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Stop-Skipping to Reduce Delays in Train Rescheduling

Sonia Di Cola, Bianca Pascariu, Paola Pellegrini, and Valentina Cacchiani

Abstract In railway systems, unexpected disturbances often make the planned train schedule infeasible. The real-time Railway Traffic Management Problem (rtRTMP) consists in applying retiming, reordering and rerouting of trains with the aim of minimizing delay propagation. In this work, we additionally consider the option of skipping stops to further reduce delays. We extend the RECIFE-MILP model, a Mixed Integer Linear Programming based heuristic for the rtRTMP with microscopic network description, by including stop-skipping. We evaluate the benefit and impact of this rescheduling measure on train and passenger delays in a suburban railway network.

Keywords Stop-skipping · Train rescheduling · MILP model

1 Introduction

Unexpected delays and disturbances occur on a daily basis and cause conflicts between trains running on the railway infrastructure, and, as a consequence, inconvenience to passengers. Train rescheduling [3] consists in retiming, reordering and rerouting trains to determine a new conflict-free schedule with the goal of

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minimizing delay propagation and inconvenience to the passengers. Recently, there has been a noticeable increase in enhancing passengers' experience and focusing on passenger-oriented rescheduling approaches [7].

An additional rescheduling measure that has recently been investigated is that of skipping stops, which is particularly relevant for suburban railway or metro systems with high train frequency. In this case, Train Operators can decide to skip some stops so that train delays are reduced and passengers can reach their destination faster, thus decreasing their delays as well. Clearly, skipping stops may also negatively affect some passengers who needed to get on/off the train at a skipped stop: these passengers have to get on the following train or have to get off at the previous stop and wait for the following train. Therefore, an appropriate trade-off has to be obtained between delay minimization and stop-skipping.

The main contribution of this work is that we extend the RECIFE-MILP model [6], a Mixed Integer Linear Programming (MILP) based heuristic for the rtRTMP, by including stop-skipping. This model uses a microscopic level of detail to describe the railway network. In particular, the infrastructure is modeled considering *track-circuits*, i.e., track segments on which the presence of a train is automatically detected [6]. Sequences of track-circuits are grouped into block sections, which start and end with a light signal. Several block sections can share track-circuits, for example in presence of a switch: two block sections may have the same entry signal, share the first track-circuits, split through the switch and have different exit signals. A sequence of block sections composes a route. We consider a suburban railway network and compare the new model with the classical RECIFE-MILP to evaluate how train delays can be reduced by stop-skipping. In addition, we embed the new model in a framework to evaluate the impact of stop-skipping on the passengers' delays at destination by considering the assignment of passenger demand to trains computed as in [9].

In Sect. 2 we review the related literature. In Sect. 3 we present the new model and the framework for passengers' evaluation. In Sect. 4 we report computational results on real-life instances. Finally, we draw some conclusions and present directions for future research in Sect. 5.

2 Literature Review

The literature on train rescheduling is extremely broad. In this section, we focus only on works that apply stop-skipping to train rescheduling during operations. The real-time stop-skipping technique was first used in [10] who developed a simulation study to evaluate two stop-skipping policies by considering passenger distribution and disruption duration. Several years later, in [1], an ILP model was proposed with stop-skipping and including rolling stock constraints with the goal of minimizing the passengers' waiting time and the number of skipped stops in a dense railway system. A macroscopic level of detail of the network was employed. Recently, in [2], the model by [1] was extended by considering decisions on canceling or short-turning trains and adding stops, and by including multiple objectives. A simulation-optimization approach was proposed to derive multiple non-dominated solutions. In [5], stop-skipping is adopted to effectively reduce the number of passengers stranded on the platform to avoid overcrowded situations during the recovery period after a disruption in a bi-directional metro line. An optimization model that includes passenger flows is proposed with a macroscopic description of the network. An iterative heuristic algorithm, based on a model decomposition, is developed to solve the problem.

