It is also necessary to reflect crowding levels in PT services adequately by incorporating passengers starting their journey outside the AM *peak, who affect crowding levels of passengers who started their journey within the AM peak. After applying the abovementioned transfer inference algorithm, for an average working day 71,301 journeys starting between 6-10AM are simulated. 48,810 journeys (68.5%) are passengers who started their journey between 7-9AM. Journeys started between 7-9AM are the main focus of our case study for which simulation results are presented.*

To construct a multi-level stop-to-stop OD matrix, the OD matrix generated solely for the urban PT network is amended based on transfer information between the train and urban PT network (Nijenstein and Bussink 2015). As the train and urban PT network are operated by different PT operators, AFC systems of these network levels are generally not linked together. Therefore, no direct multi-level OD matrix is available. However, in 2015 Nijenstein and Bussink performed a study to integrate AFC data specifically for the urban PT network of The Hague and the surrounding train network, what resulted in a relative passenger transfer flow distribution between the three train corridors (directions Leiden, Gouda or Delft) and between intercity and local train services, and the urban PT network for each multi-level transfer location in The Hague. These transfer flows are distributed proportionally over the different urban PT stops as origins and destinations, thereby replacing the multi-level transfer location as origin/destination for the original urban PT journey, resulting in an OD matrix for the integrated multi-level PT network.

2.4. Interchange hub layer

The representation of the network has been extracted from detailed images of the station and transformed into a usable format thanks to a CAD package. The network is composed of three main parts: the ground floor, the tram interchange platforms and the E-Line. These elements are separated since they are on different levels. The bus terminal has been simplified to one single arrival and departure zone since this is the way the urban model has taken care of the bus lines. As a technical note, the simulation requires the three different levels to be placed side-by-side on the same level. Pedestrian are "teleported" from one level to another when they reach the top or bottom of the stairs/escalators connecting the different levels.

The pedestrian demand comes mainly from the public transport modes present in the vicinity of the station: trams, trains and buses. When the vehicle arrives at the station the passengers disembark and become pedestrians inside the hub model. The pedestrians can be categorized into the following groups:

- *Transferring pedestrians: their origin and destination are PT vehicles. This demand pattern is well known and we have reliable information since the urban model provides the full timetable and platform allocation of trains.*
- *Arriving in Den Haag: their origin is a PT vehicle and they leave on foot. The data regarding the origin is well defined but the destination of pedestrians is unclear. Approximate estimations of the destination of the pedestrians at the aggregate level is available. Therefore, the destination of each pedestrian is sampled based on the estimate of the fraction of people using each exit.*
- *Leaving Den Haag: they arrive on foot and take a PT mode. Pedestrians in this category are problematic as there is no information regarding where or when they enter the hub area.*

No pedestrian control strategies are used in the common case study. Focus is given on providing a reliable estimate of the transfer times for passengers needing to change service. The motion of pedestrians is controlled by the NOMAD model at the operation level and the tactical level is modelled using a graph: pedestrian choose the shortest path from their current position to the destination.

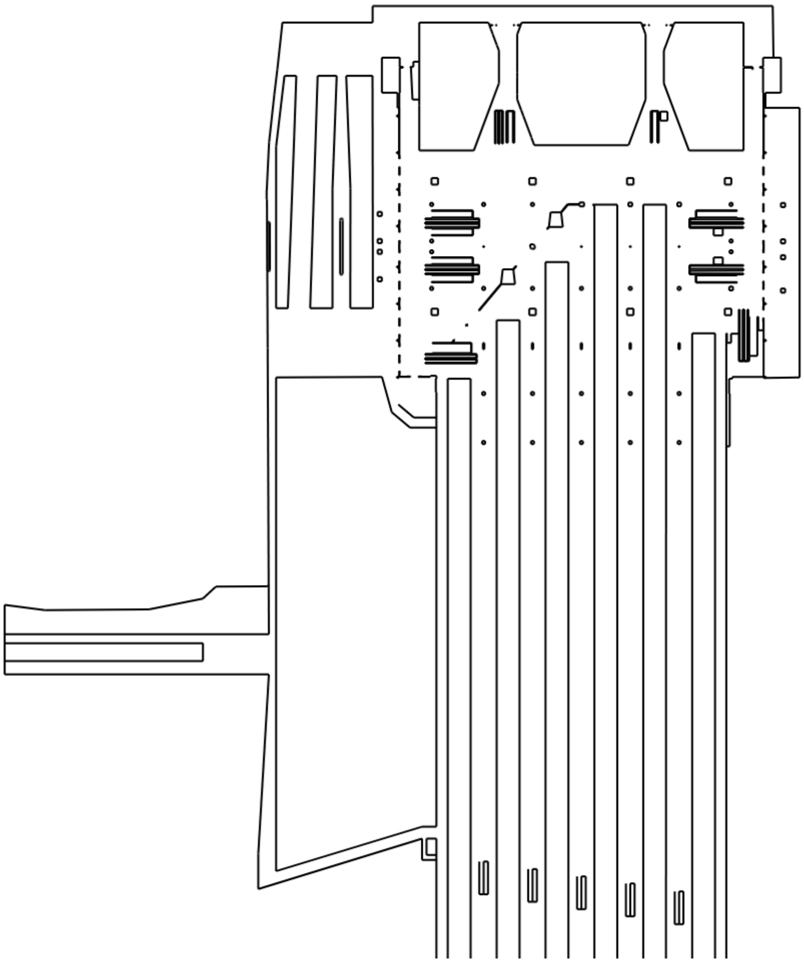


Figure 2 Main floor of Den Haag station

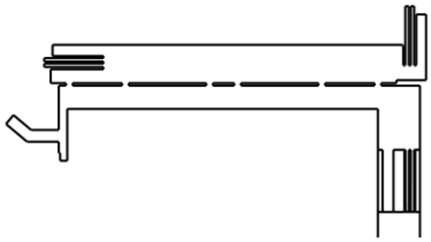


Figure 2 Tram interchange level

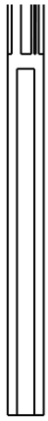


Figure 4 E-Line terminal stop in Den Haag station

3. Scenarios

In our study we develop two different disruption scenarios where a disruption occurs on the (inter)regional train network level. For these scenarios we quantify how the impact of this train network level disruption propagates to the urban PT network level, after applying optimised rescheduling and control strategies to train services on the disrupted (inter)regional network level. In line with the categories defined in section 2.2 we investigate multi-level delay for a 'local delay' (disruption category 3) and 'moving delay' (disruption category 2), which are further detailed below and in Table 1.

Table 1. *Description disruption scenarios*

	Disruption 1	Disruption 2
Disruption	Local delay (category 3)	Moving delay (category 2)
Disruption type	Infrastructure failure (e.g. signal / switch failure)	Vehicle malfunctioning
Location	Leiden: all inbound trains from Schiphol to The Hague	1 local train from Gouda towards The Hague
Start-End time	6AM – 9AM	07:24 – 07:49
Directly affected PT services	1700, 11800, 22400, 42400, 24600, 44600	37800

The first disruption type is a local delay, reflecting an infrastructure failure such as a signal failure or switch failure at a certain (fixed) location, resulting in lower speeds and thus delays for all passing trains. The disruption is simulated just before Leiden for all inbound trains towards The Hague coming from Schiphol Airport. The disruption is simulated to last during the simulation period from 6AM to 9AM. The simulation hour from 9AM to 10AM is used for service recovery. It is assumed that all trains passing this location obtain a stochastic delay of 15 minutes average. In the train rescheduling model, no train cancellations in response to this disruption are assumed.

The second disruption type represents a moving delay where one specific train is permanently malfunctioning. It is assumed this train can still finish its trip to the final destination, but at reduced speed, where it will be replaced by another train. In this scenario it is assumed that local train 237800 with scheduled departure 07:24AM from Gouda towards The Hague Central (scheduled arrival 07:49AM) suffers from this malfunctioning. This train arrives with a 10-minute delay at Gouda and operates at low speed further to The Hague. Due to this speed restriction, this train needs 50% more runtime between Gouda and The Hague than normally scheduled (12.5 minutes additional runtime), which in turn affects other train services stuck behind this train on the two-track route from Gouda to The Hague. No train cancellations are further assumed in this scenario.

4. Results

4.1. Steady-state transfer flows

The scenario analysed for exploring the mutual influence of the hub model and the urban PT model is presented here. The exact scenario is the following successive runs of each model: Urban -> Hub -> urban -> Hub -> Urban (UHUHU). With this setup, the influence of the hub model on the transfer location choice can be analysed as well as the sensitivity of the pedestrian travel times inside the hub as a function of the PT demand.

Figure 5 presents the change in median walking time between the two hub iterations. The first observation is the absence of signficant changes in demand for any given OD pair. This is visible since all points are located along the diagonal of the figure. The changes are relatively more important for OD pairs with low demand, which is expected. The change in median travel time is signficant for OD pairs with very low demand. This is caused by the very few pedestrians taken into account for computing this indicator. The statistical validity is questionable for these cases. On the other, when hundreds or thoudans of pedestrians use a specific OD, then the results are meaningful. For the higher demand cases the changes in travel time are between 0 and 10 percent. No systematic pattern is visible regarding an increase or decrease as a function of the demand levels. Further analysis would be required to determine whether a patterns exists.

Figure 6 and Figure 7 show the absolute and relative change in the number of boarding passengers per line at The Hague Central hub, respectively, between the situation without walking time distribution and with walking time distribution. From Figure 6 can be seen that the absolute change in passenger boardings is generally relatively small. The summed absolute difference equals 80, indicating that incorporating a walking time distribution does however influence passenger route choice to a limited extent. The relative differences in Figure 7 are large for lines where the absolute number of boarding passengers is low; for lines with a medium- to high number of boarding passengers, relative differences typically range between -5% and +5%. An explanation for the limited influence of incorporating a walking time distribution might be found in the relative limited crowding levels at this particular station. Combined with the lack of narrow spaces at this specific station, this results is limited differences when using a walking time distribution compared to assuming an average walking speed. However, it can be hypothesized that more substantial differences might be found, if demand levels would increase and/or this method would be applied to a station having more confined spaces.

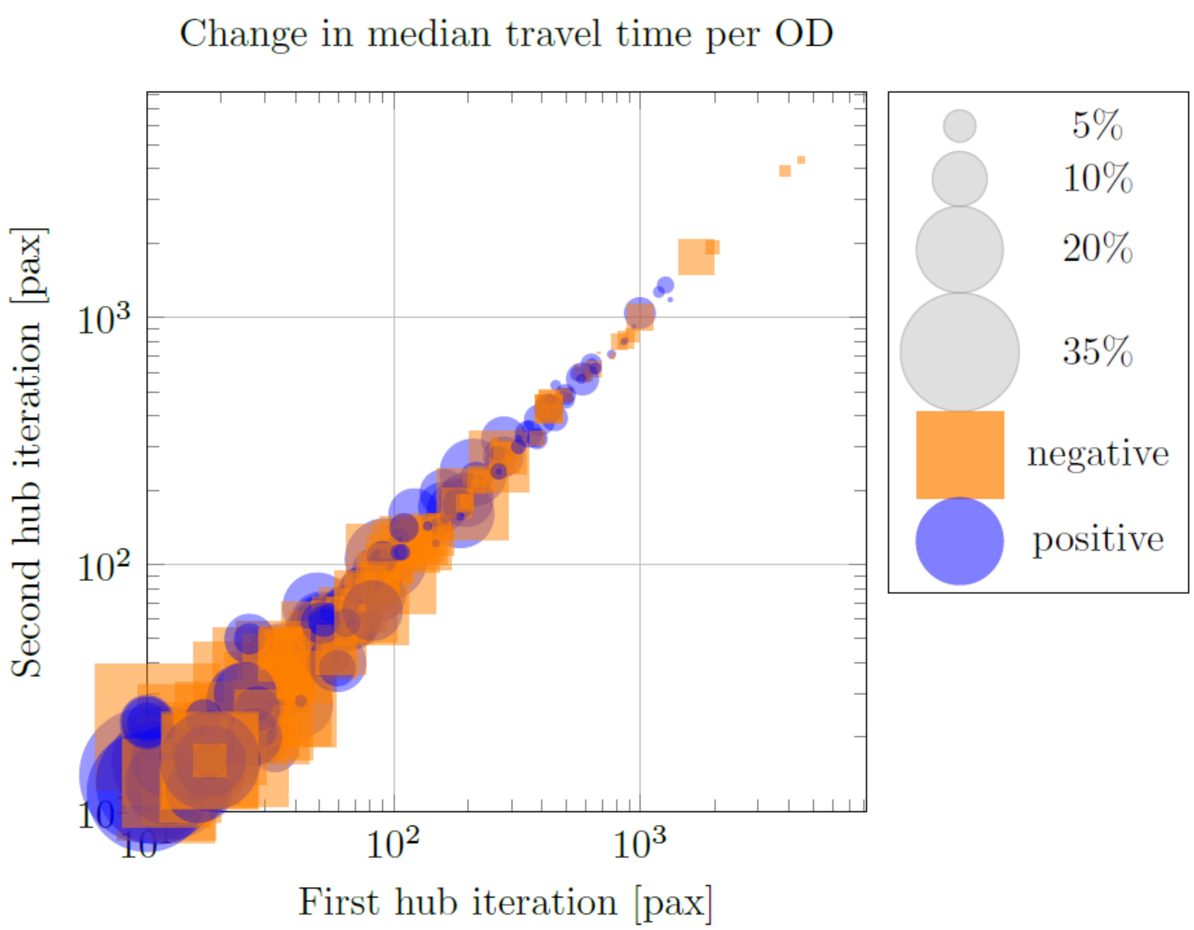


Figure 5: Change in median travel time for each origin-destination pair in the hub for two successive iterations of the hub and urban network simulations.

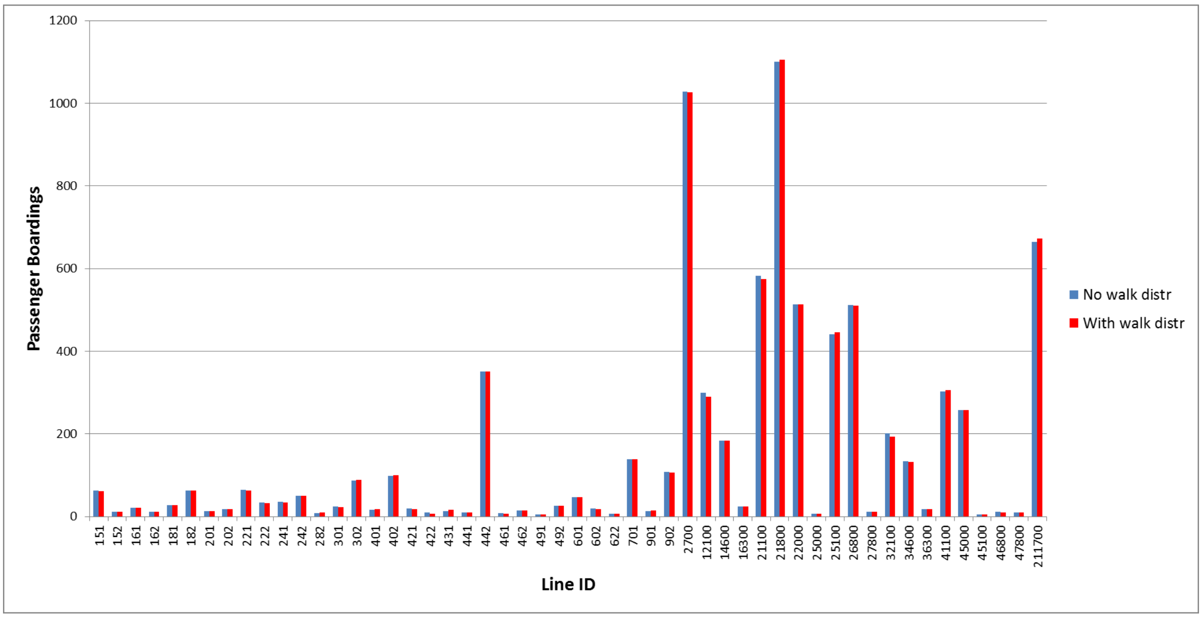


Figure 6: Change in number of boarding passengers per line at The Hague Central hub

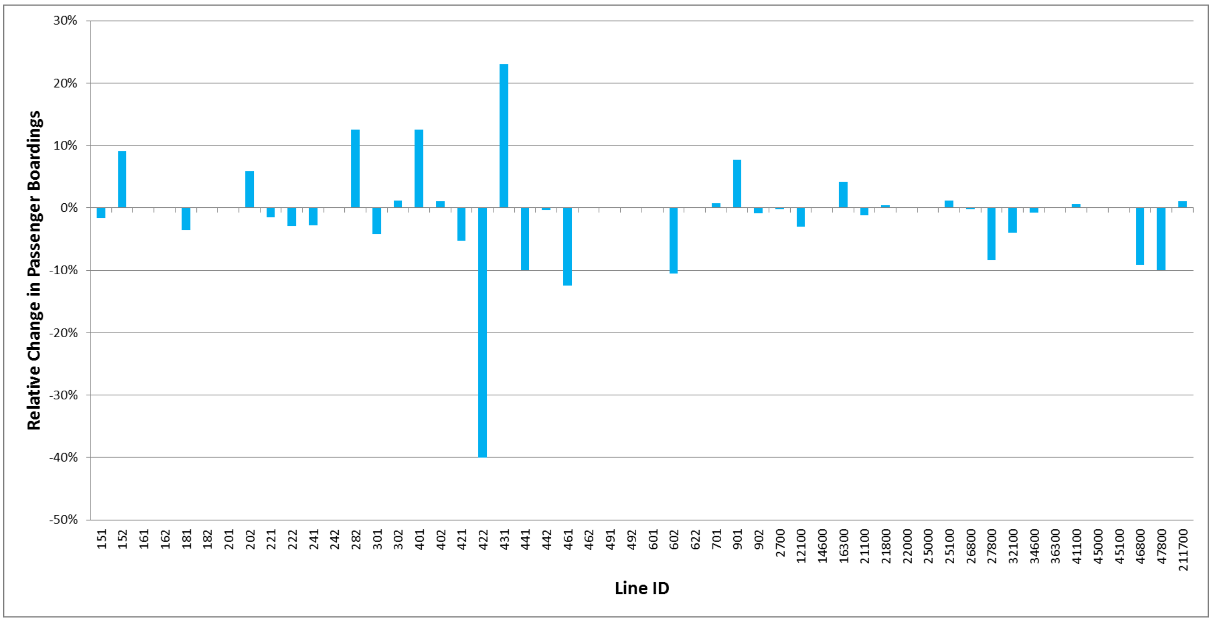


Figure 7: Relative change in number of boarding passengers per line at The Hague Central hub

4.2. Railway re-scheduling

We have used the commercial solver Gurobi version 6.5.1 to solve the optimization problems for the disruption scenarios mentioned in section 3. The reported computation times refer to when the problems are solved using a laptop with a 64-bit Windows 10, equipped with an Intel i7-5600U CPU, 2.60 GHz, with 8 Gigabytes of RAM and 8 cores.

