Modelling customer inconvenience in train rescheduling

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Abstract

When railway traffic is perturbed, train rescheduling primarily aims at restoring feasibility, which is subject to prescribed safety and operational rules. Secondary objectives may be minimizing the negative effects on customers or traffic. Mathematical optimization models have been proposed to cope with perturbations of different sizes: small such as delays or malfunctioning of single infrastructure elements; or large as traffic interruptions on entire sections or through stations. Linear constraints usually model the main objective, preventing violations of safety and operational requirements. The objective function usually models the secondary objectives and depends on the context (small/ large perturbations, dedicated passengers/ goods/ mixed traffic, customer/ operator perspective).

This work focuses on small perturbations and mixed traffic and aims at including customer inconvenience in the objectives of a mathematical optimization model for train rescheduling. In this framework, the objective function usually models the cumulative train delay, which approximates the effects of perturbations on traffic but neglects the inconvenience experienced by customers along their transport chains. In networks with very interconnected traffic (e.g. the Swiss rail network), despite small train delays, customer inconvenience may be quite large and thus cannot be neglected. We draft different proposals and compare them using simulations.

Keywords
customer inconvenience, modelling objectives, train rescheduling

1 Introduction

Rescheduling rail traffic aims at adapting the published timetable to the current operational situation in order to reach a predetermined goal. However, opinions diverge on what this goal is. Depending on the economic environment in which railways are operated and the strategic objectives set by the company's leaders, the goals to be achieved during operations may be different. Companies operating in fully deregulated markets, where customers can easily switch to a different operator, are usually more interested in maximizing customers satisfaction than monopolist companies. Companies committed to minimum service levels by agreements with either customers or the public authority may be very interested in keeping the agreed service measures high without considering the actual effects on customers. Some works have proposed models with different objective functions (Törnquist, 2007, Samà *et al.*, 2015).

Different approaches to railway rescheduling have adopted different objective functions, such as maximize train punctuality (e.g. Samà *et al.*, 2015), minimize maximum, total, final or accumulated train delays or their costs (e.g. Törnquist, 2007, Törnquist and Persson, 2007, Samà *et al.*, 2015, Corman *et al.*, 2014), minimize passenger delays (e.g. Dollevoet *et al.*, 2015, Schöbel, 2009), minimize the generalized travel costs for passengers (e.g. Binder *et al.*, 2015), minimize customers discomfort (e.g. Fuchsberger, 2012, Tomii *et al.*, 2005), minimize energy consumption (e.g. Martinis and Weidmann, 2015). Most researchers have chosen a measure without much explanations. This work aims at stimulating the discussion about this key issue in railway rescheduling and proposing a possible solution.

Modelling objectives related to train delays and punctuality is usually quite straightforward, while objectives accounting for passenger satisfaction are more difficult to model. However, as the success of companies providing services in an open market is determined by customers, European operators will have to include passengers into their rescheduling policies. This work focuses on small perturbations and mixed traffic and aims at including customer inconvenience in the objectives of a mathematical optimization model for train rescheduling. The next section includes a short literature review. Section 3 describes the rescheduling model and different objective functions. Section 4 presents numerical experiments. Conclusions and future work are presented in section 5.

2 Literature review

In this section, literature about real-time rescheduling is reviewed with respect to customers expectations. Literature about timetabling will be neglected and the interested reader can refer to the recent work by Parbo *et al.* (2015) which reviewed a large amount of papers on timetabling and compared the approaches with passengers perceptions of railway operations identifying a gap between timetable design and passengers expectations. In the following, the focus is set on works that have explicitly considered customers in their formulations or model attributes that are particularly relevant for developing a formulation of customers' satisfaction. For more exhaustive reviews of rescheduling models, the reader may refer to Cacchiani *et al.* (2014) and Corman and Quaglietta (2015).

Opposed to timetabling (Parbo *et al.,* 2015), several approaches to support operations have considered the customer perspective, particularly in the framework of delay management (decisions about connections, e.g. Schöbel, 2009, Kanai *et al.,* 2011, Dollevoet *et al.,* 2012, Kanai *et al.,* 2011). Note that the classical delay management problem is solved at a macroscopic level, i.e. it does not consider capacity issues and the solutions may be infeasible at the microscopic level. Schöbel (2009) approximates the effects on passengers as a weighted sum of dropped connections and train delays in a capacitated delay management problem (i.e. considering track capacity). *In general, this is a very accurate approximation for the sum of additional delays over all passengers (idealmente reference to Schoebel2007).* Dollevoet *et al.* (2015) go one step forward by combining the delay management problem with the platform track assignment problem (i.e. deciding the arrival and departure platforms of trains). Dollevoet *et al.* (2012) do not consider capacity issues but include passenger rerouting possibilities into the delay management problem by inserting the OD matrices and assuming that all passengers take the shortest path. Kanai *et al.* (2011) model passengers' disutility as a weighted sum of the on-board time, the waiting time at stations, the number of transfers, and the running time weighted by a congestion-related factor. The values of all parameters are set according to the results of a survey conducted in Japan. The optimization model is tested using different functions of passengers' disutility (average, standard deviation, etc.) and is fed with the results of traffic and passenger flow simulations for realistic passengers behaviour.