Recently, to address the rescheduling problem during complete track blockages, in [11], a MILP model that employs flexible stopping (i.e., skipping stops and adding stops) and flexible short-turning (i.e., a rolling stock unit turns at a station to be used for another train service in the opposite direction), combined with retiming, reordering, and canceling, has been proposed. The model considers networks with double-track and single-track lines described at a macroscopic level, and passenger demand is handled in a static way. The objective is to minimize passenger delays. To further extend previous works, dynamic passenger flows have been included in [4, 12]. In [12], a passenger-oriented timetable rescheduling model is proposed to cope with railway disruptions. This model accounts for flexible stopping (adding and skipping stops) and for passenger re-routing with passenger transfers. The railway infrastructure is described at a macroscopic level. An adapted fix-and-optimize algorithm is developed to solve the problem. In [4], the stop-skipping technique is considered while taking into account rolling stock constraints and dynamic passenger flows. A model predictive control algorithm is applied that solves the problem in a rolling horizon setting. The method is tested on a metro line described at a macroscopic level.

From the literature analysis, we can see that the railway infrastructure is described at a macroscopic level of detail. In this work, we extend the RECIFE-MILP model by adding the possibility of skipping stops while considering a very detailed description of the railway network.

3 Stop-Skipping and Passenger Delays Evaluation

This section is devoted to presenting the RECIFE-MILP model extended by stop-skipping options (Sect. 3.1) and the framework used to evaluate the effects on passengers' delays (Sect. 3.2).

3.1 Stop-Skipping in RECIFE-MILP

In this section, we report the RECIFE-MILP model enhanced with the new possibility of skipping stops. We first introduce all sets, parameters and variables used in the classical version of RECIFE-MILP [6]. Then, we present the new sets, parameters and variables and show the complete MILP model.

As already mentioned, RECIFE-MILP considers a detailed description of the railway infrastructure. In particular, the infrastructure is modeled considering track-circuits. The model takes as input the actual traffic state and computes new train schedules by allowing for reordering, retiming and rerouting trains with the goal of minimizing train delays [6]. RECIFE-MILP uses the following sets and parameters:

- T, R_t: the set of trains and of routes available to train $t \in T$;
- TC^r, TC_t: the set of track-circuits belonging to route $r \in R$ and of those which can be used by train $t \in T$;
- S_t, $TCS_{t,s}$: the set of stations where $t \in T$ has a scheduled stop and set of track-circuits that can be used by t for stopping at $s \in S_t$;
- S: the set of stations;
- $sched_t$: scheduled arrival time of train $t \in T$ at destination;
- $init_t$, $exit_t$: earliest time at which train $t \in T$ can be operated and earliest time at which it can reach its destination given $init_t$, the route assigned in the timetable and the intermediate stops;
- $rt_{r,t,tc}$, $ct_{r,t,tc}$: running and clearing time of $tc \in TC^r$ along $r \in R$ for train $t \in T$;
- $ref_{r,tc}$: reference track-circuit for the reservation of $tc \in TC^r$ along $r \in R$, depending on block section structure and interlocking system;
- for_{bs}, rel_{bs}: formation and release time for block section bs;
- $dw_{t,s}$, $a_{t,s}$, $d_{t,s}$: minimum dwell time, scheduled arrival and scheduled departure times for train $t \in T$ at station $s \in S_t$;
- $p_{r,tc}$, $s_{r,tc}$: track-circuits preceding and following $tc \in TC^r$ along $r \in R$;
- w_t: weight of train t delay;
- M: a large constant.