Disruption 1

At the station Leiden (LEDN), the following trains arrive and depart late according to the disruption specification, which is implemented by giving an additional (pseudo-randomly generated) dwell time at Leiden within the interval 5-20 minutes, resulting in the following initial train delays.

In Table 2 and Table 3 the results are summarized.

Table 2. Summary of the results from solving disruption 1 with the two alternative re-scheduling policies. They grey-shaded cells indicate the best value out of the two alternatives.

	Disruption 1	
Metric	**Train-oriented policy**	**Passenger-oriented policy**
TFD(minutes)	265	267
TFD2(minutes)	214	204
TFD5(minutes)	164	148
#trains TFD2	18	22
#trains TFD5	16	16
#track changes	29	27
TAPD(#paxdelayminutes)	145279	129438
DP2(#pax)	13622	15190
Computation time (s)	600 (time limit)	212,86
Gap (%)	0,74	0,19

TFD refers to the total final delay at final destination for all trains, where TFD+X refers to that only delays larger than X minutes are considered. Final destination is the final station within the cut out (time and geographical cut).

DP2 refers to the number of passengers that experience a delay larger than two minutes when alighting, while TAPD2 refers to the total accumulated passenger delay, counting delays larger than two minutes and where the passengers alight. At the final destination within the "cut out" of the timetable, we assume that all onboard passengers alight.

#trains TFD2 refers to the number of trains that are recorded to have a delay larger than two minutes at the final destination while #trains TFD5 refers to the number of trains that are recorded to have a delay larger than five minutes at the final destination.

It may appear odd that the passenger-oriented strategy would generate solutions that have a lower TFD2-value compared to the train-oriented strategy, but since both policies consider the same components - but weighted differently - this can occur. Similarly, it may seem strange that the value for DP2 is lower for the train-oriented policy, but since DP2 do not reflect the size of the passenger delays, but instead how many that are delayed more than two minutes at their final destination, this can occur as the results show.

Table 3. The initial and final delay of the initially delayed trains coming from Leiden, depending on re-scheduling policy used. Each has 16 trains that arrive with a delay larger than five minutes at the final stop.

Train nr	Itinerary	Initial delay (minutes)	Final delay (minutes) using the Train-oriented policy	Final delay (minutes) using the Passenger-oriented policy
117001	LEDN-GVC	19	16	16
1118001	LEDN-GVC	10	7	7
1224001	LEDN-DTZ	25	22	22
1424001	LEDN-DTZ	18	16	16
1246001	LEDN-GVC	19	20	20
1446001	LEDN-GVC	6	3	3
217001	LEDN-GVC	14	13	11
2118001	LEDN-GVC	15	13	13
2224001	LEDN-DTZ	13	10	10
2424001	LEDN-DTZ	11	8	8
2246001	LEDN-GVC	15	21	12
2446001	LEDN-GVC	17	17	20
317001	LEDN-GVC	10	8	7
3118001	LEDN-GVC	16	14	13
3224001	LEDN-DTZ	12	10	10
3424001	LEDN-DTZ	22	19	19
3246001	LEDN-GVC	16	22	14

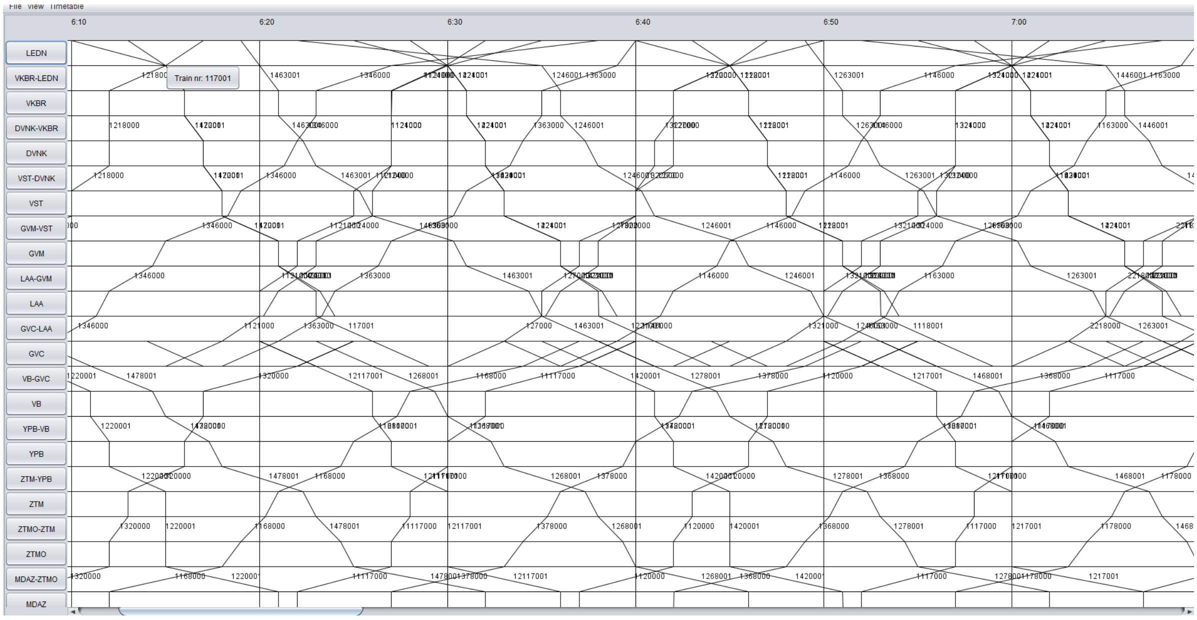


Figure. 8 . A snapshot of a selected part of the undisrupted timetable. The time window for re-scheduling is four hours (between 06:00-10:00 am) and the corresponding considered timetable, includes 208 trains to re-schedule, even though it is primarily the trains on the stretch Leiden (LEDN) to Den Haag Central (GVC) that need to be re-scheduled.

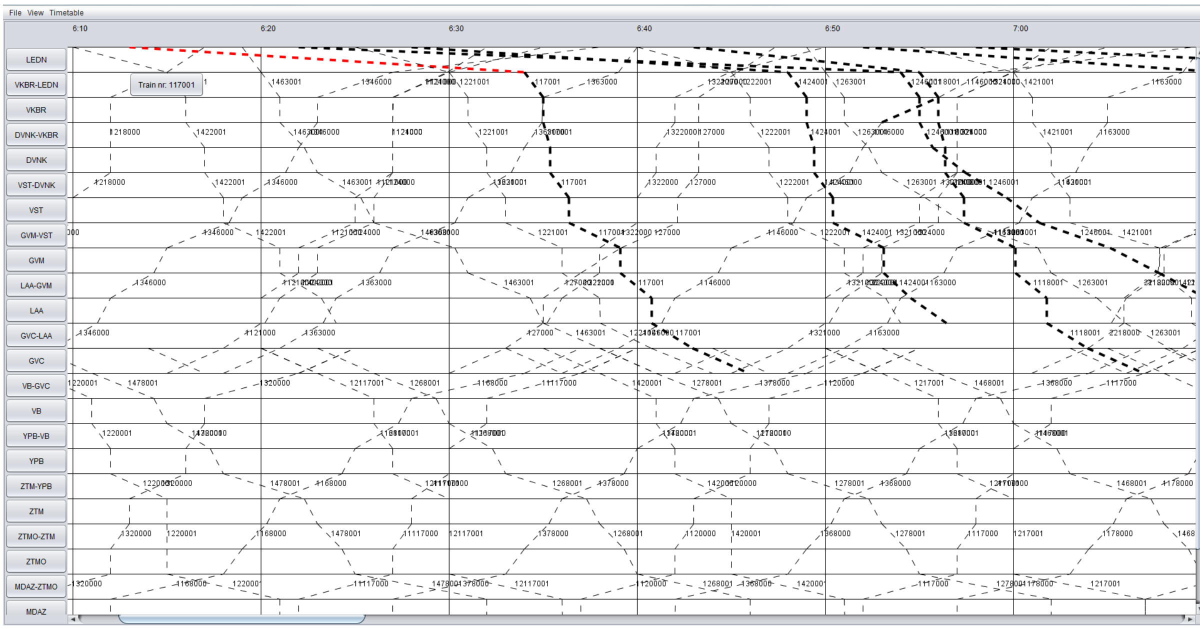


Figure. 9. A snapshot of a selected part of the re-scheduled timetable using the train-oriented re-scheduling strategy. The bold, dashed lines represent the delayed trains.

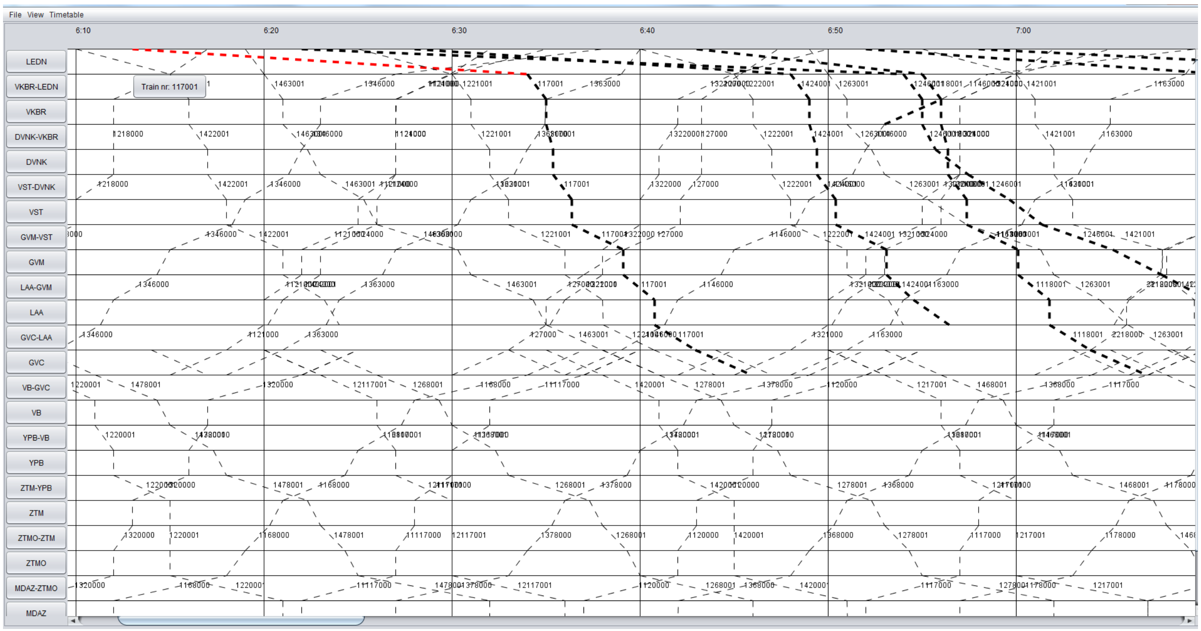


Figure. 10. A snapshot of a selected part of the re-scheduled timetable using the passenger-oriented re-scheduling strategy.

Disruption 2

As described in section 3, in this scenario it is assumed that local train 237800 with scheduled departure 07:24AM from Gouda towards The Hague (scheduled arrival 07:49AM) suffers from this malfunctioning. This train arrives with a 10-minute delay at Gouda and operates at low speed further to The Hague. Due to this speed restriction, this train needs 50% more runtime between Gouda and The Hague than normally scheduled (12.5 minutes additional runtime), which in turn may affect other train services stuck behind this train on the two-track route from Gouda to The Hague.

In Table 4.2.3 the results are summarized and show that the policies solve the disruption in a similar manner. In both solutions, the initially delayed train 2378000 arrives 15 minutes late to its final destination, while the only affected other train arrives with a delay between 2 and 5 minutes.

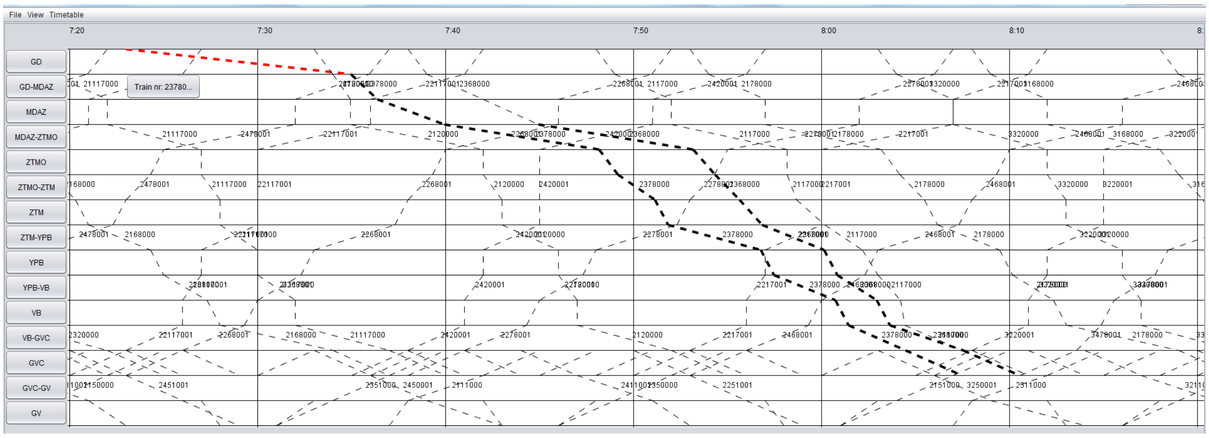


Figure. 11. A snapshot of a selected part of the re-scheduled timetable using the train-oriented re-scheduling strategy. One additional train is delayed (a knock-on delay) as an effect of the initial delay, but that train arrive with a delay less than five minutes at its final destination.

Table 4. Summary of the results from solving disruption 2 with the two alternative re-scheduling policies. They grey-shaded cells indicate the best value out of the two alternatives.

	Disruption 2	
Metric	**Train-oriented policy**	**Passenger-oriented policy**
TFD(minutes)	19	19
TFD2(minutes)	15	15
TFD5(minutes)	10	10
#trains TFD2	2	2
#trains TFD5	1	1
#track changes	1	3
TAPD(#paxdelayminutes)	2326	2326
DP2(#pax)	334	334
Computation time (s)	139,75	141,16
Gap (%)	0,22	0,126

4.3. Disruption impact

The (inter)regional train timetable which is optimised in response to the considered train network disruption is used as input in the agent-based dynamic public transport assignment model BusMezzo. A passenger demand reassignment is performed in BusMezzo using the updated train timetable, such that the propagation of the disruption impact to the urban public transport network can be quantified.