The main objective of rescheduling is to provide a new schedule adapted to the current traffic situation. On the one hand, macroscopic approaches are based on model with the same granularity of the delay management problem and several ones consider customers satisfactions (e.g. Binder *et al.,* 2015, Tomii *et al.,* 2005, Sato *et al.,* 2013, Almodóvar and García-Ródenas, 2013) On the other hand, microscopic approaches provide feasible routings and schedules but usually focus on the train-side (Samá *et al.,* 2016, Yan and Yang, 2012, e.g.) with few exceptions (Fuchsberger, 2012, Corman *et al.*, 2012, Espinosa-Aranda and García-Ródenas, 2013).

Binder *et al.* (2015) propose a passenger centric macroscopic rescheduling for severe disruptions with passengers rerouting. They model the problem as an IP based on a time-extended graph including arc activities connected to both trains (depart, run dwell) and passengers (enter/leave the system, ride, wait, transfer). The objective is to minimize the combination of operating costs (expressed as the sum of running times for all services) and cumulated generalized travel times of passengers, which are a weighted sum of travel and waiting times, penalties for transfers and early/late departures. Tomii *et al.* (2005) highlight the difficulties related to rescheduling, where multiple opposed objectives, combinatoric issues, immediacy and lack of information have to be addressed. In order to deal with the different opposed objectives in rescheduling, they propose the minimization of passengers dissatisfaction as rescheduling objective. Their ”dissatisfaction index” is a weighted sum of arrival and departure delays, prolonged dwell times, prolonged running times, the interval between trains, lost connections. Sato *et al.* (2013) reschedule train operations minimizing passenger discomfort resulting from disruptions, which is a weighted sum of running time, waiting time and transfers with respect to the planned trip. The model also represents of passengers behaviour. Almodóvar and García-Ródenas (2013) provide a vehicle rescheduling problem to bring vehicles to lines experiencing extremely huge unexpected demand (e.g. in case of temporary unavailability of alternative transport systems). The problem is tackled using predictive simulation and on-line optimization aiming at minimizing the time of passengers in the system.

Fuchsberger (2012) models passenger dissatisfaction as a weighted sum of train cancellations, arrival and departure delays, and connections dropped. The model is a mixed integer linear program based on the blocking time theory (microscopic, see e.g. Pachl, 2008, for further information on blocking time theory). Corman *et al.* (2012) Espinosa-Aranda and García-Ródenas (2013) combine train rescheduling and delay management (via alternative graphs, see e.g. Mazzarello and Ottaviani, 2007, for a description). Corman *et al.* (2012) include decisions about connections as weighted terms in the objective function, while Espinosa-Aranda and García-Ródenas (2013) include estimations of origin-destination-matrices such that the objective function represents the total passenger delay.

Several other microscopic (e.g. Yan and Yang, 2012, Samà *et al.*, 2015) and macroscopic (Kraay and Harker, 1995) approaches do not consider customers explicitly but aim at minimizing the deviation from the timetable or operator inconvenience. Yan and Yang (2012) focus on on-line scheduling of freight services and aim at minimizing the operational costs, including costs associated with delays. Samà *et al.* (2015) propose a operation-centric microscopic rescheduling approach (based on the alternative graph) evaluating multiple criteria (punctuality, (weighted) train delays, et.c) via Data Envelopment Analysis. Kraay and Harker (1995) propose a real-time scheduling model which minimizes the operational cost that is a weighted sum of (a convex function) of the departure and arrival delays, the penalty for extending a crew shift beyond the legal amount of hours and a penalty for blocks missing a connection with another train. Note that the latter work is one of the few publications dealing with real-time optimization of freight schedules.

3 Model

We formulate the rescheduling problem as a Resource Conflict Graph (Caimi *et al.,* 2012). We consider a general zone with stations $\mathcal{S}$, trains $\mathcal{T}$, and a set $\mathcal{CN}$ of scheduled connections. For each station $s \in \mathcal{S}$, P_s denotes the platforms and $P_{s,t}$ the platforms where a train $t \in \mathcal{T} \in \mathcal{T}$ may stop. We define $S_t = (s_0, s_1, \ldots, s_{n_t})$ where s_0 represents either the departure station/depot or the portal from which the train enters the considered compensation zone, s_{n_t} either the last station/depot or the exit portal, and $(s_1, \ldots, s_{n_t-1})$ the ordered sequence of scheduled stops in-between. For each train t, let $\mathcal{B}_{t,i}$ be a set of blocking time stairways for the run from s_{i-1} to s_i. In the following numerical experiment these blocking stairways are obtained via simulations.