RECIFE-MILP employs the following decision variables:

- $sU_{t,tc}$, $eU_{t,tc}$: continuous positive variables representing the time at which $tc \in TC_t$ starts and ends being utilized by $t \in T$;
- $x_{t,r}$: binary variable equal to 1 if train $t \in T$ uses route $r \in R_t$, 0 otherwise;
- $y_{t,t',tc}$: binary variable equal to 1 if train $t \in T$ utilizes track-circuit tc before train t', such that index t is smaller than index t' ($t \prec t'$), with $tc \in TC_t \cap TC_{t'}$, and 0 otherwise.
- $o_{t,r,tc}$: time in which $t \in T$ starts the occupation of $tc \in TC^r$ along $r \in R_t$;
- $l_{t,r,tc}$: longer stay of the head of $t \in T$ on $tc \in TC^r$ along $r \in R_t$, due to dwell time and scheduling decisions (delay);
- D_t: delay suffered by train t when exiting the infrastructure, if the exit does not correspond to a station.

To include the possibility of skipping stops, we introduce the following sets and parameters:

- S_{skip}: set of stations that can be skipped;
- $\Delta dec_{t,r,tc}$: deceleration time of train t on tc along route r;
- $\Delta acc_{t,r,tc}$: acceleration time of train t on tc along route r;
- w^s: penalty for skipping a stop at station s.

In addition, we introduce the following decision variables:

- $k_{t,s}$: binary variable equal to 1 if train $t \in T$ skips its stop at station $s \in S_{skip} \cap S_t$, 0 otherwise. Defined for all the trains on the stations that can be skipped;
- $art_{t,r,tc} \in \mathbb{R}_+$: actual running time of train t on tc along route r.

Differently from the RECIFE-MILP model from the literature, when including the option of skipping stops, we have to account for the shorter running times that a train can achieve since it does not have to decelerate and accelerate after a stop. In addition, if a stop is skipped it is not necessary to respect the scheduled departure and dwell times at that stop.

The stop-skipping RECIFE-MILP objective function is to minimize the weighted sum of train delays and penalties for skipping stops:

$$\min \sum_{t \in T} \left(w_t D_t + \sum_{s \in S_t \cap S_{skip}} w^s k_{t,s} \right). \tag{1}$$

Obviously, skipping a stop causes inconvenience to passengers who should get on or off the train at that stop. Therefore, we penalize skipping stops. On the other hand, skipping a stop can reduce delays for other passengers. The weights of the two terms in the objective function are used to find a trade-off between the two conflicting objectives. The values of w^s ($s \in S_{skip}$) can be selected based on the relevance of stop s according to the experience of the practitioners (e.g., if it is a stop where several passengers transfer to other lines the corresponding penalty should be high) but can also be chosen based on the current train delays and predicted passenger flows. In Sect. 4, we consider several values for w^s ($s \in S_{skip}$) to analyze their impact on train and passenger delays.

Constraints (2) set the start time for the occupation of track circuit tc by train t along route r to be at least the earliest time for operating train t, while constraints (3) set this time to 0 if the train does not use route r:

$$o_{t,r,tc} \geq init_t\, x_{t,r} \qquad \forall t \in T, r \in R_t, tc \in TC^r, \tag{2}$$

$$o_{t,r,tc} \leq M x_{t,r} \qquad \forall t \in T, r \in R_t, tc \in TC^r, \tag{3}$$

Constraints (4)–(8) define the actual running time of train t on track circuit tc along route r by considering the effect of stop-skipping. In particular, the actual running time corresponds to the scheduled running time if the stop cannot be skipped. On the contrary, if a stop is skipped, acceleration and deceleration times do not have to be included, thus the actual running time is smaller than the scheduled one:

$$art_{t,r,tc} = rt_{r,t,tc} x_{t,r}$$

$$\forall t \in T, r \in R_t, tc \in TC^r : \nexists s \in S_{skip}, tc \in TCS_{t,s} \vee p_{r,tc} \in TCS_{t,s} \tag{4}$$

$$art_{t,r,tc} \geq rt_{r,t,tc} - \Delta dec_{t,r,tc} k_{t,s} - M(1 - x_{t,r})$$

$$\forall t \in T, r \in R_t, s \in S_{skip}, tc \in TC^r \cap TCS_{t,s}, \tag{5}$$