Tabular results

The disruption propagation is quantified for three separate passenger journey segments:

- *Urban-to-Urban journeys: journeys having both the origin and destination at the urban PT network.*
- *Regional-to-Urban journeys: journeys having the origin at the regional network, and the destination at the urban network.*
- *Urban-to-Regional journeys: journeys having the origin at the urban network and the destination at the regional network.*

For each of these segments it is quantified how the journey travel times and costs are affected by the different train network level disruptions. Summation of these costs over the three journey segments results in the total disruption propagation to the urban network level. Table 5 provides the summary statistics of the monetised impact the different disruptions have for the different journey segments, expressed in generalised costs. We can conclude that the disruption propagation costs of the considered 'local delay' (disruption 1) are forest to be equal to almost € 1,800, whereas the predicted disruption propagation costs for the 'moving delay' disruption are € 900. As the number of train trips directly affected by disruption 1 is substantially larger than for disruption 2, it can be noted that the disruption propagation costs for disruption 2 are still relatively high (50% of the costs of disruption 1). This might be explained by the location of disruption 1 being more distant from the considered urban network. This implies that more regional journeys which do not start or end at the urban network will be affected. Besides, there is more buffer time available for train trips to (partially) recover from delays before they arrive at The Hague Central as transfer point from regional to urban network level. In both scenarios the Urban-to-Urban journeys suffer most from the delay propagation. This can be explained by an increase in nominal and perceived in-vehicle time on the urban network due to irregular peaks in transfer demand, and by increases in waiting time due to denied boarding.

Table 5. Summary of generalised journey cost impacts of each considered train network level disruption for journeys starting and/or ending at the urban network level (rounded to nearest 25).

Passenger journey segment	Disruption 1 (local delay)	Disruption 2 (moving delay)
Urban-to-Urban journeys	€ 1,100	€ 700
Regional-to-Urban journeys	€ 0	€ 300
Urban-to-Regional journeys	€ 675	- € 100
Total	€ 1,775	€ 900

In-vehicle time impacts

Figure 12 and Figure 13 visualise the additional nominal in-vehicle time and additional perceived in-vehicle time for the different journeys segments, respectively. The disruptions result in a different transfer pattern between regional and urban network level, what can result in increases in average crowding levels. This can result in higher perceived in-vehicle times, as well as longer dwell times or potential re-routing of passengers making an urban journey. Both cases can increase nominal in-vehicle times as consequence. It can be seen that nominal in-vehicle time increases are larger in case of disruption 2, whereas perceived in-vehicle time increases – incorporating crowding levels – is of similar magnitude for both disruptions.

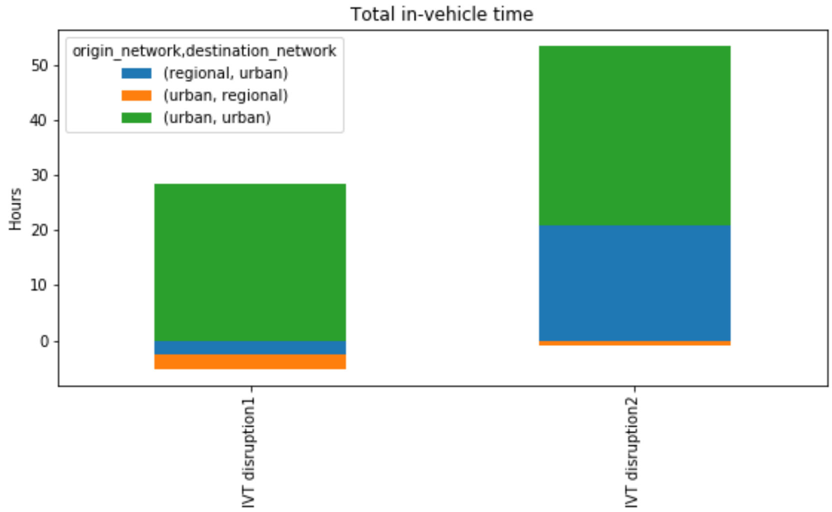


Figure 12. Additional nominal in-vehicle time.

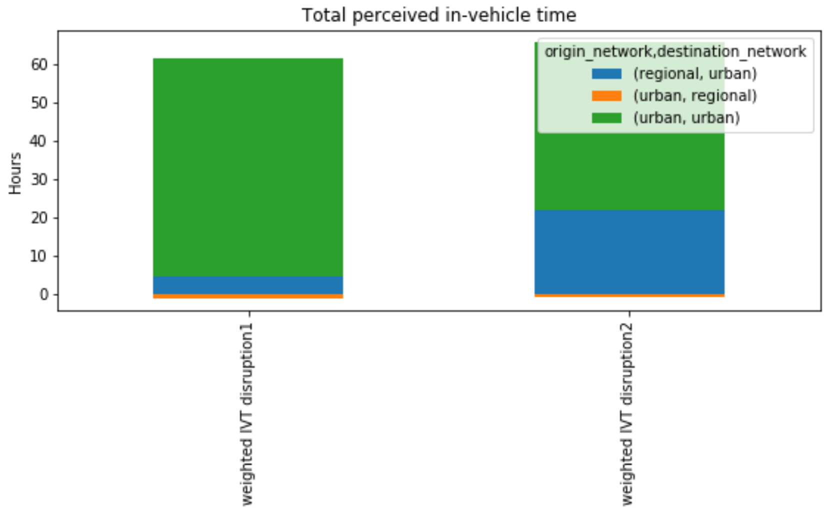


Figure 13. Additional perceived in-vehicle time.

Waiting time impacts

Figure 14 and Figure 15 present the disruption propagation in terms of total additional waiting time, and total additional waiting time due to denied boarding. The latter is a subset of the total additional waiting time. For both scenarios can be concluded that the disruption results in an increase in additional waiting time. As the additional waiting time increase is larger than the additional waiting time increase due to denied boarding, we can conclude that denied boarding is resonsible only partially for the waiting time increase. Additional waiting times caused by disruption 1 are about 2-3 higher compared to disruption 2. Particularly Urban-to-Urban and Regional-to-Urban journeys suffer from additional waiting times caused by disruption 1.

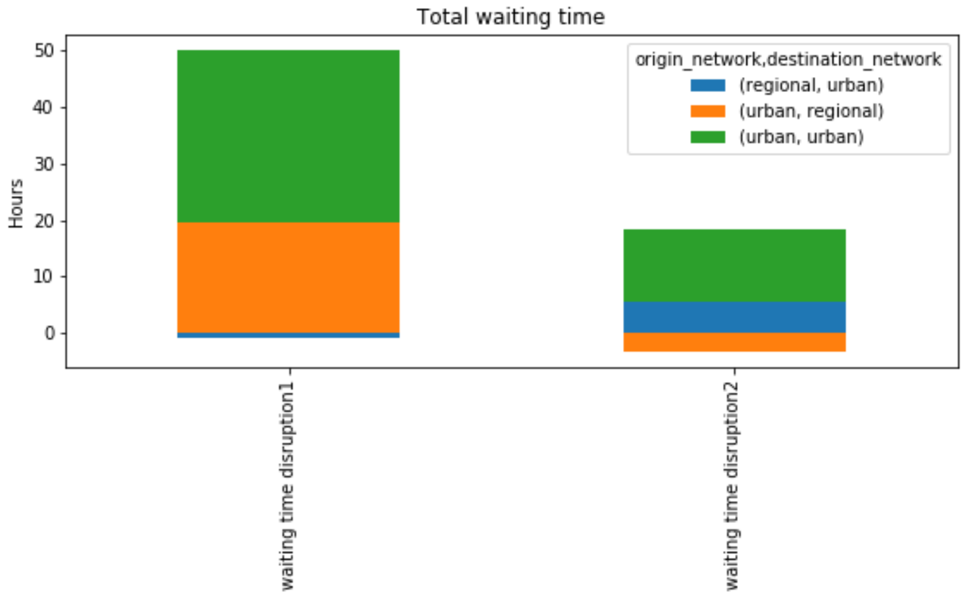


Figure 14. Additional waiting time.

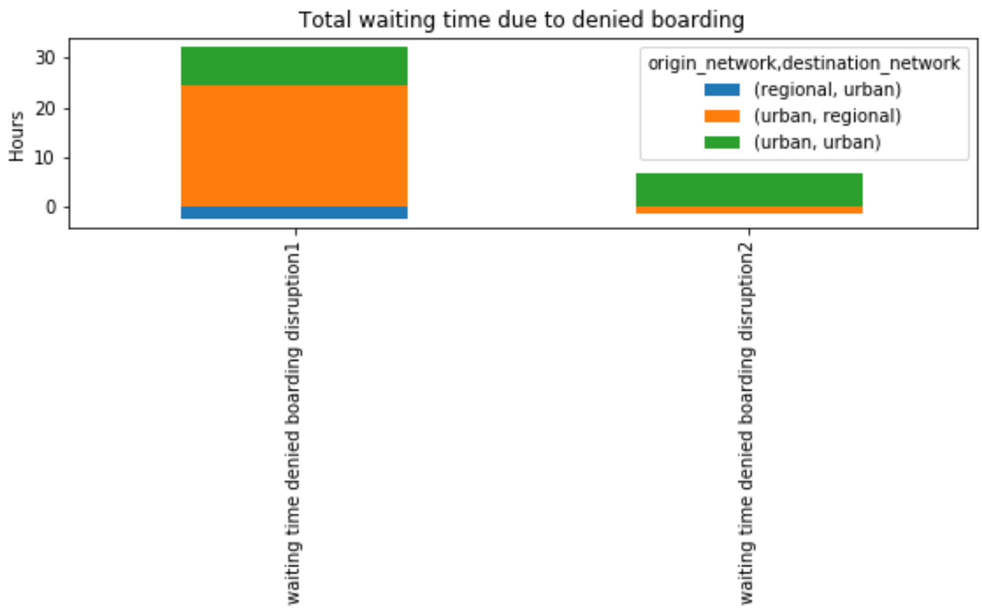


Figure 15. Additional waiting time due to denied boarding.

Journey time impacts

The total nominal and perceived journey time impacts are shown in Figure 16 and Figure 17. Summed over the different journey segments, it can be concluded that for both disruption 1 and disruption 2 the predicted nominal journey time increase is about 70 hours. The predicted perceived journey time increase for disruption 1 is however substantially larger (about 200 hours) compared to disruption 2 (just above 100 hours). The figures *presented above show that the higher nominal waiting times for disruption 1 are cancelled out by the lower nominal in-vehicle times, resulting in similar total nominal journey time increases for disruption scenarios 1 and 2. As waiting time is generally perceived more negative by passengers compared to in-vehicle times, the larger waiting time increases by disruption 1 however result in higher perceived journey times compared to scenario 2.*

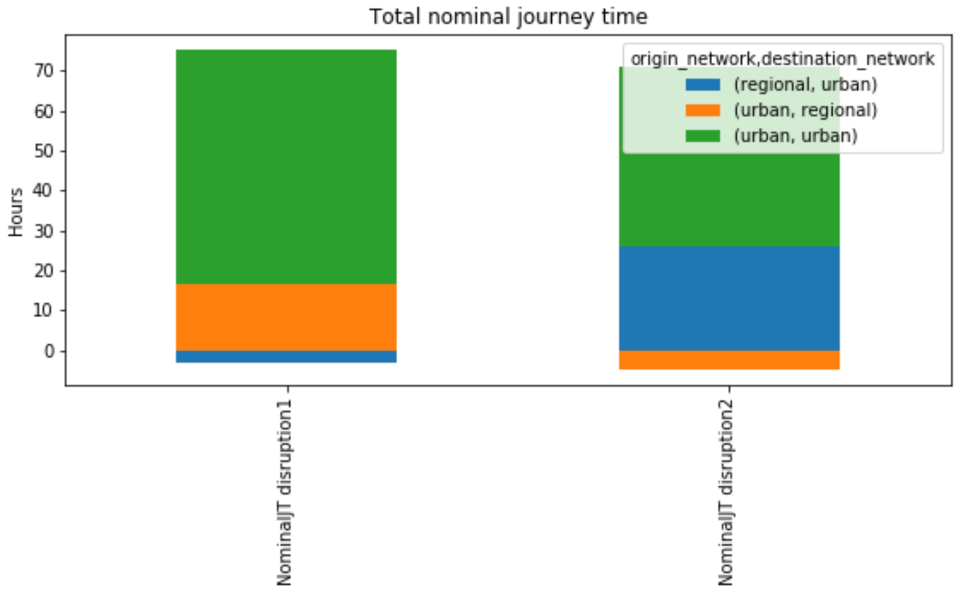


Figure 16. Total additional nominal journey time.

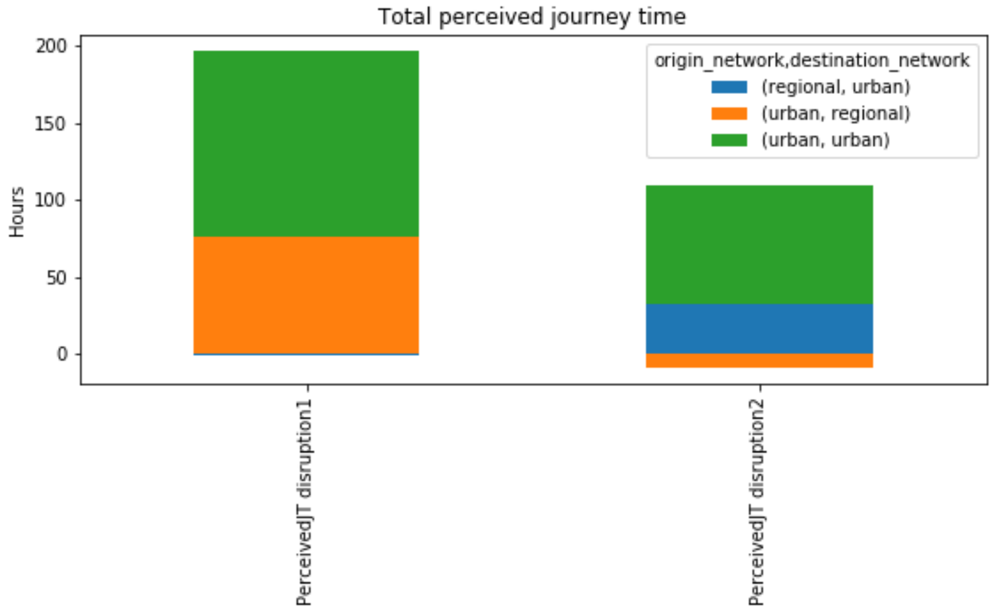


Figure 17. Total additional perceived journey time.

5 Railway scheduling case study

5.1 Case study description

Attractive, reliable and cost-effective public transport is an important means to build welfare societies, particularly from a sustainability perspective. In many countries, public transport is occurring on three levels; the local, regional and national level. In countries where the public transport market has been (partially) deregulated, the coordination of these levels and within levels are not always sufficient to enable smooth transfers and effective disturbance management. In sparsely populated areas like the region of Blekinge, where the public transport network may not be fully developed, and the frequency of direct services is low, the importance of coordinated transport services and transfer are vital, especially during disturbances.

The focus of the Swedish case study is therefore on passenger-oriented regional public transport management policies and associated optimization-based approach that serves to integrate the traffic management of regional bus services and regional train services. The aim is to evaluate management strategies that can utilize coordination between the two types of services.

Traditionally, the focus of delay management in public transportation has been on one mode and transport system, rather than two different, only implicitly connected systems. Furthermore, approaches for railway traffic management have primarily been on train delays rather than on passenger delays, and the use of passenger flow data in the models is rather rare so far, see e.g. the survey by Josyula and Törnquist Krasemann (2017).

The presented optimization-based approach is an extension of an existing optimization-based approach for real-time railway traffic management presented in Törnquist and Persson (2007). The approach in Törnquist and Persson (2007) is based on an event-based model that does not explicitly include passenger flow variables. Without passenger flow variables in the model, passenger satisfaction objectives will be limited to objectives that can be expressed in terms of train movements, see Törnquist and Persson (2005) and Törnquist (2007). This implies that it is possible to use, for example, an objective function where the passenger delays associated with train arrivals are minimized, but this assumes that the passengers do not change their route during disturbances. Hence, there is no possibility for modelling passenger dynamic route choice, in case of disturbances leading to considerations of alternative itineraries.

To allow the passengers to adapt their itinerary and complete their journey to the destination using train or other means of public transports, as fast as possible, the model is modified. To include passenger dynamic route choice, the current model is extended to include an assignment of passengers to routes and trains and busses. The approach adopted here is based on an integrated rescheduling and assignment model, which is of MILP type.

To support the passenger-centric approach, historic passenger flows are generated from smart-card data. The origin, destination and trip start time for the passengers are identified and is used as input to the optimization model. The assignment of the passenger demand is based on utility maximization (based on travel time), inspired by the work in Binder et.al. (2017). The utility is computed for the route level, where a route is a specification of the service(s) used from the origin to the destination. The passengers are grouped based on the origin and destination in their initial itineraries. For each group, a set of routes in the regional public transport network, including both train and bus services, are pre-defined. The routes used in the undisrupted case are generated from the smart-card data, and alternative routes, not used by the travellers historically, are manually generated and used as input to the optimization model.