Let $\mathcal{R}$ denote the resources in the zone. Each resource is an infrastructure subset that can host at most one train at a time whose elements (e.g. tracks and switches) are reserved and released a the same time (cfr. Blocking Time Theory, in e.g. Pachl, 2008)(). Let $\mathcal{B}^r$ be the set of stairways using $r \in \mathcal{R}$. $\underline{b(r)}$ and $\overline{b(r)}$ denote the start and end of the blocking time interval of resource r in blocking time stairway $b \in \mathcal{B}^r$. For each resource $r \in \mathcal{R}$, let C^r be the set of maximal conflict cliques.

Let $m^{t,t'}_{p,p'}$ be the minimum time needed between an event of train t on platform p and an event of t' on p'. e.g. the minimum dwelling time if $t = t'$, $p = p'$ or the minimum connection time for passenger transfer from train t on platform p to train t' on platform p'. Blocking time stairways that are not separated by this minimum time are said to be incompatible. $\Omega^{t,t'}_{p,p'}$ denotes the set of maximal incompatible sets.

The binary decision variables of our problem indicate whether runs corresponding to the blocking time stairways are scheduled and whether scheduled connections are kept. i.e.

$$x_b = \begin{cases} 1, & \text{if the new schedule uses } b \\ 0, & \text{else} \end{cases} \tag{1}$$

$$c_{s,t,t'} = \begin{cases} 1, & \text{if the connection from } t \text{ to } t' \\ & \text{in station } s \text{ is kept} \\ 0, & \text{else} \end{cases} \tag{2}$$

$$\sum_{b \in \mathcal{B}_{t,1}} x_b \leq 1 \qquad \forall t \in \mathcal{T} | s_0 \text{ is no portal} \tag{3a}$$

$$\sum_{b \in \mathcal{B}_{t,1}} x_b = 1 \qquad \forall t \in \mathcal{T} | s_0 \text{ is a portal} \tag{3b}$$

$$\sum_{b \in \mathcal{B}_t, i} x_b \leq \sum_{b \in \mathcal{B}_t, i-1} x_b \qquad \forall t \in \mathcal{T}, i = 2, \ldots, n_t \tag{4}$$

$$\sum_{b \in C} x_b \leq 1 \qquad \forall C \in C^r, r \in \mathcal{R} \setminus \bigcup_{s \in \mathcal{S}} P_s \tag{5a}$$

$$0 \leq \sum_{\underline{b(p)} \leq \alpha} x_b - \sum_{\overline{b(p)} < \alpha} x_b \leq 1 \qquad \forall \alpha \in \{\underline{b(p)}, b \in \mathcal{B}^p\}, p \in P_s, s \in \mathcal{S} \tag{5b}$$

$$\sum_{b \in A_{t,p}} x_b - \sum_{b \in D_{t,p}} x_b = 0 \qquad \forall p \in P_{\cdot,t}, t \in \mathcal{T} \tag{6}$$

$$\sum_{b \in U} x_b + \sum_{b \in V} x_b \leq 1 \qquad \forall (U, V) \in \Omega^{t,t}_{p,p}, p \in P_{s,t} \tag{7}$$

$$c_{s,t,t'} + \sum_{b \in U} x_b + \sum_{b \in V} x_b \leq 2 \qquad \begin{array}{l} (U, V) \in \Omega^{t,t'}_{p,p'}, p \in P_{s,t}, p' \in P_{s,t'}, \\ (s, t, t') \in C\mathcal{N} \end{array} \tag{8}$$

Constraints (3a) state that at most one slot is given to each train leaving a station or a deposit, while (3b) state that trains entering from a portal must have a slot to the next planned stop. Constraints (4) ensure that at most one blocking time stairway is allocated to each successive section and no slot is allocated to trains that have been cancelled at previous stations. Conflicts are avoided thanks to constraints (5a-5b): (5b) prevent conflicts on platforms where some trains may stop, while (5a) is more efficient and is used for the other resources. Constraints (6) force trains to depart from the same platform where they have arrived. The "self-connection" constraints (7) ensure that trains only depart after they have arrived to the platform and the minimum dwelling time has expired. Connection constraints (8) model decisions about passenger connections.