$$art_{t,r,tc} \leq rt_{r,t,tc} - \Delta dec_{t,r,tc} k_{t,s} + M(1 - x_{t,r})$$

$$\forall t \in T, r \in R_t, s \in S_{skip}, tc \in TC^r \cap TCS_{t,s}, \tag{6}$$

$$art_{t,r,tc} \geq rt_{r,t,tc} - \Delta acc_{t,r,tc} k_{t,s} - M(1 - x_{t,r})$$

$$\forall t \in T, r \in R_t, s \in S_{skip}, tc \in TC^r, p_{r,tc} \in TCS_{t,s}, \tag{7}$$

$$art_{t,r,tc} \leq rt_{r,t,tc} - \Delta acc_{t,r,tc} k_{t,s} + M(1 - x_{t,r})$$

$$\forall t \in T, r \in R_t, s \in S_{skip}, tc \in TC^r, p_{r,tc} \in TCS_{t,s}, \tag{8}$$

Constraints (9) define the start time of occupation of track circuit tc by train t along route r based on the potential longer stay $l_{t,r,tc}$ on the track circuit and on the actual running time $art_{r,t,tc}$. Constraints (10)–(11) impose the start time of the occupation of the track circuit following a stop to be at least the scheduled departure time, unless the stop is skipped:

$$o_{t,r,s_{r,tc}} = o_{t,r,tc} + l_{t,r,tc} + art_{r,t,tc} \qquad \forall t \in T, r \in R_t, tc \in TC^r \tag{9}$$

$$o_{t,r,s_{r,tc}} \geq d_{t,s} x_{t,r} \qquad \forall t \in T, r \in R_t, s \in S_t \setminus S_{skip}, tc \in TCS_{t,s} \cap TC^r \tag{10}$$

$$o_{t,r,s_{r,tc}} \geq d_{t,s}(x_{t,r} - k_{t,s}) \qquad \forall t \in T, r \in R_t, s \in S_t \cap S_{skip}, tc \in TCS_{t,s} \cap TC^r \tag{11}$$

The longer stay of train t on track circuit tc along route r is required to be at least the minimum dwell time (constraints (12)) unless the stop is skipped (constraints (13)):

$$l_{t,r,tc} \geq dw_{t,s} x_{t,r} \qquad \forall t \in T, r \in R_t, s \in S_t \setminus S_{skip}, tc \in TCS_{t,s} \cap TC^r \tag{12}$$

$$l_{t,r,tc} \geq dw_{t,s}(x_{t,r} - k_{t,s}) \qquad \forall t \in T, r \in R_t, s \in S_t \cap S_{skip}, tc \in TCS_{t,s} \cap TC^r \tag{13}$$

Constraints (14) define the delay of train t at destination (to be minimized in the objective function), while constraints (15) require to select one route for each train $t \in T$:

$$D_t \geq \sum_{r \in R_t} o_{t,r,tc_\infty} - sched_t \qquad \forall t \in T, \tag{14}$$

$$\sum_{r \in R_t} x_{t,r} = 1 \qquad \forall t \in T \tag{15}$$

Constraints are used to define the start and end utilization times of track circuit tc by train t:

$$sU_{t,tc} = \sum_{r\in R_t: tc\in TC^r} \left(o_{t,r,ref_{r,tc}} - for_{bs_{r,tc}}\, x_{t,r}\right) \qquad \forall t \in T,\ tc \in TC_t \tag{16}$$

$$eU_{t,tc} = \sum_{\substack{r\in R_t:\\ tc\in TC^r}} o_{t,r,tc} + \sum_{\substack{tc'\in TC^r:\\ tc\in OTC_{t,r,tc}}} l_{t,r,tc'} + art_{r,t,tc} + (ct_{r,t,tc} + rel_{bs_{r,tc}})x_{t,r} \qquad \forall t \in T, tc \in TC_t, \tag{17}$$

$$eU_{t,tc} - M(1 - y_{t,t',tc}) \leq sU_{t',tc} \qquad \forall t, t' \in T, t \prec t',\ tc \in TC_t \cap TC_{t'}, \tag{18}$$

$$eU_{t',tc} - My_{t,t',tc} \leq sU_{t,tc} \qquad \forall t, t' \in T, t \prec t',\ tc \in TC_t \cap TC_{t'}. \tag{19}$$