The extended optimization model also uses the timetable and infrastructure data from the National Rail Administration (Trafikverket) as input and it permits:

1) *re-timing of regional train and bus services,*

2) *re-ordering of train services*
3) *train platform re-assignments,*
4) *holding decisions for buses and trains.*

The outline of the extended optimization model is found in Appendix A including a discussion concerning alternative objective functions.

The case study covers the extended Blekinge county region, and specifically "Blekinge Kustbana" and trains northbound from Karlskrona (Krösatåg). The main emphasis is on the larger travel relations in the expanded Blekinge region, although the southern main railway line (södra stambanan), connecting Hässleholm with Alvesta is also included in the model. The stations covered in the study are illustrated in Figure . The Euclidian distance from Hässleholm to Karlskrona is approximately 130 kilometers. The blue dots represent the stations included in the case study. The yellow zone marked in Figure 18 is Blekinge county. The stations Karlskrona, Bergåsa, Holmsjö, Ronneby, Bräkne-Hoby, Karlshamn, Mörrum and Sölvesborg are within Blekinge county, the other stations in the study area are not. The solid blue double lines in Figure 18 illustrates the train tracks, and the dashed lines illustrated the regional bus routes for the busses numbered 350, 330, 600 and 150 which are the regional busses in the study area. The two blue circles named A and H, connected with solid blue lines to the stations Alvesta and Hässleholm, respectively, represent "virtual stops" which are used to model demand to and from outside of the case study area. The numbers within brackets shows the stop ID number.

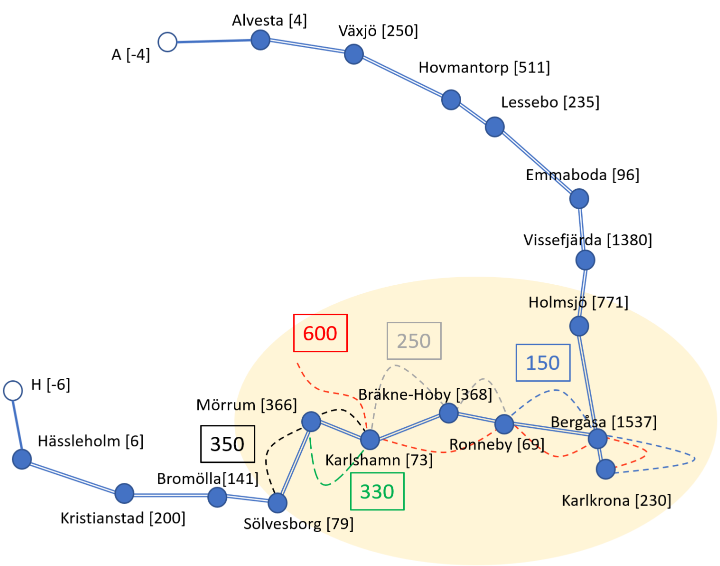


Figure 18: Map of stations included in the area of study.

Ticket data has been used to analyze how trips by train and bus are made in the region. The ticket data is used for creating travel demand patterns and routes for trains and busses within the study area. Ticket data comes from Blekingetrafiken ticket system. Most of the trips made in the Karlskrona region is paid by tapping a Blekingetrafiken card when boarding the vehicle. However, at stations outside of Blekinge, other payment cards are more common, and those trips are not logged in the Blekingetrafiken system. The experiments are using passenger flow data extracted from smart-card data during October 2016 and provided by the regional public transport service provider in Blekinge, Blekingetrafiken. The smart-card data includes information about the boarding station, line and time, but not the alighting station. The process described in Trépanier and Chapleau (2006) is applied to infer the alighting station for the trips and to complete the passenger demand description. This demand data is scaled based on information from a regional travel survey (Mind research, 2015), in order to capture trips that are paid by other means than a smart-card. The scaling is done by computing the proportion of the number of journeys in the survey to the number of journeys inferred from the ticket data for each pair of origin and destination. For example, in the relation Karlskrona to Ronneby this proportion is 148/108. This proportion is then applied to the number of inferred journeys from the ticket data for all trains *connecting this origin and destination. In the case of Karlskrona to Ronneby, the resulting demand profile of journeys during the day is shown in Figure 19, where the blue line shows the number of journeys per train departure inferred from the ticket data, and the red line show the number of journeys per departure after the scaling. The x-axis in Figure 19 shows all train departures from Karlskrona towards Ronneby during Monday to Thursday, that is, one train every hour between 04:47 and 21:47. The y-axis shows the number of passengers per departure in this travel relation.*

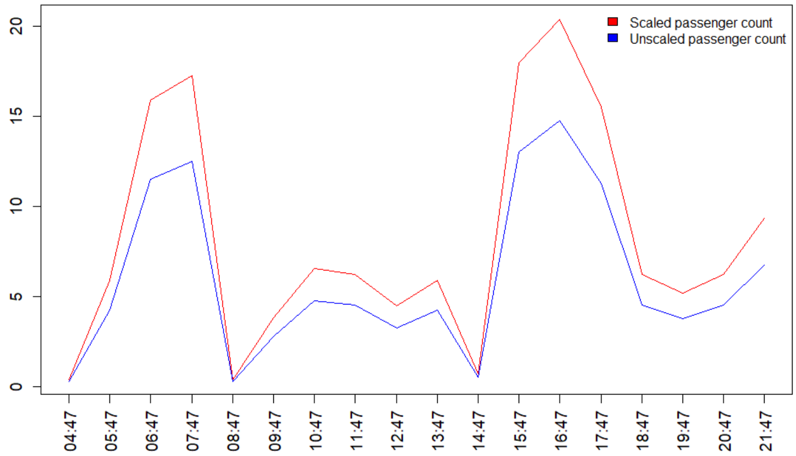


Figure 19: Number of passengers per train departure in the relation between Karlskrona and Ronneby with unscaled and scaled number of passengers.

No survey data is available for the north-south bound trains from Karlskrona nor for the busses. For the busses, there are reasons to believe that a higher percentage is using a Blekingetrafiken ticket. The number of bus journeys inferences is not scaled.

5.2 Experimental setup and scenarios

The intentions of the experiments are primarily to study how:

- *the selection of disturbance management strategy (i.e. choice of alternative objective functions) and the passenger route choice affect the resulting train prioritization,*
- *different configurations of the bus holding policy affect the passenger route choice and train prioritization.*

The optimization model outlined in Appendix A is used and the objective functions defined by Eq.A32 and Eq.A33 are adopted, separately, to simulate two alternative disturbance management strategies, which focuses on train delays, or passenger delays, respectively. All time variables are given in seconds. The following parameter values are used: $\alpha = 30$, $\beta = 10$, $\rho = 3600$ *seconds, and* $d_{tr} = 120$ *seconds.*

There are two main scenarios. In the first scenario, train 1064 is delayed minimum {20, 25, 30, 35} minutes before departing Hässleholm (Hm). The disturbance occurs during rush hour and the time window for re-scheduling the bus and train services and associated passenger route assignments is 16:00-20:00.

In the second scenario train 1064 is delayed minimum {20, 25, 30, 35} minutes before departing Kristianstad (Cr). The time window for re-scheduling the bus and train services and associated passenger route assignments is 16:35-20:00.

The railway line between Hässleholm-Kristianstad-Karlskrona is single-track and delays easily propagate. The graphical timetable for the trains scheduled on this track between Hässleholm and Bromölla, is shown in Figure 21. There are only alternative rail services on the stretch Hässleholm-Kristianstad-Karlshamn. Alternative transport services on the stretch Karlshamn-Ronneby-Karlskrona are a few, rather infrequent regional bus *services. Hence a selection of passenger groups originally scheduled to travel with 1064, has the option to choose an alternative route, but the number of alternatives is modest. See Table 6 for an overview of the passenger groups that are given alternative routes (in addition to the final optional route as described in Appendix A). Figure 20 shows the number of passengers boarding and alighting at the stops along the line from Hässleholm to Karlskrona using train number 1064. The number of passengers on the train when entering Hässleholm is shown in as the bar for the station "+Hässleholm". In Table 7, the alternative services are presented.*

Table 6: Hm+ refers to that the actual origin of the passenger group is outside of the studied area and the passenger group enters the sub-network at Hm (Hässleholm). The sum of passengers is 290. In addition, there are two passenger groups with four passengers in total that also are associated with train 1064, but where there are no alternative routes for them.

Pax group ID	#Passengers	ServiceID_last	Itinerary
2	11	1064	+Hm⇒Rb
7	27	1064	+Hm⇒Kh
20	16	1064	+Hm⇒Mru
38	10	1064	Hm⇒Kh
40	10	1064	Hm⇒Sög
263	14	1064	Cr⇒Rb
392	63	1064	+Hm⇒Sög
588	16	1064	+Hm⇒Bml
611	3	1064	Rb⇒Ck
615	5	1064	Rb⇒Båa
618	3	1064	Kh⇒Rb
625	2	1064	Kh⇒Ck
639	3	1064	Sög⇒Kh
666	3	1064	Bml⇒Kh
671	3	1064	Bml⇒Sög
676	1	1064	Bml⇒Ck
683	18	1064	Cr⇒Kh
685	37	1064	Cr⇒Sög
689	21	1064	Cr⇒Bml
739	1	1064	+Hm⇒Cr
787	1	1064	Sög⇒Ck
825	4	1064	Cr⇒Ck
826	18	1064	Cr⇒Mru

Table 7: The scheduled alternative services that are the basis for defining alternative routes for the passenger groups that intend to alight the delayed train 1064. The alternatives have been compared to the alternatives suggested by the Swedish journey planner Resrobot. Note the color, not feasible connection between the train 1976 and the bus service 600. This connection may become available depending on the configuration of the bus holding policy we have included in the model.

Station / Service nr	Ö-tåg 1064	Pågatåg 1224	Pågatåg 1976	Pågatåg 1876	Bus 600 (156493)	Bus 150 (275340)
Hässleholm (Hm) Departure	16:13	16:24		16:58		
Kristianstad (Cr) Arrival	16:32	16:52		17:19		
Kristianstad (Cr) Departure	16:39		17:02			
Karlshamn (Kh) Arrival	17:18		17:50		17:48	
Karlshamn (Kh) Departure	17:20				17:48	
Ronneby (Rb) Arrival	17:45				18:20	
Ronneby (Rb) Departure	17:46				18:20	18:02
Karlskrona (Ck) Arrival	18:12				18:52	18:40

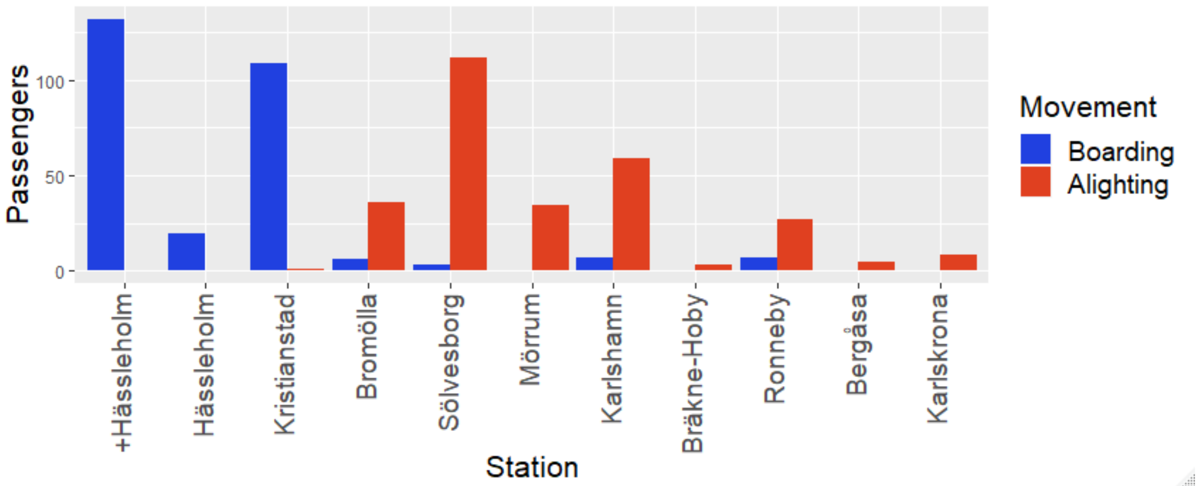


Figure 20: Number of boarding and alighting passengers at the stops on train number 1064. The station "+Hässleholm" refers to the number of passengers already on the train when entering Hässleholm.

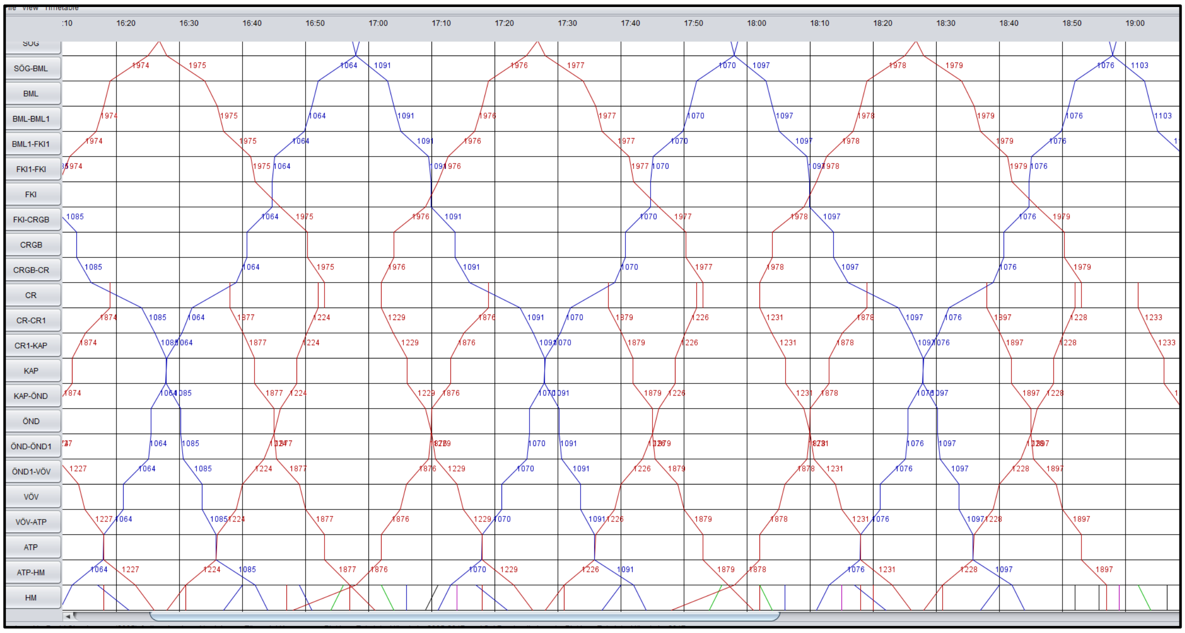


Figure 21: A screen shot of the initial timetable on the stretch Hässleholm (Hm) toward Sölvesborg (Sög) during the studied time period 16:00—20:00 where the east-bound train 1064 is subject to a number of different disturbances according to the scenario specification.

We have solved each scenario using the commercial solver Gurobi version 6.5.1 using a laptop with a 64-bit Windows 10, equipped with an Intel i7-5600U CPU, 2.60 GHz, with 8 Gigabytes of RAM and 8 cores.

We have assessed the resulting re-scheduling solutions based on the following metrics:

- *TFD = Total final delay at the final destination for all trains, where TFD+X refers to that only delays larger than X minutes are considered. Final destination is the final station within the cut out (time and geographical cut).*
- *DP2 = Number of passengers that experience a delay larger than two minutes when alighting.*
- *TAPD2 = Total accumulated passenger delay, counting delays larger than two minutes and where the passengers alight. At the final destination within the "cut out" of the timetable, we assume that all onboard passengers alight.*

- *#trains TFD2 refers to the number of trains that are recorded to have a delay larger than two minutes at the final destination while #trains TFD5 refers to the number of trains that are recorded to have a delay larger than five minutes at the final destination.*

We have also visually analyzed the revised train schedules to better understand the train prioritization and to verify the passenger route choices.

5.3 Initial results and analysis

In Table 8 is a summary of the experimental results from scenario 1, where train 1064 suffers from a temporary problem at Hässleholm and thus cannot leave Hässleholm earlier than {20,25,30, 35} minutes after scheduled departure time. The top matrix of the table provides some key properties of the solutions generated by the re-scheduling strategy that focuses on minimizing trains delays (i.e. the train-oriented strategy), while the middle contains the results when the passenger delays are primarily minimized (i.e. the passenger-oriented strategy). The third matrix contains the results when the passenger-oriented strategy is applied and alternative routes are enabled for the passenger groups listed in Table 6.