The objective must be expressed in terms of the variables x_b and $c_{s,t,t'}$. In this context we consider the following possibilities:

$$\text{Maximize:} \quad f_a(x,c) = \sum_{t\in\mathcal{T}} \left(\omega_t \sum_{b\in\mathcal{B}_{t,n_t}} x_b - \sum_{i=1}^{n_t} \mathbf{1}_{\{stop\}}(t,i) \sum_{b\in\mathcal{B}_{t,i}} (\alpha(b) - \hat{\alpha}_{t,i})_{\{\geq 0\}} x_b \right) + \sum_{(s,t,t')\in\mathcal{CN}} \omega_{s,t,t'} c_{s,t,t'} \tag{9a}$$

$$\text{Maximize:} \quad f_b(x,c) = \sum_{t\in\mathcal{T}} \left(\eta_t \cdot \omega_t \sum_{b\in\mathcal{B}_{t,n_t}} x_b - \sum_{i=1}^{n_t} \mathbf{1}_{\{stop\}}(t,i) \cdot \eta^a_{t,i} \cdot \sum_{b\in\mathcal{B}_{t,i}} (\alpha(b) - \hat{\alpha}_{t,i})_{\{\geq 0\}} x_b \right) + \sum_{(s,t,t')\in\mathcal{CN}} \eta_{s,t,t'} \cdot \omega_{s,t,t'} c_{s,t,t'} \tag{9b}$$

$$\begin{aligned} \text{Maximize:} \quad f_c(x,c) = \sum_{t\in\mathcal{T}} \Bigg(& 2 \cdot \eta_t \cdot \omega_t \sum_{b\in\mathcal{B}_{t,n_t}} x_b - \sum_{i=1}^{n_t} \mathbf{1}_{\{stop\}}(t,i) \cdot \eta^a_{t,i} \cdot \sum_{b\in\mathcal{B}_{t,i}} (\alpha(b) - \hat{\alpha}_{t,i})_{\{\geq 0\}} x_b \\ & - \sum_{i=1}^{n_t} \mathbf{1}_{\{stop\}}(t,i-1) \cdot \eta^d_{t,i} \cdot \sum_{b\in\mathcal{B}_{t,i}} (\delta(b) - \hat{\delta}_{t,i-1})_{\{\geq 0\}} x_b \Bigg) \\ & + \sum_{(s,t,t')\in\mathcal{CN}} 2 \cdot \eta_{s,t,t'} \cdot \omega_{s,t,t'} c_{s,t,t'} \end{aligned} \tag{9c}$$

where $\alpha(b)$ and $\delta(b)$ denote the arrival and departure times connected with blocking stairway b, $\hat{\alpha}_{t,i}$ and $\hat{\delta}_{t,i}$ the scheduled arrival at and departure from station s_i,

$$\mathbf{1}_{\{stop\}}(t,i) = \begin{cases} 1 & \text{if train } t \text{ has a scheduled stop at } s_i \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

$$(x)_{\{\geq 0\}} = \begin{cases} x & \text{if } x \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