3.2 Passenger Delays Evaluation

The enhanced RECIFE-MILP model is embedded in the framework illustrated in Fig. 1. The goal of this framework is to evaluate the impact of train rescheduling strategies on the passenger delays. Indeed, objective function (1) minimizes the weighted sum of train delays at destination and penalties for stop-skipping. However, depending on which and how many stops are skipped, some passengers may incur high delays or even may not be able to reach their destination within the considered rescheduling horizon. In particular, passengers may not be able to reach their destination if no train stops at their origin or destination station after their arrival in the system: we say that they are *stranded passengers* who should reach their destination outside the considered rescheduling period. Therefore, we want to investigate how passenger trips are affected by skipping stops, and evaluate whether passengers can have alternative trains to reach their destination. Moreover, we want to assess if

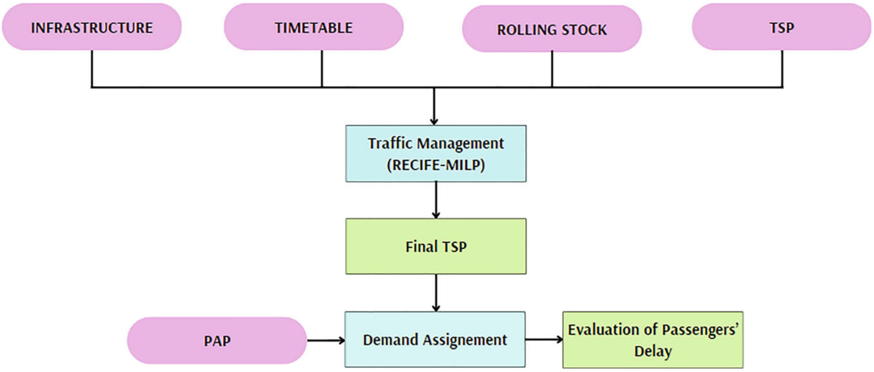


Fig. 1 Proposed framework's illustration

skipping stops may bring an overall gain, in terms of delays, both for passengers that needed to get on/off at the skipped stops and for passengers who were not affected by skipping stops.

The input data, highlighted in pink, consists of the planned timetable, the infrastructure and rolling stock description, the Traffic State Prediction (TSP) and the Passenger Assignment Plan (PAP). The TSP provides the information regarding the traffic flow which needs to be optimized, including the observed perturbations and delays. The PAP includes the relevant data regarding the passengers, such as their number, the origin-destination (OD) combination for each passenger group, and all the train-based paths, i.e., the subset of trains that can be employed for an OD pair. The specific format of these data is detailed in [8]. In particular, for each passenger group, the PAP indicates the desired time to arrive at the destination under unperturbed conditions and the actual arrival time considering the current traffic status.

Starting from the timetable, infrastructure, rolling stock and TSP, the traffic flow is optimized by RECIFE-MILP, with a focus on train delays. This leads to the generation of a new TSP that reflects the optimized traffic. Based on the final TSP and PAP, the demand assignment is conducted [9]: each passenger group is assigned to trains, and the difference between desired and actual arrival time is computed.