Table 8: A summary of the experimental results for scenario 1. The grey-shaded cells indicate where the best values for each metric and scenario is found. The optimality gap is always less than or equal to 0.5%.

	Scenario 1 - Minimizing train delays primarily - no bus holding			
Metric	**Initial delay 20 min**	**Initial delay 25 min**	**Initial delay 30 min**	**Initial delay 35 min**
TFD(minutes)	10	51	47	44
TFD2(minutes)	2	43	42	41
TFD5(minutes)	0	38	38	38
#trains TFD2	3	3	2	1
#trains TFD5	0	1	1	1
#track changes	5	5	6	4
DP2(#pax)	322	295	314	294
TAPD(#paxdelayminutes)	3639	8145	8238	9949
Computation time (s)	36,08	155,66	64,97	40,46
	Scenario 1 - Minimizing pax delays primarily - with/without bus holding			
Metric	**Initial delay 20 min**	**Initial delay 25 min**	**Initial delay 30 min**	**Initial delay 35 min**
TFD(minutes)	10	51	72	65
TFD2(minutes)	2	31	66	57
TFD5(minutes)	0	13	57	48
#trains TFD2	3	9	3	3
#trains TFD5	0	3	3	3
#track changes	5	9	8	8
DP2(#pax)	322	403	331	314
TAPD(#paxdelayminutes)	3639	5549	7703	9115
Computation time (s)	43,38	170,86	163,72	200,76
	Scenario 1 - Minimizing pax delays primarily - hold bus max 5 minutes + alternative routes			
Metric	**Initial delay 20 min**	**Initial delay 25 min**	**Initial delay 30 min**	**Initial delay 35 min**
TFD(minutes)	10	51	72	43
TFD2(minutes)	2	31	66	41
TFD5(minutes)	0	13	57	38
#trains TFD2	3	9	3	1
#trains TFD5	0	3	3	1
#track changes	5	9	8	4
DP2(#pax)	322	403	331	297
TAPD(#paxdelayminutes)	3639	5549	7455	8426
Computation time (s)	101,1	221,74	246,6	235,07

As can be observed, the differences between the three alternative re-scheduling configurations are insignificant for an initial delay of 20 minutes. The train-oriented strategy that minimizes train delays, primarily but also track deviations and route changes performs rather stable also for reducing the number of passengers that arrive later than two minutes. However, the accumulated passenger delay (TAPD) is naturally higher than when the passenger-oriented strategy is used.

It can also be observed that the passenger-oriented strategy is not really useful when there are no alternative routes. Furthermore, for this particular case study, the bus holding policy is very critical for enabling a route choice in Karlshamn, since the initial timetables would not allow for a transfer from train 1976 to bus 600 in Karlshamn, and we also require a minimum transfer time of two minutes for walking from the train platform to the bus stop some 50 meters away.

It may intuitively appear problematic that the passenger-oriented strategy would generate solutions that have better TFD2- and TFD5-values than the train-oriented strategy (as when the initial delay is 25 minutes), but since both strategies consider the same components - but weighted differently - this can occur. If the penalty for delays larger than two minutes would increase by a certain factor in the train-oriented strategy, this would not occur. The lower limit for TFD2 is around 20 for the mentioned scenario with an initial delay of 25 minutes.

It may also appear strange that the value for DP2 decreases with an increasing initial delay, but since DP2 do not reflect the size of the passenger delays, only how many that are delayed more than two minutes at their final destination, this can occur.

In the analysis of how and when the alternative routes are selected, we can observe that it is only when the delay is 30 minutes or larger the route choice has an effect. In Table 9, the passenger groups that were delayed (>= 1 minutes) and which service they were associated with initially is presented.

Table 9: An overview of which passenger groups that become affected by the re-scheduling of trains and buses.

Scen 1: Passenger-oriented strategy, enabled alternative routes, hold bus max 5 min											
Initial delay 30 minutes						**Initial delay 35 minutes**					
Pax group	#Pax	ServiceID	Itinerary	Arrival delay(minu	Selected route	Pax group	#Pax	ServiceID	Itinerary	Arrival delay(mi	Selected route (#routes)
2	11	1064	+Hm⇒Rb	43	1(3)	2	11	1064	+Hm⇒Rb	32	2(3)
7	27	1064	+Hm⇒Kh	22	1(3)	7	27	1064	+Hm⇒Kh	30	2(3)
20	16	1064	+Hm⇒Mru	23	1(3)	20	16	1064	+Hm⇒Mru	28	2(3)
35	1	1097	BS⇒Mru	5	1(2)	38	10	1064	Hm⇒Kh	30	2(3)
38	10	1064	Hm⇒Kh	22	1(3)	40	10	1064	Hm⇒Sög	26	2(3)
40	10	1064	Hm⇒Sög	23	1(3)	163	3	1064	Kh⇒Bhb	32	1(2)
61	2	1097	Rb⇒Sög	2	1(2)	263	14	1064	Cr⇒Rb	43	1(3)
123	1	1097	Kh⇒Sög	2	1(2)	392	63	1064	+Hm⇒Sög	26	2(3)
152	1	1097	Kh⇒Mru	5	1(2)	588	16	1064	+Hm⇒Bml	26	2(3)
163	3	1064	Kh⇒Bhb	20	1(2)	611	3	1064	Rb⇒Ck	26	2(4)
194	3	1097	Sög⇒Bml	2	1(2)	615	5	1064	Rb⇒Båa	18	2(4)
204	4	1097	Sög⇒Cr	2	1(2)	618	3	1064	Kh⇒Rb	32	2(3)
263	14	1064	Cr⇒Rb	43	1(3)	625	2	1064	Kh⇒Ck	35	2(3)
392	63	1064	+Hm⇒Sög	23	1(3)	639	3	1064	Sög⇒Kh	30	2(3)
588	16	1064	+Hm⇒Bml	24	1(3)	666	3	1064	Bml⇒Kh	30	2(3)
611	3	1064	Rb⇒Ck	26	2(4)	671	3	1064	Bml⇒Sög	26	2(3)
615	5	1064	Rb⇒Båa	18	2(4)	676	1	1064	Bml⇒Ck	35	2(3)
618	3	1064	Kh⇒Rb	29	2(3)	683	18	1064	Cr⇒Kh	30	2(3)
625	2	1064	Kh⇒Ck	38	2(3)	685	37	1064	Cr⇒Sög	26	2(3)
639	3	1064	Sög⇒Kh	22	1(3)	689	21	1064	Cr⇒Bml	26	2(3)
666	3	1064	Bml⇒Kh	22	1(3)	739	1	1064	+Hm⇒Cr	19	2(4)
671	3	1064	Bml⇒Sög	23	1(3)	750	1	1064	BS⇒Bhb	32	1(2)
676	1	1064	Bml⇒Ck	43	1(3)	787	1	1064	Sög⇒Ck	35	2(3)
683	18	1064	Cr⇒Kh	22	1(3)	825	4	1064	Cr⇒Ck	35	2(3)
685	37	1064	Cr⇒Sög	23	1(3)	826	18	1064	Cr⇒Mru	33	1(2)
689	21	1064	Cr⇒Bml	24	1(3)	959	3	Bus 600	BS⇒Kh	3	1(2)
700	3	1097	Ck⇒Sög	2	1(2)	**Sum:**	**297**			**744**	
722	16	1097	Mru⇒Cr	2	1(2)						
739	1	1064	+Hm⇒Cr	20	2(4)						
750	1	1064	BS⇒Bhb	20	1(2)						
772	1	1097	Kh⇒Cr	2	1(2)						
787	1	1064	Sög⇒Ck	43	1(3)						
808	5	1097	Bml⇒Cr	2	1(2)						
825	4	1064	Cr⇒Ck	43	1(3)						
826	18	1064	Cr⇒Mru	23	1(2)						
Sum:	331			708							

In the leftmost part of Table 9, corresponding to the results when we have an initial delay of 30 minutes, we can see that only the passenger groups that have an alternative route with no transfers change their route. While in the next scenario where the initial delay is 35 minutes, a route change pays off also for the passenger groups that can use the alternative train services 1224 and/or 1976, with a possible transfer to bus 600 in Karlshamn.

This is only possible due to that the trains in this case are prioritized differently. That is, the train services 1224 and 1976 are scheduled to run after train 1064 (see Figure 21 above), so it is expected that those trains run after 1064 also when 1064 is delayed 10-15 minutes. Train 1064 does also run over a larger stretch on the single-tracked line, thus causing significant knock-on-effects. However, train 1224 and 1976 will in addition get an even lower priority in this particular case when the passenger-oriented strategy is applied since there are no passenger flows associated with those two trains due to limitations in the smart-card data we have received and used. In Figure 22, the resulting, revised train schedule for the scenario when the initial delay is 30 minutes is shown. In Figure 23, the resulting, revised train schedule for the scenario when the initial delay is 35 minutes is shown.

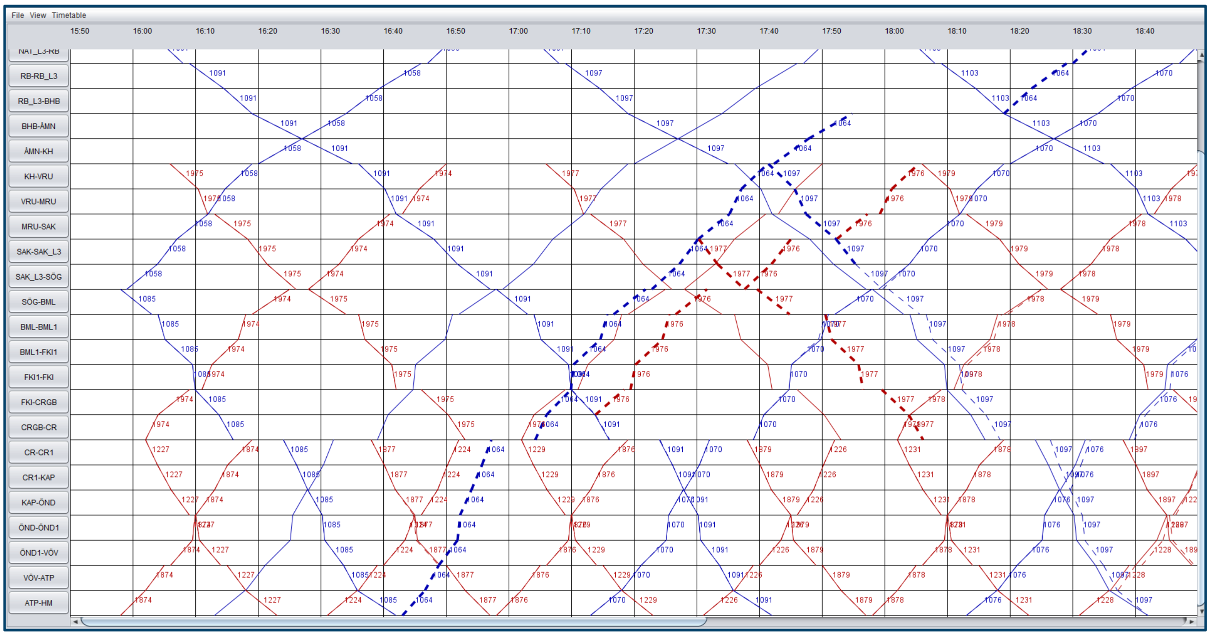


Figure 22: The solid lines are the initial scheduled train paths, while the dotted lines are the paths after disturbance management and re-scheduling., Hence only the trains that deviate from the initial schedule have a dotted path and for the on-time trains the solid and the dotted lines overlap. As can be seen train 1064 are now re-scheduled to run after train 1224, but before train 1976.

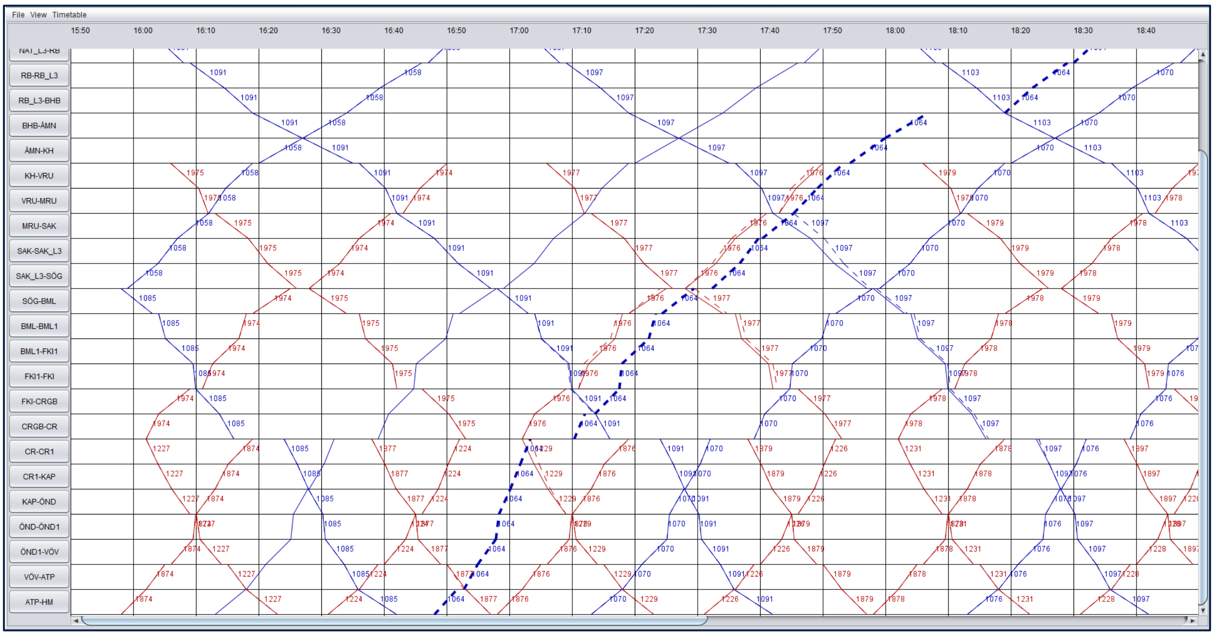


Figure 23: The solid lines are the initial scheduled train paths, while the dotted lines are the paths after disturbance management and re-scheduling., Hence only the trains that deviate from the initial schedule have a dotted path and for the on-time trains the solid and the dotted lines overlap. As can be seen train 1064 are now re-scheduled to run after both train 1224 and train 1976 which makes it beneficial for e.g. passenger groups 2 to select an alternative route that would generate a lower arrival delay.

5.4 Discussion and Preliminary conclusions

In regions such as Blekinge, where the frequency of regional public transport services is rather low, the importance of coordinated transport services and transfers are vital, especially during disturbances.

The results from this study indicate that the passenger-oriented policy itself is relevant to consider in the studied context. However, a real-life implementation would be associated with significant organizational challenges since the real-time transport service management and train service operations are currently associated with different contractual agreements and several different organizations. Investigating the potential benefits of synchronizing a sub-set of regional buses with selected train arrivals during disturbances could, however, be a first step towards a more robust and passenger-oriented regional public transport system.

When train delays occur, it is typically very challenging to arrange replacement buses for a possibly large amount of people with different itineraries. Using regular bus services as alternatives are sometimes considered by the transport coordinators as a possible partial solution, but it is also known to be associated with the risk of overcrowding those buses and that the delay is then spreading further into the bus service network. Therefore, it is often up to the experienced commuters to find alternative routes in real-time during disturbances, whereas the non-familiar network users, are dependent on the advice and help of others.

The applicability of the passenger-oriented optimization approach applied in this study is, not surprisingly and as already mentioned, sensitive to the distribution of passengers (i.e. the availability of sufficient passenger flow data). The computation time for the commercial solver is rather high for a real-time application, but since the problem instances studied here are rather large, covering a larger part of the railway network in the region and considering a time horizon of almost four hours, it may not be a significant problem. However, an alternative solution approach would be to extend the parallel algorithm for train traffic disturbance management developed in this project, see Josyula et. al. (2018) and Josyula et. al. (2019) for further information.

6 Hub pedestrian flow control case study

6.1 Case study description

Comfort and reliability are two important aspects which pedestrians seek when transferring inside transportation hubs. A lack of these aspects might make users change mode and discourage them from using public transport modes. Therefore, to ensure a high attractivity of the public transport network the hubs must also be analyzed in depth.

The present case study focuses on the train station in Lausanne, Switzerland. The station is composed of two pedestrian underpasses which allow passengers to transfer from one train to another, or to the urban network (bus ans metro). Pedestrian tracking data has been collected in both underpasses but the western underpass generally of more interest as more people use it.
The objective of the analysis is to investigate the effectiveness of two control strategies for improving the pedestrian dynamics. The first is gating which aims to prevent excessive congestion in the intersection of corridors and the second is flow separators which minimize pedestrian counter flow. This is done in a microscopic pedestrian simulator combined (based on NOMAD) with a discrete event simulator which takes care of managing and simulating the traffic controller and the control devices.