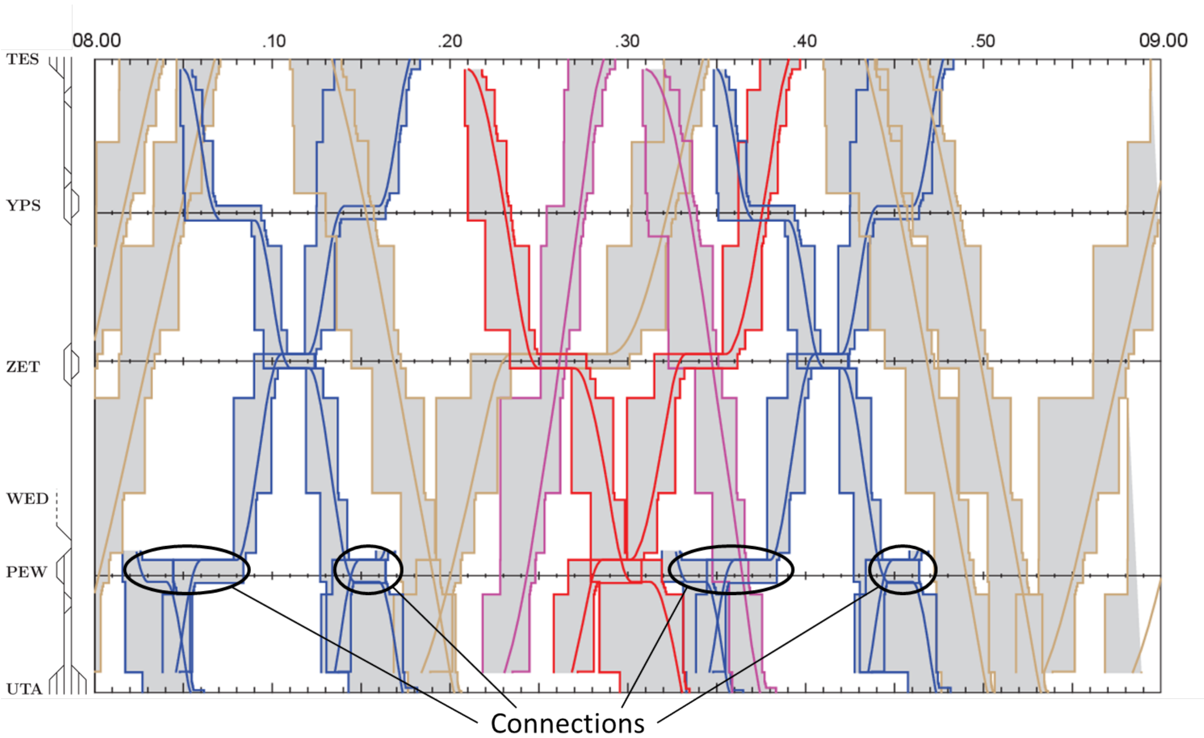
$$\tag{12}$$

Objective (9a) minimizes cumulative train delays at all stations and portals, a cancellation of a service or of a connection is considered as a delay equals the service periodicity (terms ω_t and $\omega_{s,t,t'}$ respectively). Objective (9b) minimizes passengers delays, as it considers the number of passengers using each service, alighting at each stop and using each connection (η_t, $\eta^a_{t,i}$, and $\eta_{s,t,t'}$ respectively). Objective (9c) minimizes the positive difference between experienced and scheduled passengers inconvenience (in this case the waiting time at a platform is considered twice as inconvenient as the time on board, cfr. Sato *et al.,* 2013).

4 Numerical experiments

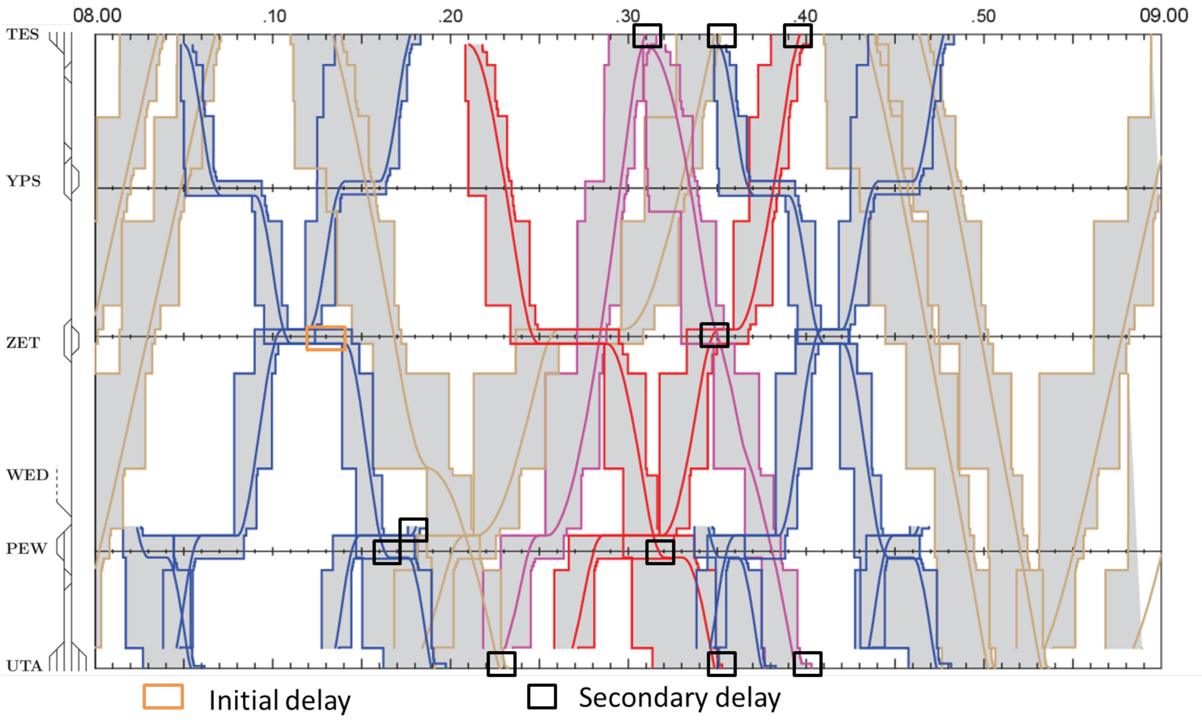
To test the different objective functions (9a)-(9c), we run a small numerical experiment in which we simulate a small perturbation of the planned railway operations and reschedule traffic using the model described above. The scheduled operations considered are shown in Figure 1. The considered network partition consists of a (partly single-track) corridor connecting two large stations (TES and UTA) and passing through three minor stations (YPS, ZET, and PEW) plus a single-track line going to another minor station (WED). Traffic is mixed: two 30-minutes periodic suburban passenger lines (blue) link UTA with TES and with PEW stopping at all stations in-between; to allow passengers to travel from TES to WED (and the other way round) connections are scheduled in PEW; hourly regional services connect the two main stations stopping in ZET and PEW (red); hourly long-distance trains travel non-stop from TES to UTA (pink); the remaining capacity is mostly allocated to freight trains (brown), which only stop for crossing and overtaking.