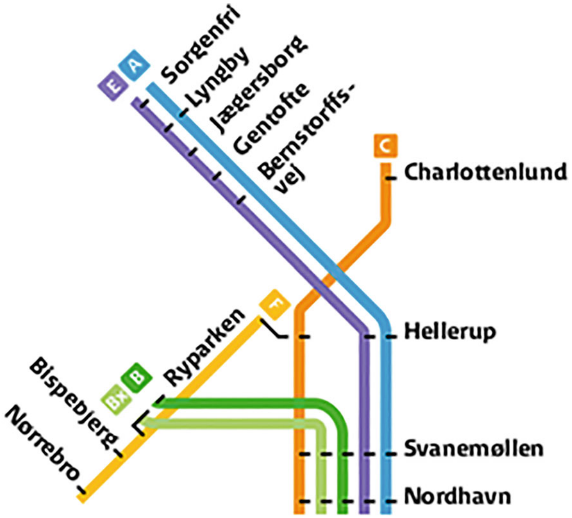
The described procedure is first executed with the classical RECIFE-MILP, i.e., stop-skipping is not allowed. Subsequently, the stop-skipping constraints are incorporated: several penalty values w^s ($s \in S_{skip}$) are considered, in order to determine a good trade-off penalty to improve both train and passenger delays.

4 Computational Results

We conduct computational experiments on a real-life case study related to the part of the Copenhagen suburban railway network shown in Fig. 2. To generate perturbed traffic situations, delays between 5 and 15 min are randomly applied to 20% of the trains. Traffic is assumed to evolve following the planned routes and passing orders until the optimization occurs. For the TSP, we consider two instances (*Inst1* and *Inst2*) representing 40 min of traffic starting at 8 a.m. and 9 a.m., respectively: in each instance, all trains that are traveling in the infrastructure at the starting time are considered, as well as all trains expected to enter within the next 40 min. For the PAP, we consider arrival of passengers within an interval of 20 min, according to the historical demand on September 9, 2017. By considering 40 min of traffic and only 20 min of passenger arrivals, we ensure that all passengers entering have available trains to complete their journey, at least when no stops are skipped. *Inst1* has 89 trains and 251 passengers, while *Inst2* has 91 trains and 76 passengers.

We execute the procedure described in Sect. 3.2 in three settings. Firstly, we impose that *None* of the stops can be skipped. Then, for the stop-skipping case, we evaluate two alternative scenarios. In the first one, *No HL-LY*, we require that HL (Hellerup) and LY (Lyngby) stations cannot be skipped: in fact, HL is used by many

Fig. 2 Part of Copenhagen suburban railway used as a case study



passengers to transfer to other lines and LY is the destination of many passengers. Remark that the a priori selection of which stops can be skipped or not is often done in the practice. It is typically based on experience and historical data on passenger demand. In the second scenario, *All*, we allow for skipping any stop. We execute the procedure for both scenarios by considering in turn a single value for w^s ($s \in S_{skip}$) in set $\{10, 25, 50, 75, 100\}$. We impose a time limit of 180 s for each execution: in the first at most 30 s, a solution with fixed timetable routes is obtained; then this solution is used as a warm-start for the routing and scheduling problem solution in the remaining time. The results are reported in Table 1. For each instance, we report the solution objective value, the sum of train delays and the sum and average of passenger delays (in seconds), the percentage *Strd%* of stranded passengers who could not reach their destination due to stop-skipping, the number of skipped stops and the optimality gap when the time limit is reached. The total number of stops that can be skipped (skippable stations) for all train services is reported in brackets for each case. We show in gray train and passenger delays when they are smaller than in the no-skip case.

By looking at the results in Table 1, we can observe that stop-skipping allows a significant reduction of train delays in both instances and with almost all penalty values, thanks to the reduction in train running and dwell times. On the other hand, when many stops are skipped (i.e., when the penalty is equal to 10 or 25), the percentage of stranded passengers is not negligible, reaching 24%.