The demand which is used comes from two possible sources, either a real scenario from the measured data or a simulated scenario which models the arrival of trains. The advantage of the first is the similarity to reality, while the second option allows for more control over the scenario.

6.2 Scenarios

As experienced by many individuals and shown in studies, counter flow in pedestrian traffic is responsible for a significant increase in travel time. This happens as people have to "slalom" between the people coming in the opposite direction. In order to prevent this, we propose a control strategy for preventing counter flow in corridors: flow separators. Counter flow can be prevented by splitting the corridors dynamically based on the pedestrian flows coming in each direction. Figure 24: The width dedicated to each direction is adjusted based on the flows entering the corridor. presents a schematic setup where a flow separator is installed in a corridor.

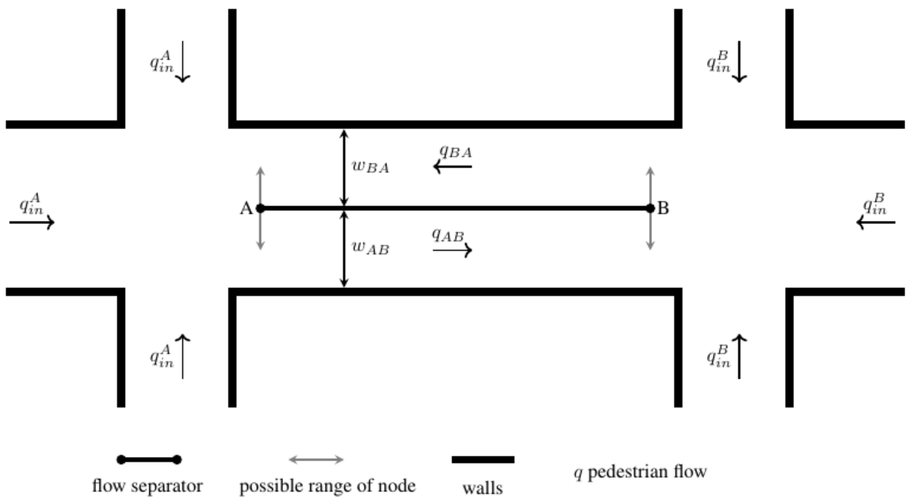


Figure 24: The width dedicated to each direction is adjusted based on the flows entering the corridor.

Unlike the gating strategy, there is no feedback loop for the dynamic separators as the pedestrian flows are measured upstream from the devices. This situation could occur when an important queue forms in front of the separator, inducing spillback. Nevertheless, we assume that this situation does not occur. Therefore, the width *available for the pedestrians moving from A to B is function of the flows going from A to B and the flows going from B to A. These flows can either be measured (past or present) or predicted (future):*

$$w_{AB}(t) = f(q_{AB}(t), q_{BA}(t)), \text{ with}$$
$$f(q_{AB}(t), q_{BA}(t)) = w \cdot \frac{q_{AB}}{q_{BA} + q_{BA}}$$

where w_{AB} is the width dedicated to pedestrians walking from A to B. This formulation was chosen to keep the calibration to a strict minimum, we propose a function which relies only the measured flows at the current time. This way, the width dedicated to each direction is proportional to the flows. In order to prevent the width dedicated to a specific direction become too small for pedestrians to move freely, there are lower and upper bounds on the widths. These bounds, denominated w^{min}_{AB} and w^{max}_{AB} correspond to the minimum width required by an individual to walk comfortably along a corridor The full specification of the width, at time t, dedicated to pedestrian walking from A to B is therefore:

$$w_{AB}(t) = \begin{cases} w_{AB}^{min}, & \text{if } w \cdot \dfrac{q_{AB}}{q_{AB} + q_{BA}} \leq w_{AB}^{min} \\ w_{AB}^{max}, & \text{if } w \cdot \dfrac{q_{AB}}{q_{AB} + q_{BA}} \geq w_{AB}^{max} \\ w \cdot \dfrac{q_{AB}}{q_{AB} + q_{BA}}, & \text{otherwise} \end{cases}$$

6.3 Results

The control strategy presented in the previous section has been implemented in a pedestrian simulator. This simulator uses the pedestrian motion model from NOMAD. First, the impact of the dynamic flow separator is compared to the "no strategy" situation and a static version of the flow separators. The static version is a fixed separator in the middle of the corridor. Secondly, the effectiveness of this control strategy is shown for different demand levels. Finally, a sensitivity analysis to the compliance (i.e. following the rules) is accomplished. We chose a demand pattern such which is a rough approximation of the flows which can occur inside a train station when trains alight their passengers. This demand pattern is used in all numerical experiments, except in some cases the amplitude is changed.

As the simulation is a stochastic process, multiple runs of the same setup must be performed to evaluate the stability of the process. From each of these simulations, one indicator is computed (either the median or the variance of the travel times), then we consider the mean of this indicator across simulations. Therefore we have either the mean of medians, or the mean of variances to consider.

6.3.1 Influence of dynamic flow separators

The flow separators are tested on the short section of corridor presented inFigure 25. The objective is to decrease the travel time and also the variation in travel time of the pedestrians. The improvement is significant when comparing the "no separator" scenario to the "with separator" scenarios. The number of simulations to perform has been determined by using Figure, where the mean square error (MSE) is computed using bootstrapping. This technique is used since no analytical solution exists for estimating the MSE of the medians. The number of simulations required to guarantee an acceptable MSE is fixed at 60. The MSE is already acceptable for our purpose and it decreases slowly after this point. For all subsequent simulations, we target 60 replications.

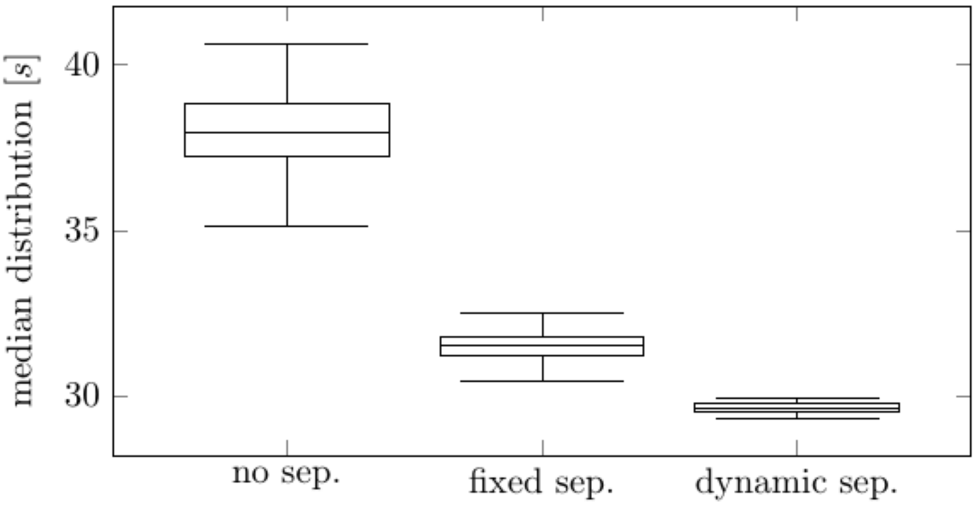


Figure 25: The pedestrian flow separators are very efficient for reducing the travel times. 100 simulations were performed, and for each simulation the median travel time is computed. The boxplots of the medians per scenario show that the travel time and variance in travel time are significantly reduced

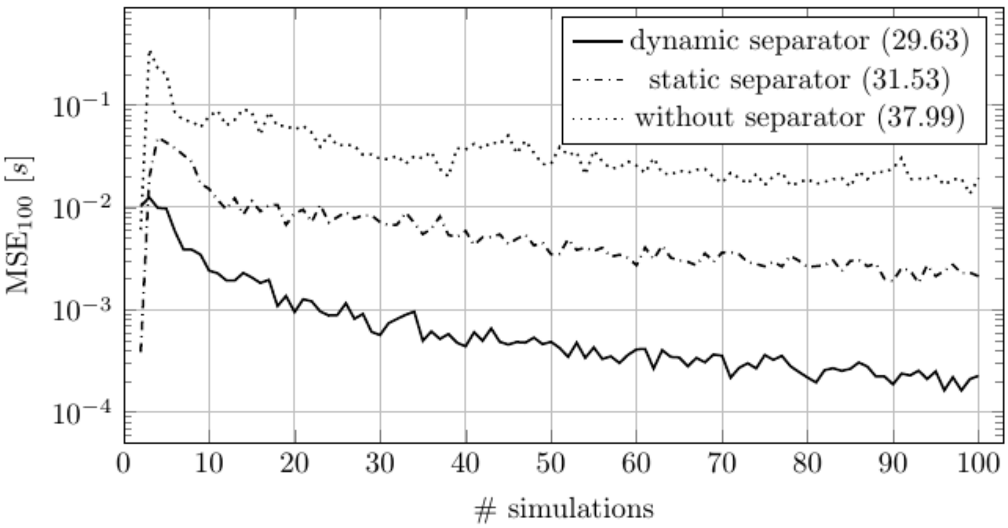
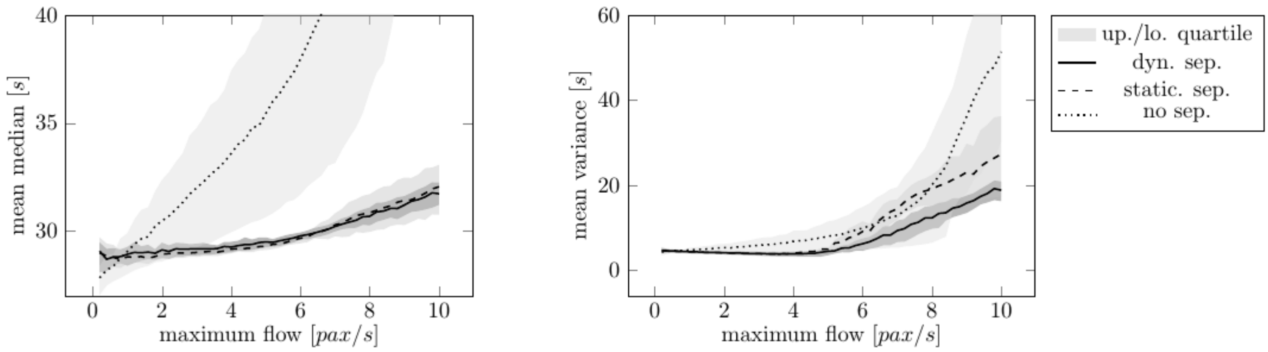


Figure 26: The mean square error computed using bootstrapping for the three scenarios. The usage of flow separators means the required number of simulations to reach a given error is significantly lower

Naturally, flow separators will not be efficient for all scenarios and demand patterns. In order to explore the flow domains where the flow separators are efficient, the same demand pattern is used but the amplitude is changed. The results from this sensitivity analysis to demand are presented below. For very low demand levels, the flow separators induce a small increase in travel time since the pedestrian must add a small walking distance to cross the corridor to the same side. This excess is quickly compensated as from a demand of 1.0 passengers per second the flow separators are beneficial when considering the medians of travel times. If we consider only the medians, then dynamic flow separators have little benefit on the travel times compared to the static flow separators. Nevertheless, when considering the travel time variance per simulation, the dynamic flow separators are beneficial for the pedestrians. At high demand levels, the variance is significantly lower when dynamic flow separators are used instead of static ones.



(a) Mean of median travel times. (b) Mean of travel time variance.

Figure 27: Travel time median and variance analysis for the different scenarios considered. The bands indicate the upper and lower quartiles of the distributions.

6.3.2 Sensitivity to compliance

As pedestrians are generally not restricted in their movements, nothing enforces the pedestrians to follow the rules. Therefore, the impact of compliance to the rules is explored in this section. The objective is to explore the cost induced by a small percentage (5% or 10%) of the pedestrians taking the sub-corridor dedicated to the opposite walking direction.

Figure 28 presents the travel time variance for full compliance, 5% and 10% of un-compliant pedestrians. Figure 29 shows the median travel time per direction for the three compliance scenarios. When considering Figure 28, it is clear that the case with 100% compliance shows the lowest variance in travel, which is expected. As already seen from Figure 27, the dynamic flow separators present clear advantage as they keep the variance lower compared to a static separation of flows. This behaviour is also true for cases where a small percentage of pedestrians do not follow the rules. The dynamic flow separator keeps the travel time variance significantly lower than the static case, this is indicated by the gray lines being above the corresponding black lines from Figure 28.

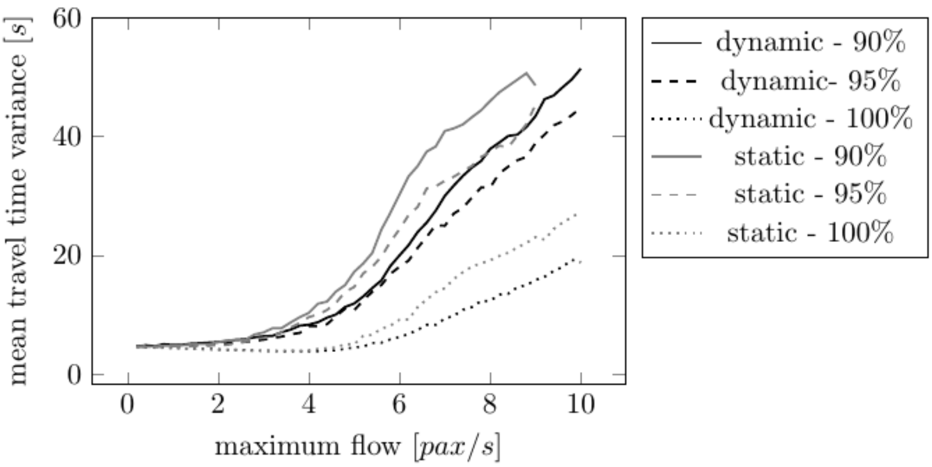
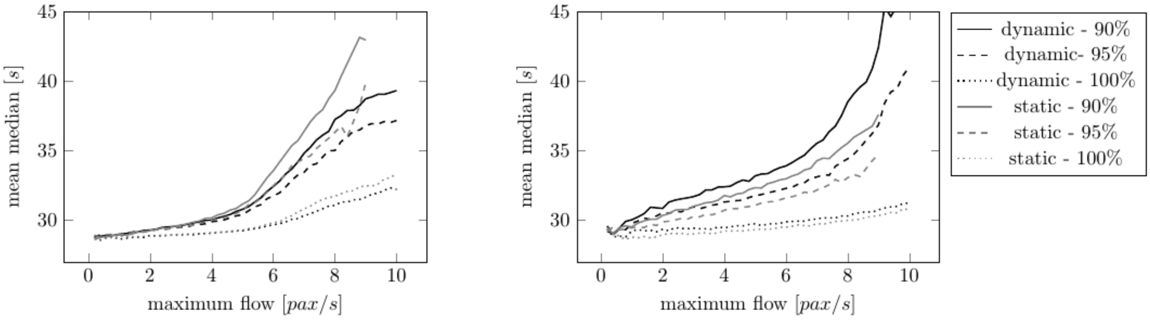


Figure 28: Comparison of the travel time variance between the static flow separators and the dynamic ones for different compliance levels. The dynamic flow separators effectively reduce the variance in travel time for higher demand levels.

By analyzing the travel time medians per direction, we can see two opposite situations. The pedestrian flow going from A to B is the dominant flow, while the opposite flow from B to A is the dominated one (i.e. a small group of people moving against a larger group). First of all, the general behaviour of the dynamic flow separator is to give more space to the larger flow. This means that the dominant flow will generally benefit from this strategy, while the dominated flow will see it's reserved space decrease. Hence it is generally penalized by this *approach. The impact on the travel times will therefore reflect this idea, as seen in Figure 29. When comparing the dynamic to the static flow separator for the dominant flow (Figure 29), the dynamic flow separator is beneficial for this group. On the other hand, for the dominated flow (Figure 29) the opposite is true: the dynamic version increases the travel times of the pedestrians. This happens because this group has less space to move around in, hence creating higher congestion.*



(a) Pedestrians moving from $A \to B$. (b) Pedestrians moving from $B \to A$.

Figure 29: Travel time comparison for the opposing directions with different compliance levels. The dynamic flow separators are useful for reducing the impact of the uncompliant pedestrians.

6.3.3 Train station corridor

After exploring the impact the separation of pedestrian flows has on a single straight corridor. The impact on a more complex and realistic infrastructure is analysed. Individual tracking data has been collected for ten days in 2013 for both pedestrian underpasses (PIs) of the main station in Lausanne, Switzerland. This data is firstly used to validate the pedestrian simulator which is chosen, but more importantly as demand scenarios for testing the effectiveness of pedestrian flow separators. The general idea is the same, prevent head-on collisions between pedestrians by dedicating parts of the corridor to each flow direction. This is done by installing three independent flow separators in the corridor, as seen in Figure 30. The demand pattern which is taken from the empirical data is presented in Figure 31. Since only ten days of data are available, using these days as separate replications isn't possible for statistical reasons therefore we considered these ten days as independent scenarios. For each of these ten scenarios, a given number of simulation replications where performed to build the distribution of the KPIs. In this case, we kept travel time but also investigated mean walking speed.