Figure 1: Context of numerical experiment: scheduled operations



At 8.14 a.m., a suburban train departs from ZET with a two minutes delay. Figure 2 shows the consequences if no action is taken: the delay spreads on all successive trains, resulting in 34 minutes of total train delays, 1750 minutes of total passenger delays, and almost 160 waiting minutes at stations. At this point, the rescheduling procedure is launched. The model is solved

Figure 2: Context of numerical experiment: disturbed operations



using IBM ILOG CPLEX Optimization Studio version 12.6. The blocking stairways considered as decision variables are obtained via (off-line) simulations in OpenTrack: each train runs alone on the infrastructure and departures after stops are delayed by one minute up to thirty times. The cancellation penalties (ω_t) are set equal to the service periodicity for passenger trains and to one hour for freight trains, while the penalties for cancelling connections are set equal to the time to the next service in the destination direction. It is assumed that the average number of passengers alighting each train at each station and using scheduled connections are known, and we generated the "actual" number of passengers using a Poisson distribution with the known average number of passengers as parameter (mean). Initially, freight trains are considered as trains transporting 1 passenger. Then, the value is increased to analyse the sensitivity with respect to these parameters. The model is solved using the three objectives (9a)-(9c) and both the average and the "actual" number of passengers for functions (9b) and (9c).

The results are summarized in table 1. Note that there are some "scheduled" minor delays. This is due to the coarse granularity we used for representing published arrivals and departures: we set the scheduled time of all events with minute-precision (an event occurring at x:59 has a published time equals x).

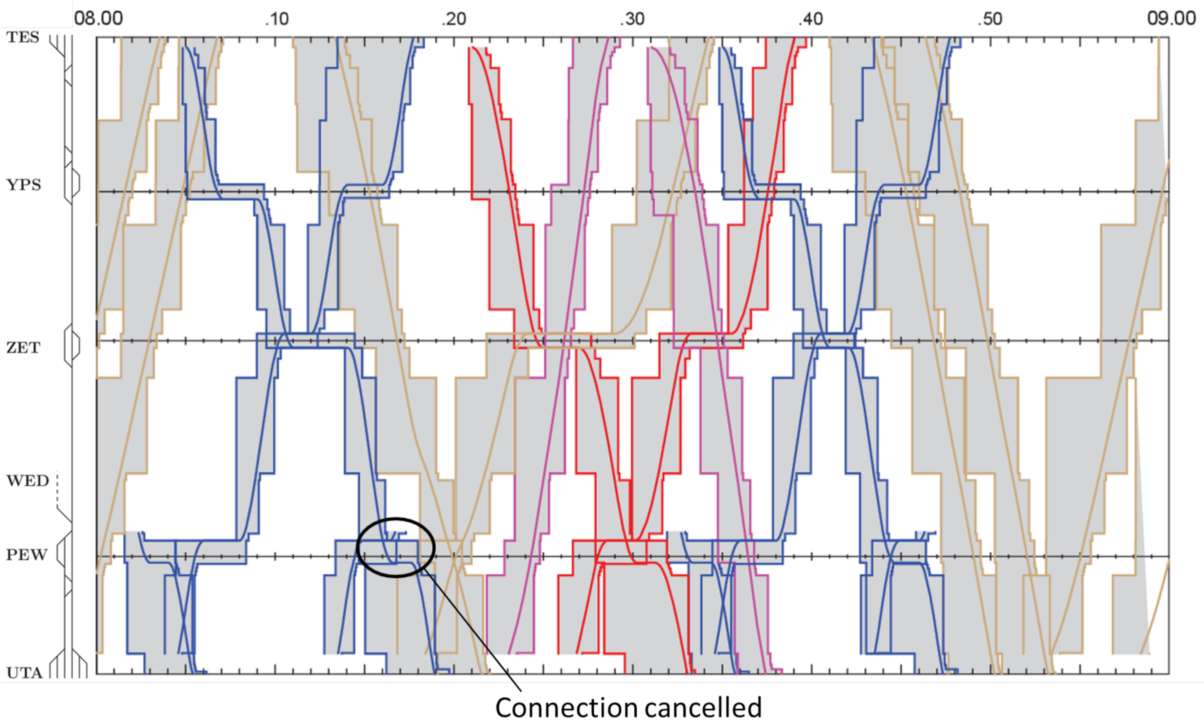
The solution obtained using (9a) (i.e. minimize train delays) consists in cancelling the connection from the delayed train at PEW and letting the connecting train depart as soon as possible. The