If we impose that stops HL and LY cannot be skipped, the percentage of stranded passengers is reduced with respect to the case in which all stops can be skipped, but no benefit on passenger delays is obtained for *Inst1*. On the contrary, if all stops can

Table 1 Experimental results: grey cells show delay reduction obtained when skipping stops

Inst1 (89 trains, 251 pax)

Skippable stations	Pen	Obj	Tr. Del.	Pax Del. (avg.)	Strd%	N. Sk.	Gap
None (0)	-	13700	13700	39128 (156)	0.00	0	0.13
No HL-LY (153)	10	12061	11551	43897 (192)	8.74	51	0.16
	25	12855	11930	39852 (166)	4.37	37	0.17
	50	13349	12699	39470 (162)	2.90	13	0.17
	75	13532	13157	40976 (166)	1.63	5	0.15
	100	13680	13280	40507 (164)	1.62	4	0.15
All (234)	10	11427	10577	59933 (281)	15.00	85	0.16
	25	12494	11219	55111 (246)	10.80	51	0.20
	50	13325	12675	37121 (157)	6.00	13	0.19
	75	13508	13133	40440 (169)	4.60	5	0.17
	100	13616	13216	40812 (171)	5.00	4	0.17

Inst2 (91 trains, 76 pax)

Skippable stations	Pen	Obj	Tr. Del.	Pax Del. (avg.)	Strd%	N. Sk.	Gap
None (0)	-	18527	18527	15254 (201)	0.00	0	0.11
No HL-LY (155)	10	16624	16014	15843 (404)	9.00	61	0.11
	25	17428	16328	16196 (218)	2.30	44	0.13
	50	18024	17274	15095 (201)	0.88	15	0.13
	75	18309	18159	14876 (186)	0.04	2	0.13
	100	18340	18240	14831 (196)	0.00	1	0.12
All (234)	10	15763	14853	23369 (229)	23.90	91	0.16
	25	17269	15744	16196 (218)	2.30	61	0.20
	50	18173	17623	14930 (200)	2.04	11	0.19
	75	18062	17237	13818 (196)	2.00	11	0.17
	100	18394	18294	14869 (195)	0.04	1	0.17

be skipped, passenger delays can be reduced for both instances when the penalty is 50, thus suggesting that an intermediate value is the most appropriate to reach a good trade-off between stranded passengers and delay reduction.

For all settings, the performance of RECIFE-MILP in terms of optimality gap is similar, hence stop-skipping can be handled in the model even when all stops can be skipped. By looking at the solution objective value, we can see that it almost always improves when allowing all stops to be canceled, with a few exceptions due the heuristic nature of the solution approach.

We underline that the choice of which stops to skip (and not only the number of stops to skip) is very relevant: indeed, in *Inst1* with penalty 50, the number of skipped stops is 13 both when HL and LY cannot be skipped and when all stops can be skipped, but only in the latter case an improvement is obtained on the passenger delays, both in total and in average. This suggests that it is hard to decide a priori the set of stops that can be skipped to reduce passenger delays, while the decision should be made by directly embedding passenger choices inside the model. Similarly, it would be useful to add to the objective function a penalization accounting for the stranded passengers. Obviously, this would imply considering the passenger flows within the model and thus solving a model with a larger number of variables and constraints, which may be harder especially in a real-time setting.

5 Conclusions

In this paper, we presented a variant of a state-of-the-art algorithm for railway traffic management. In this variant, we allow the algorithm to skip planned stops to reduce delay propagation. Stop-skipping is a quite frequently applied measure in urban railway, but few algorithms exist including it in the optimization. To the best of our knowledge, this is the first paper in which this measure is optimized when considering a microscopic representation of the railway infrastructure.

In the experimental analysis, we assessed the system performance in various contexts: we considered the possibility of skipping any stop, or we impose that stops at some critical stations must be performed. We assessed the performance in terms of both train and passenger delays, and we show that in some cases it is possible to reduce both train and passenger delays by wisely selecting the stops to skip. However, this wise selection is not trivial and a priori decisions are not always beneficial.

As future work, one could consider including information on static passenger demand to partially evaluate the impact of skipping stops or including passenger delay evaluation with a feedback mechanism to dynamically adjust the penalty values used in the objective function. Embedding passenger routing or passenger delay evaluation directly within the model is also an interesting research direction to be exploited. Furthermore, it could be useful to develop machine learning techniques to compute the penalties associated with skipping stops based on observed and historical data of passenger demand in the network.

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