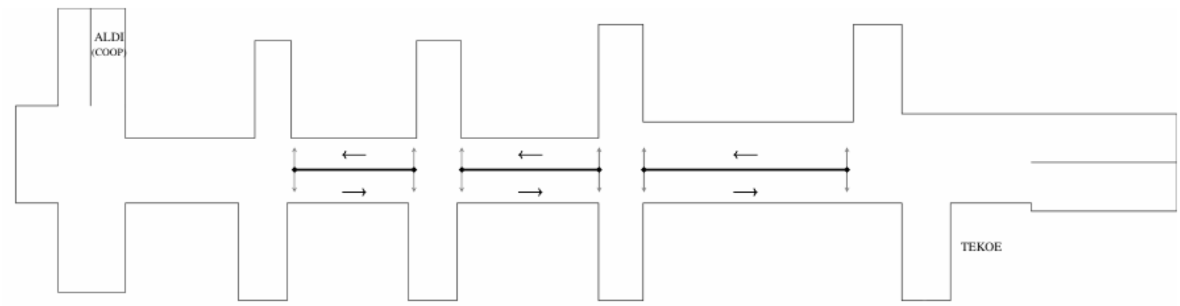


Figure 30: Western pedestrian underpass from the station in Lausanne, Switzerland. Three flow separators are installed in the central part of the corridor.

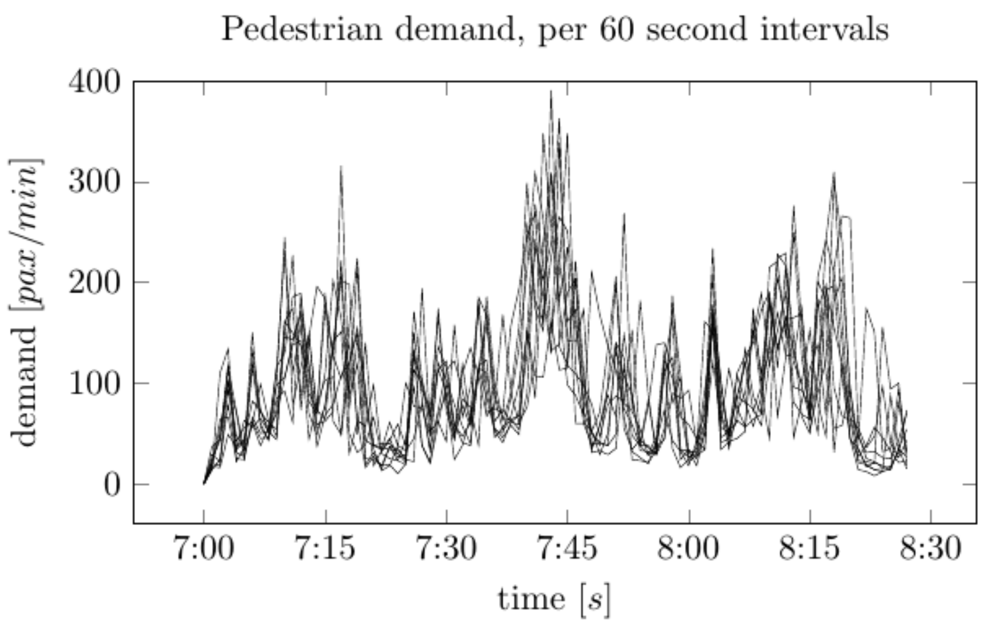


Figure 31: Aggregate empirical demand pattern used as input in the simulations for evaluating the flow separators. Each curve represents one day (ten days in total). The influence of the cyclic timetable is visible at 7h15, 7h45 and 8h15 since a peak in demand appears at those time.

Since the travel time of all pedestrian are not significantly impacted, we categorized the walking times into groups based on the trip characteristics. Two criteria are used: trip length and number of times pedestrians must cross the "junctions" (or equivalently the number of left turns they must do). This leads to nine groups in total since there are three different trips lengths and three different groups of "left-turns": zero left turns, one left turn and two left turns. The comparison of the median of median travel time and average walking speed for each group are presented in Figure 32 and Figure 33. In these figures, each point indicates 50 replications of one scenario (based on the empirical data).

The impact of the flows separators depends on the group under examination. If pedestrians did not require to make any left turns (i.e. cross the junction areas), their travel time decreases regardless of the length of their trip. This sub-population benefits from this control strategy. The group of pedestrians doing on left turn are positively influenced if they are doing a "long" trip. The short trips where the pedestrian change side of the corridor (one left turn) suffer from an increases travel time. Finally, trips involving two left turns are at best not affected by the flow separators. This is the case since the walking time gained by the separated flow is compensated by the time needed to cross twice the junctions.

At this stage it might be tempting to say that this is caused simply by the extra walking distance induced by the usage of flow separators. By considering the change in average walking time (Figure 33) it is clear that all groups of pedestrians benefit from the flow separators as their walking speeds increase. This happens since the flow separators effectively prevent the weaving effects and head-on collisions between pedestrians. Some groups do indeed walk a longer distance, but their travel time is not impacted since the can walk it faster.

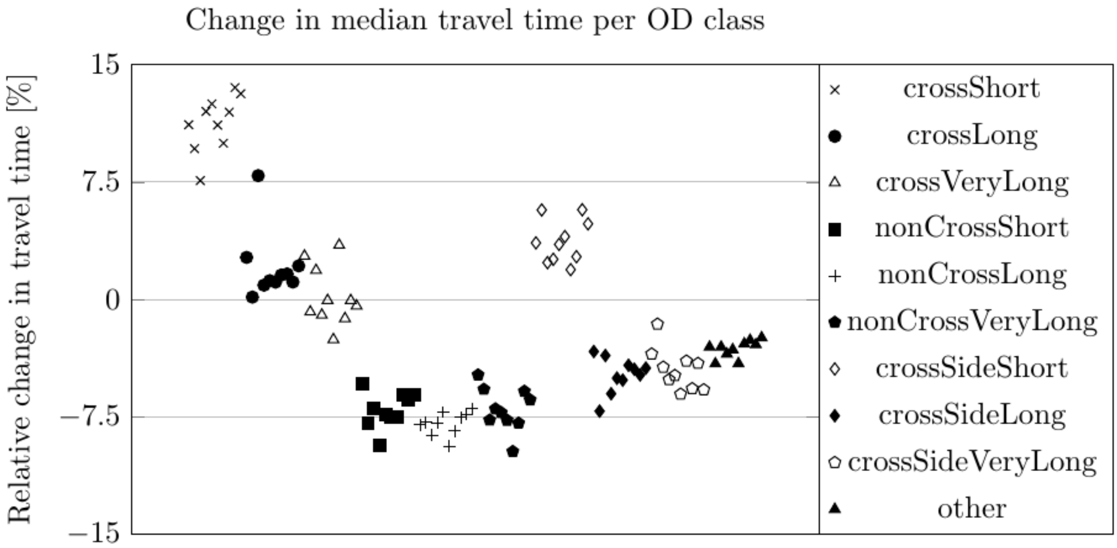


Figure 32: Travel time change per OD class when flow separators are installed in the main corridor. The travel times decreases for class which don't involve crossing the corridor in any way. For longer trips, the travel time decreases even if pedestrians must cross the corridor

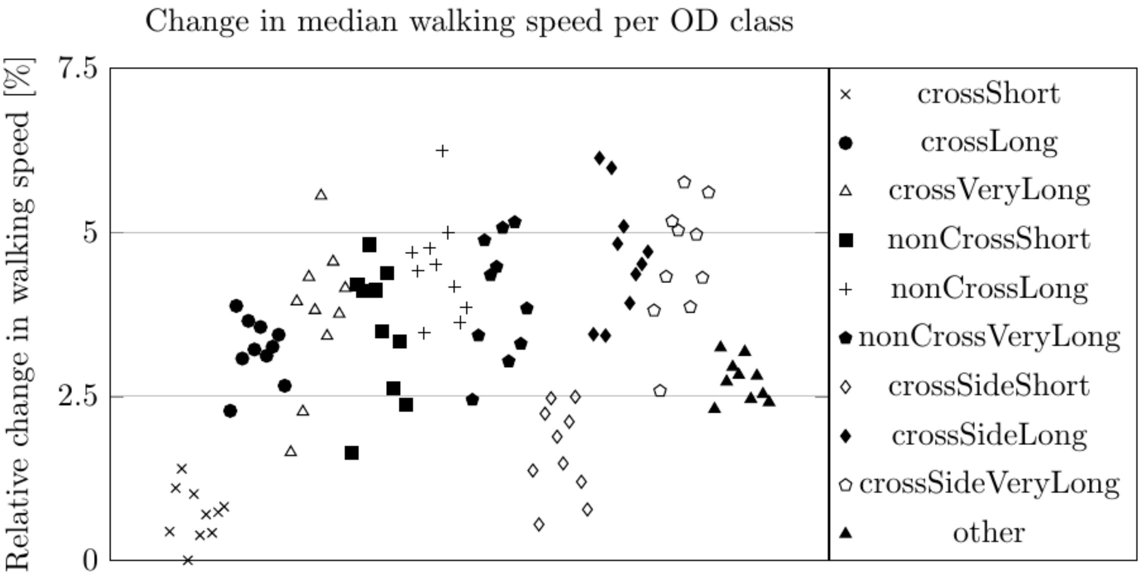


Figure 33: Mean speed evolution after flow separator are used. The mean speed per OD class increases for all classes except two: pedestrians who cross the corridor with short trips.

7 Closing Remarks

This deliverable demonstrates the feasibility and capabilities associated with the multi-layer modelling as well as with the train and pedestrian traffic control measures. Applications included different sub-systems of the public transport system, different types of disruptions, case studies varing in scale and characteristics and different control approaches. The results provide confidence that the proposed solutions can provide insightful findings for analyzing the consequences of service disruptions as well as measures to mitigate their impacts. This is the first study to implement and allow the qunatification of disruptions while accoutning for passenger flow distribution across regional, urban and hub service layers.

The application results reported in the previous sections allow to derive some initial suggestions for public transport planners and policy makers in relation to passenger-oriented real-time mamagement of public transport systems. Future directions of research include the impacts of hub perfromance on transfer station choice, the impacts of multiple simultanous disruptions and evaluating the impacts of synchronoziations measures. We will elaborate on the practical implications and scientific limitations and future prospects in the following deliverable, namely D4.2:Summary of the case studies results and practical recommendations.

References

Binder, S., Maknoon, Y., Bierlaire, M., (2017), "The multi-objective railway timetable rescheduling problem", Transportation Research Part C, 78, Pages 78-94.

Corman, F., D'Ariano A., Marra, A.D., Pacciarelli, D., Samà, M., (2017), "Integrating train scheduling and delay management in real-time railway traffic control", Transportation Research Part E, 105, 213-239.

Gordon, J.B., Koutsopoulos, H.N., Wilson, N.H.M. & Attanucci, J.P. (2013). Automated inference of linked transit journeys in London using fare-transaction and vehicle location data. Transportation Research Record: Journal of the Transportation Research Board, 2343, 17-24.

Josyula, S., Törnquist Krasemann, J., (2017),"Passenger-oriented Railway Traffic Re-scheduling: A Review of Alternative Strategies utilizing Passenger Flow Data". Proceedings from RailLille - the 7th International Conference on Railway Operations Modelling and Analysis, Lille, France, April 2017.
Josyula, S., Törnquist Krasemann, J., Lundberg, L., (2018). "A Parallel Algorithm for Train Rescheduling", Transportation Research Part C 95, pp. 545-569.

Josyula, S., Törnquist Krasemann, J., Lundberg, L., (2019). "Exploring the Potential of GPU Computing in Train Rescheduling", Peer-reviewed conference paper in the proceedings from RailNorrköping – the 8th International Conference on Railway Operations Modelling and Analysis, Norrköping, Sweden.

Mind research, (2015), Resvaneundersökning Blekinge kustbana 2015. Slutrapport. Travel survey report provided by Blekingetrafiken.

Munizaga, M.A. & Palma, C. (2012). Estimation of a disaggregate multimodal public transport origin-destination matrix from passive smart card data from Santiago, Chile. Transportation Research part C, 24, 9-18.

Nijënstein, S. and Bussink, B. (2015). Combining multimodal smart card data: exploring quality improvements between multiple public transport systems. European Transport Conference, Germany.

Sato, K., Tamura, K., Tomii, N., (2013), "MIP-based timetable rescheduling formulation and algorithm minimizing further inconvenience to passengers", Journal of Rail Transport Planning & Management, 3, 38-53.

Trépanier, M. and Chapleau, R., (2006), "Destination estimation from public transport smartcard data", IFAC Proceedings Volumes, 39, 393-398.

Törnquist, J., Persson, J.A., (2007), "N-tracked railway traffic re-scheduling during disturbances", Transportation Research Part B: Methodological, Volume 41, 342-362.

Törnquist, J., Persson, J.A., (2005), "Train traffic deviation handling using Tabu Search and Simulated Annealing", in Proceedings of HICSS38, Big Island, Hawaii, January 2005.

Törnquist, J., (2007), "Railway traffic disturbance management: An experimental analysis of disturbance complexity, management objectives and limitations in planning horizon". Transportation Research Part A: Policy and Practice No. 41 (3), 249-266.

Törnquist Krasemann, J. (2012), "Design of an effective algorithm for fast response to the re-scheduling of railway traffic during disturbances", Transportation Research Part C (20), pp. 62-78, Elsevier Ltd.

Yap, M.D., Cats, O., Van Oort, N. & Hoogendoorn, S.P. (2017). A robust transfer inference algorithm for public transport journeys during disruptions. Transportation Research Procedia, 27, 1042-1049.

Zhu Y., and Goverde, R.M.P., (2017), "Dynamic passenger assignment during disruptions in railway systems", In proceedings of 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), 146-151.

Appendix A. Extended optimization model for regional public transport disturbance management

The optimization model outlined below is an extension of the model by Törnquist and Persson (2007), which focuses primarily on train delay minimization but allows also for weighting of the delay by, for example, the number of passengers in the trains. The extensions of this model include incorporating dynamic passenger route choice as an effect of disturbances, including both bus services and train services.

Let V represent the set of all train services in the selected train traffic network and also all alternative relevant public transport services, which refers to regional buses in this case.

Let T refer to the set of all train services in the set V (i.e. $T \subseteq V$), and let B^{rail} denote the set of segments that defines the rail infrastructure and B^{bus} denote the set of bus stations and associated links in between.

Let E denote the set of events, where an event can be seen as a time slot request by a train or bus for a specific network segment.

The index i is associated with a specific transport service in the set V (i.e. $i \in V$), while the index j with a specific network segment, and index k is associated with an event. An event is connected both to a network segment and a transport service. The sets $K_i \subseteq E$ are ordered sets of events for each transport service i, while $L_j \subseteq E$ are ordered sets of events for each network segment j.

Each event has a point of origin, $o_{i,k}$, which is used for determining a change in the direction of traffic when that is important. Further, for each event there is a scheduled start time and end time, denoted by $b_{i,k}^{inital}$ and $e_{i,k}^{inital}$, which are given by the established timetable. The disturbance is modelled using parameters $b_{i,k}^{static}$ and $e_{i,k}^{static}$, denoting the perturbed start and end time of the event.

In B^{rail}, there are two types network segments, modelling the rail infrastructure between stations and within stations. Each segment j in B^{rail} has a number of parallel tracks, indicated by the sets P_j and each track requires a separation in time between its events (one train leaving the track and the next enters the same track). The minimum time separation between trains on a segment is denoted by Δ_j^M for trains that ride in the opposite direction, and Δ_j^F for trains that follow each other; the separation is only required if the trains use the same track on that specific segment.

The parameter $h_{i,k}$ indicates if event k includes a planned, commercial stop at the associated segment (i.e. it is then normally a station), which then forbids the service to leave the associated location before the announced, initial departure time. The parameter $d_{i,k}$ represents the minimum running time, pre-computed from the established schedule, if event i,k occurs on a line segment between stations. For station segments, $d_{i,k}$ corresponds to the minimum dwell time of commercial stops, where transfers may be scheduled.

The variables in the model of the railway traffic network, the train services as well as bus services are either binary or continuous. The continuous variables describe the timing of the events and the delays, while the binary describe the discrete decisions concerning the trains' selection of a track on rail segments with multiple tracks or platforms, and the order of trains that want to occupy the same track and/or platform. The continuous, non-negative, variables associated with the transport service events and delays are defined as follows:

$x_{i,k}^{begin}$ *= start time of event $k, k \in K_i,\ i \in V$.*

$x_{i,k}^{end}$ = *end time of event* $k, k \in K_i,\ i \in V$.
$z_{i,k}^{+\tau}$ = *delay of event k exceeding a defined threshold, where* $k \in K_i,\ i \in V$.
$w_{i,k}$ = *deviation of event* $k,\ k \in K_i,\ i \in V$.