Table 1: Results with different rescheduling objectives

	Train delays (minutes)	Passenger delays (minutes)	Waiting (minutes)	Connections cancelled	Cancellations
scheduled	1.08	50.92	0	0	0
disturbed	34.15	1750.58	159.95	0	0
Objective					
(9a)	6.13	434	102.5	1	0
(9b) average	33.3	244.17	121.5	1	0
(9b) actual	33.3	244.17	121.5	1	0
(9c) average	37.77	265.13	75	0	0
(9c) actual	37.77	265.13	75	0	0

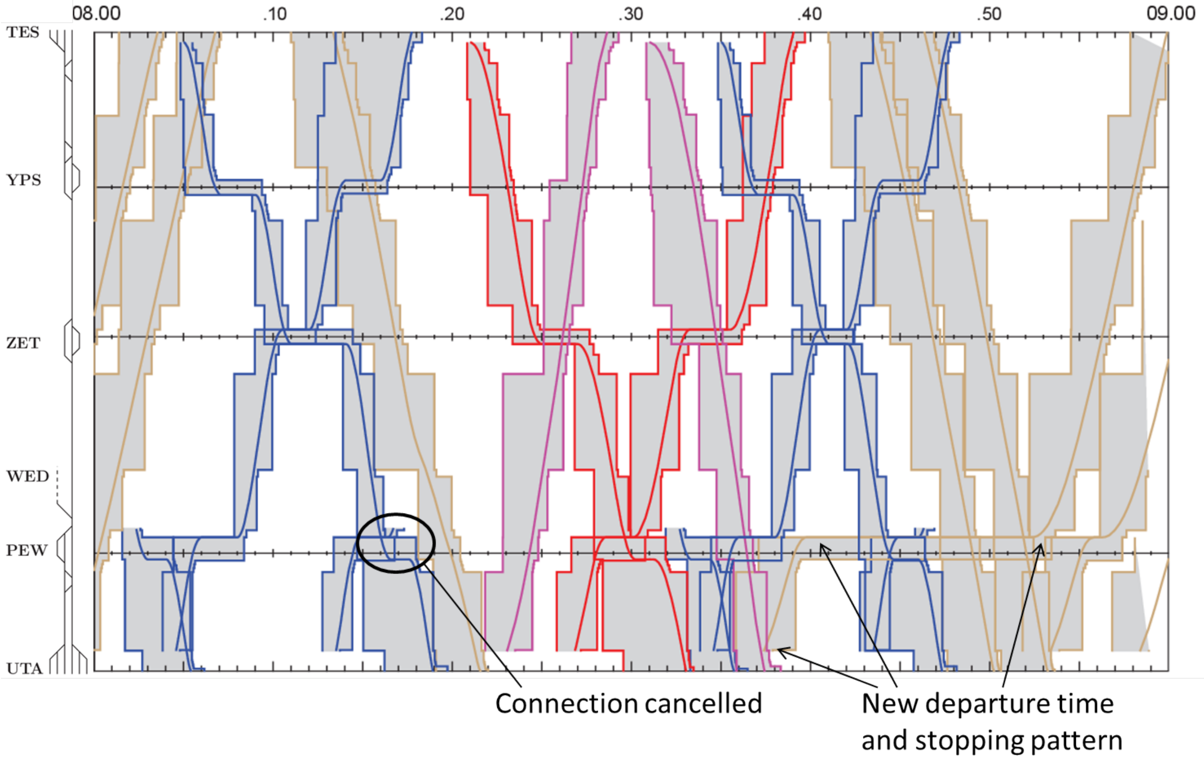
resulting train diagram is shown in figure 3. One can see that the secondary train delays are smaller than in the non-rescheduled case from figure 2 and mostly fall under the tolerance value of one minute.

Figure 3: Result of numerical experiment using objective (9a) (i.e. minimize train delays)



Minimizing passenger delays and inconvenience (objectives (9b) and (9c)) results in smaller passengers delays but larger train delays. Note that in both cases using the average and the actual number of passengers involved produce the exact same results. The solution obtained using (9b) (i.e. minimize passenger delays) consists in breaking the connection as done by (9a) but, instead of keeping the same train sequence as scheduled, the freight train coming from UTA is kept at the initial station and then stopped at PEW in order to reduce the delays of passenger trains (see figure 5).