The arrival time of service i at the associated network segment is given by $x_{i,k}^{begin}$ *and the departure from a specific segment is given by* $x_{i,k}^{end}$. $w_{i,k}$ *records the deviation of event* k *compared to the initial timetable since also running ahead of schedule is undesirable unless it is necessary to e.g. enable overtaking or crossings in order to facilitate for another train to reduce its delay. The variables* $z_{i,k}^{+\tau}$ *records the delay of event* k *when exceeding the delay threshold* τ.

The following block of constraints concerns the timing of the events belonging to each transport service i and its sequence of events, defined by the event list $K_i \subseteq E$. *These constraints define the relation between the initial schedule and the revised schedule.*

$$x_{i,k}^{end} = x_{i,k+1}^{begin}, k \in K_i, i \in V: k \neq |K_i| \qquad \text{(Eq. A1)}$$
$$x_{i,k}^{begin} = b_{i,k}^{static}, k \in K_i, i \in V: b_k^{static} > 0 \qquad \text{(Eq. A2)}$$
$$x_{i,k}^{end} = e_{i,k}^{static}, k \in K_i, i \in V: e_k^{static} > 0 \qquad \text{(Eq. A3)}$$
$$x_{i,k}^{end} \geq x_{i,k}^{begin} + d_{i,k}, k \in K_i, i \in V \qquad \text{(Eq. A4)}$$
$$x_{i,k}^{end} \geq e_{i,k}^{initial}, k \in K_i, i \in V : h_k = 1 \qquad \text{(Eq. A5)}$$
$$e_{i,k}^{initial} - x_{i,k}^{end} \leq w_{i,k}, k \in K_i, i \in V \qquad \text{(Eq. A6)}$$
$$x_{i,k}^{end} - e_{i,k}^{initial} \leq w_{i,k}, k \in K_i, i \in V \qquad \text{(Eq. A7)}$$
$$x_{i,k}^{end} - e_{i,k}^{initial} - \tau \leq z_{i,k}^{+\tau}, k \in K_i, i \in V \qquad \text{(Eq. A8)}$$
$$H_{max} \geq z_{i,k}^{+\tau} + \tau, k \in K_i, i \in V, i \notin T \qquad \text{(Eq. A9)}$$

Equation A9 defines the maximum allowed departure delay (H_{max}*) for buses, which dictates the bus holding policy adopted when disturbances occur and service connections may need to be maintained whenever feasible and beneficial. Eq.A9 will, however, only have an impact if such connections are possible (which will be discussed later in this chapter). For later purposes, we also introduce a parameter* $n_{i,k}^{alighting}$ *which specifies how many passengers that alight a specific transport service i at the service stop location corresponding to its event k.*

For the rail network segments, i.e. B^{rail}, *we also need to respect infrastructure capacity constraints and therefore define three binary variables:*

$$q_{i,k,t} = \begin{cases} 1, \text{if event } k \text{ uses track } t,\ k \in K_{i,}, i \in \mathrm{T}, k \in L_j, t \in P_j, j \in B^{rail} \\ 0, \text{otherwise} \end{cases} \qquad \textit{(Eq. A10)}$$

$$\gamma_{k\hat{k}} = \begin{cases} 1, \text{if event } k \text{ occurs before event } \hat{k}, k \in L_j, j \in B^{rail}: k < \hat{k} \\ 0, \text{otherwise} \end{cases} \qquad \textit{(Eq. A11)}$$

$$\lambda_{k\hat{k}} = \begin{cases} 1, \text{if event } k \text{ is rescheduled to occur after event } \hat{k}, k \in L_j, j \in B^{raiL}: k < \hat{k} \\ 0, \text{otherwise} \end{cases} \qquad \textit{(Eq. A12)}$$

The second block of constraints concerns the permitted interaction between trains, given the capacity limitations of the infrastructure (including safety restrictions):

$$\sum_{t \in P_j} q_{i,k,t} = 1, \qquad k \in K_{i,}, i \in \mathrm{T}, k \in L_j, t \in P_j, j \in B^{rail} \qquad \text{(Eq. A13)}$$

$$q_{i,k,t} + q_{\hat{\imath},\hat{k},t} - 1 \le \lambda_{k\hat{k}} + \gamma_{k\hat{k}}, k, \hat{k} \in L_j, k \in K_i, \hat{k} \in K_{\hat{\imath}}, t \in P_j, j \in B^{rail}, i, \hat{\imath} \in T: k < \hat{k} \quad \text{(Eq. A14)}$$

$$x^{begin}_{\hat{\imath},\hat{k}} - x^{end}_{i,k} \ge \Delta^M_j \gamma_{k\hat{k}} - M(1 - \gamma_{k\hat{k}}),$$

$$k, \hat{k} \in L_j, k \in K_i, \hat{k} \in K_{\hat{\imath}}, t \in P_j, j \in B^{rail}, i, \hat{\imath} \in T: k < \hat{k}, o_{\hat{k}} \ne o_k \quad \text{(Eq. A15)}$$

$$x^{begin}_{\hat{\imath},\hat{k}} - x^{end}_{i,k} \ge \Delta^F_j \gamma_{k\hat{k}} - M(1 - \gamma_{k\hat{k}}),$$
$$k, \hat{k} \in L_j, k \in K_i, \hat{k} \in K_{\hat{\imath}}, t \in P_j, j \in B^{rail}, i, \hat{\imath} \in T: k < \hat{k}, o_{\hat{k}} \ne o_k \quad \text{(Eq. A16)}$$

$$x^{begin}_{i,k} - x^{end}_{\hat{\imath},\hat{k}} \ge \Delta^M_j \lambda_{k\hat{k}} - M(1 - \lambda_{k\hat{k}}),$$
$$k, \hat{k} \in L_j, k \in K_i, \hat{k} \in K_{\hat{\imath}}, t \in P_j, j \in B^{rail}, i, \hat{\imath} \in T: k < \hat{k}, o_{\hat{k}} \ne o_k \quad \text{(Eq. A17)}$$

$$x^{begin}_{i,k} - x^{end}_{\hat{\imath},\hat{k}} \ge \Delta^F_j \lambda_{k\hat{k}} - M(1 - \lambda_{k\hat{k}}),$$
$$k, \hat{k} \in L_j, k \in K_i, \hat{k} \in K_{\hat{\imath}}, t \in P_j, j \in B^{rail}, i, \hat{\imath} \in T: k < \hat{k}, o_{\hat{k}} \ne o_k \quad \text{(Eq. A18)}$$

$$\lambda_{k\hat{k}} + \gamma_{k\hat{k}} \le 1, k, \hat{k} \in L_j, j \in B^{rail}: k < \hat{k} \quad \text{(Eq. A19)}$$
$$\gamma_{k\hat{k}}, \lambda_{k\hat{k}} \in \{0,1\}, \hat{k} \in L_j, j \in B^{rail}: k < \hat{k} \quad \text{(Eq. A20)}$$
$$q_{i,k,t} \in \{0,1\}, k \in K_i, k \in L_i, t \in P_j, j \in B^{rail}, i \in T \quad \text{(Eq. A21)}$$
$$x^{begin}_{i,k}, x^{end}_{i,k}, z^{+\tau}_{i,k} \ge 0, k \in K_i, i \in V \quad \text{(Eq. A22)}$$

The above three blocks of constraints define the flexibility in the re-scheduling of the bus services as well as the trains services. Note though, that it is still only trains that need to respect the infrastructure capacity restrictions outlined in the associated above constraints (Equations A13-A21). Also, only the events belonging to a train event list are included in the sets L_j.

If the regional public transport disturbance management and associated re-scheduling of trains and buses, would be conducted from a network perspective, a reasonable objective would be to minimize primarily train delays and bus delays, but also to minimize other deviations from the timetable wrt. e.g. running ahead of schedule, or track and platforms changes.

With the objective to minimize transport service delays larger than two minutes, timetable deviations and track changes, the objective function can be formulated as follows:

$$minimize \sum_{i \in V} \sum_{k \in K_i} (z^{+2}_{i,k} + w_{i,k}) + \sum_{i \in T} \sum_{k \in K_i} \sum_{t \in P_j : t \ne \mu^{train}_{i,k}} \alpha * q_{i,k,t} \quad \text{(Eq. A23)}$$

The parameter $\mu^{train}_{i,k}$ specifies which track or platform that initially is intended to be used by event k belonging to train i. The parameter α specifies with which weight track changes are to be penalized by. If the timetable values are given in e.g. seconds, the value of α needs to be set quite high in order to balance the trade-off between reducing train delays and keeping the timetable as intact as possible with respect to the planned routes of the trains through/within the stations. That is, altering the track and platform allocation may introduce operational complications, and should therefore be kept at a minimum and only be applied when it enables significant delay reductions.

Now, in order to also capture passenger flow dynamics and passenger route choice in our model, we introduce groups of passengers in a similar manner as proposed by Binder et al. (2017). We define a set of passenger groups G, where any passenger group g is characterized by the triplet (o_g, d_g, t_g) where o_g is the origin, d_g is *the destination, and t_g is the desired departure time from the origin. The parameter n_g specifies the number of passengers. For each group of passengers, the model takes a set of routes denoted R_g, from the origin to the destination within a relevant time period, as input. In a transport service network with low frequency of services, the size of the set of relevant alternative routes will be relatively small.*

Exactly one route $r \in R_g$ must be selected by passenger group g. We use the binary variable $\phi_{g,r}$ to denote if passenger group g has selected route r (=1) or not (=0).

$$\sum_{r \in R_g} \phi_{g,r} = 1 \,, g \in G \qquad \text{(Eq. } A24)$$

A route $r \in R_g$ is defined as an ordered set of service events, denoted R_g^r, which corresponds to the sequence of train/bus service events the passenger group is boarding and alighting during each route and its legs. For all routes in R_g , with the exception of the last route (i.e $r = |R_g|$), the set R_g^r always contains an even number of service events, and minimum two events, namely the event associated with the service that is boarded at first, and the event of the final service when alighting at the final destination. If a passenger group has a route containing only two events, it means that the route corresponds to a direct trip from the origin to the destination. Let us use the simple example in Figure A1to illustrate the construction of alternative routes.

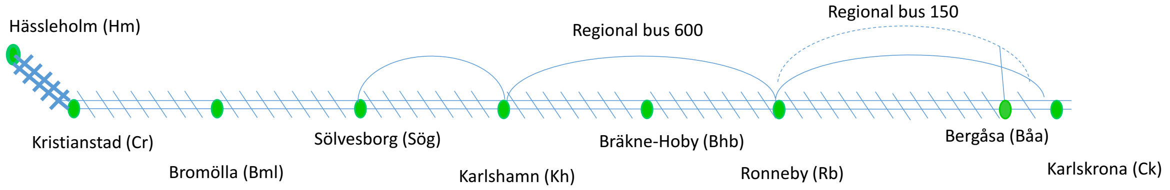


Figure A1. A simplified illustration of the regional railway line between Hässleholm-Karlskrona and a subset of parallel bus services.

Assume we have a passenger group that intend to travel from Hässleholm to Ronneby with the direct train 1064, which runs from Denmark via the Öresund Bridge, to Hässleholm and further to Karlskrona. The initial route for this passenger group will consist of references to (a) the train event for 1064 in station Hässleholm (Hm) and (b) the train event for 1064 in station Karlskrona (Ck). For a more detailed presentation of how the events and the transport service event lists are defined, see (Törnquist Krasemann, 2012)[1].

Route 1 (the initial route) would then been specified as follows:

Route 1 "Hässleholm-Ronneby – Ö-tåg direct"
Hm Rb 1064

A later alternative, but less attractive, route would be to first take the train 1224 from Hässleholm to Kristianstad, then transfer to the train service 1976 that runs to Karlshamn, where the final transfer to the regional bus line 600 with service id 156493 is made. The alternative route consisting of three connected legs, would then be defined as:

[1] *Törnquist Krasemann, J. (2012), "Design of an effective algorithm for fast response to the re-scheduling of railway traffic during disturbances", Transportation Research Part C (20), pp. 62-78.*

Route 2 "Hässleholm-Ronneby – Pågatåg and bus"
Hm Cr 1224
Cr Kh 1976
Kh Rb B600TripID156493

For sake of consistency and clarity, we use $i_{g,r,l}$ *and* $k_{g,r,l}$ *to denote the associated transport service events that each leg l in route r belonging to passenger group g is referring to. In the example above, each row in the route specification constitutes a route leg.*

In order to ensure that there will always be a feasible route for all passenger groups, a final optional, route for each passenger group corresponds to a special solution such as a taxi, or the next service in an hour, if such exists. The selection of this route will induce a fixed, large penalty and it is hence not included in the following constraints.

A route r can only be selected if all transfers between the pre-defined route legs are successful, which Eq. A25 ensures:

$$x^{end}_{i_{g,r,(l+1)},k_{g,r,(l+1)}} - x^{begin}_{i_{g,r,l},k_{g,r,l}} - d_{tr} \geq M(\phi_{g,r} - 1)$$
$$l \in R^r_g, r \in R_g, g \in G: l < |R^r_g|, i_{g,r,l} \neq i_{g,r,(l+1)}, r \neq |R_g| \qquad \text{(Eq. }A25)$$

M is a large constant and d_{tr} *is the transfer time required for a passenger to make the connection between the arriving service event* $i_{g,r,l}$, $k_{g,r,l}$ *and the departing service event* $i_{g,r,(l+1)}$, $k_{g,r,(l+1)}$. *The transfer time is here set independent of the station configuration and the dynamic platform allocations, but this could easily be incorporated if desirable.*

We also need to introduce the continuous variable $x^{paxArrival}_g$ *which refers to the arrival time of passenger group g at its final destination. The arrival time is computed based on the arrival times of the final service of each route and the route selection.*

$$x^{paxArrival}_g \geq x^{begin}_{i_{g,r,|R^r_g|},k_{g,r,|R^r_g|}} - M(1 - \phi_{g,r}), r \in R_g, g \in G: r \neq |R_g| \qquad \text{(Eq. }A26)$$

In order to assign a relevant value to $x^{paxArrival}_g$ *also when the final optional route is selected, we need an additional constraint that forces the assigned arrival time to be* ρ *time units later than initially planned:*

$$x^{paxArrival}_g \geq t^{initArr}_g + \rho - M\left(1 - \phi_{g,|R_g|}\right), \qquad g \in G \qquad \text{(Eq. }A27)$$
$$z^{paxDelay}_g \geq x^{paxArrival}_g - t^{initArr}_g, \qquad g \in G \qquad \text{(Eq. }A28)$$
$$x^{paxArrival}_g, z^{paxDelay}_g \geq 0, g \in G \qquad \text{(Eq. }A29)$$
$$\phi_{g,r} \in \{0,1\}, r \in R_g, g \in G \qquad \text{(Eq. }A30)$$

If the objective now is to minimize passenger delays rather than transport service delays, the objective function can be formulated as follows:

$$minimize \sum_{g \in G} n_g * z^{paxDelay}_g \qquad \text{(Eq. A31)}$$

The objective function thus multiples the passenger group delays with the number of passengers in each group.

The optimization model outlined above includes two alternative objectives function with different focus. However, previous experiments show that when only minimizing train delays the route choice becomes irrelevant to optimize. Similarly, when only minimizing passenger delays, the trains with few or no passengers may become re-scheduled in an inappropriate manner. Hence, we need to include both components but with different weights. The revised objective functions are outlined below.

$$minimize \sum_{i \in V} \sum_{k \in K_i} (z_{i,k}^{+2} + w_{i,k}) + \sum_{i \in T} \sum_{k \in K_i} \sum_{t \in P_j : t \neq \mu_{i,k}^{train}} \alpha * q_{i,k,t} + \sum_{g \in G} \sum_{r \in R_g : r \neq 1} \beta * r * \Phi_{g,r} \qquad \text{(Eq. A32)}$$

$$minimize \sum_{g \in G} n_g * z_g^{paxDelay} + \sum_{i \in V} \sum_{k \in K_i} (z_{i,k}^{+2} + w_{i,k}) + \sum_{i \in T} \sum_{k \in K_i} \sum_{t \in P_j : t \neq \mu_{i,k}^{train}} \alpha * q_{i,k,t} \qquad \text{(Eq. A33)}$$

Eq.A32 defines a revised objective function for minimizing primarily train delays, but also minimizing other deviations from the planned timetable and route choice. The added, last component indicates that selecting any of the alternative routes, is associated with a cost related to the rank of the route and a weight β.

The objective function defined by Eq.A33 is a combination of Eq.A21 and Eq.A31 emphasizes a minimization of passenger delays.