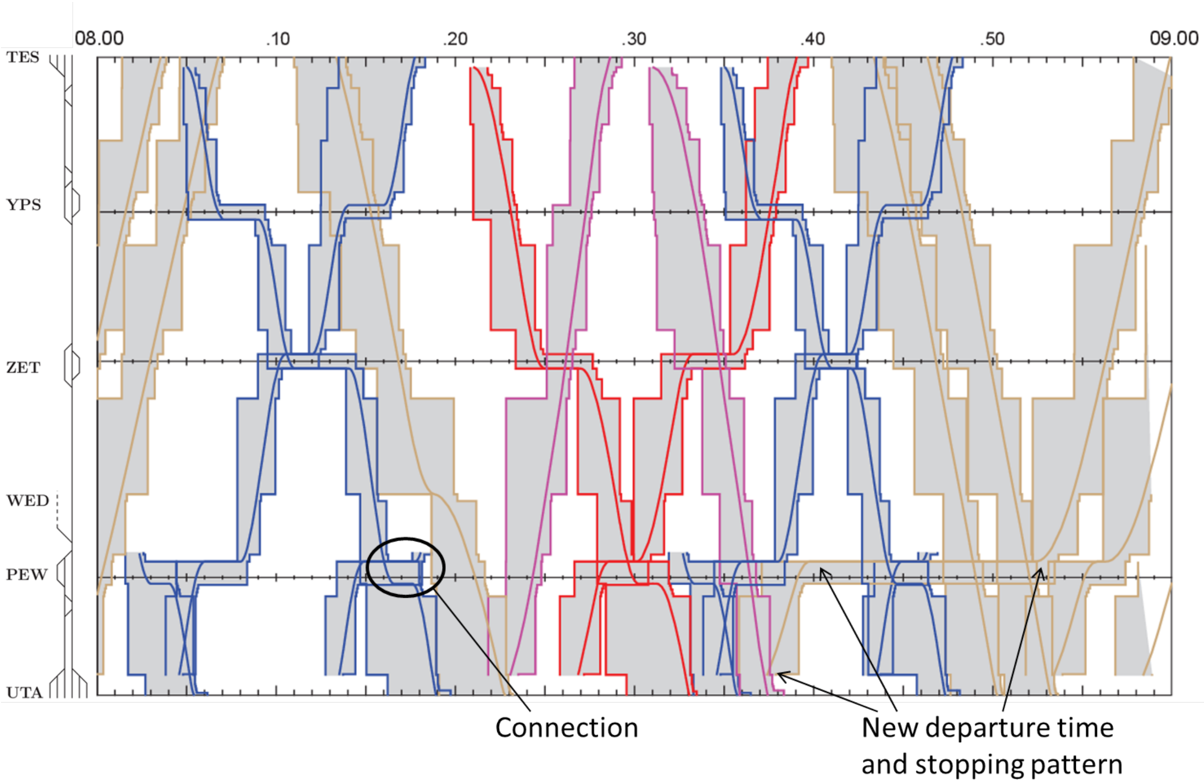
Figure 4: Result of numerical experiment using objective (9b) (i.e. minimize passenger delays)



The solution obtained using (9c) (i.e. minimize passenger inconvenience) is analogous to the previous one but for the fact that no connection is cancelled.

No run is cancelled in any of the cases. Increasing the conversion factor from freight delays to passengers delays from one to ten (i.e. now a freight train is considered as a passenger train transporting ten passengers), produces an interesting effect: now all three objective functions give the exact same solution, which corresponds to the solution produced by (9a) and shown in figure 3.

Figure 5: Result of numerical experiment using objective (9c) (i.e. minimize passenger inconvenience)



5 Conclusion

Several authors have considered the problem of finding an appropriate objective function for railway rescheduling but, at present, there is no unique answer. In particular, many approaches focus on one category of customers (either passengers or freights) and neglect the other. Thus, they are not particularly suited for rescheduling mixed traffic.

Our numerical experiment has shown that the Resource Conflict Graph is very flexible with respect to the objective function but also that different functions may lead to very different results. In particular, results obtained by minimizing only train delays tend to have extremely high impacts on passengers. Thus, passengers should be considered explicitly by any approach to railway conflict resolution. It was shown that the results obtained with average data do not differ from the ones obtained with ”actual” data. This means, that these procedures may be implemented by practitioners using historic data without loss of solution quality. An important open point is the weight to be associated with freight services. How many passenger delay minutes have to be accounted for each freight train delay minute? The numerical experiment showed that the solution strongly depends on these weights. A solution to this issue may be to include a factor for converting a freight train delay to passenger delays into slot allocation contracts in order to allow more transparent decisions in case of disturbed railway operations.

Our future work includes tests on larger numerical experiments and including other objectives such as optimizing energy efficiency. Further, we will improve the solution method in order to keep the computational effort under control even when considering large network partitions with very dense traffic. In this context, we will also study the maximum practicable size of the rescheduling area, traffic density, rescheduling variables and rescheduling horizon.

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