

Adjusting freight train paths to infrastructure possessions

Bešinović, N.; Widarno, B.; Goverde, Rob M.P.

DOI

[10.1109/ITSC45102.2020.9294192](https://doi.org/10.1109/ITSC45102.2020.9294192)

Publication date

2020

Document Version

Accepted author manuscript

Published in

2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)

Citation (APA)

Bešinović, N., Widarno, B., & Goverde, R. M. P. (2020). Adjusting freight train paths to infrastructure possessions. In *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)* Article 9294192 (2020 IEEE 23rd International Conference on Intelligent Transportation Systems, ITSC 2020). IEEE. <https://doi.org/10.1109/ITSC45102.2020.9294192>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Adjusting freight train paths to infrastructure possessions

N. Bešinović, B. Widarno, Rob M.P. Goverde*

Abstract — This paper tackles railway timetabling with infrastructure work possessions. It introduces the integrated Passenger and Freight Train Timetable Adjustment Problem (PF-TTAP) which handles both passenger as well as freight trains. To deal with possessions, passenger trains are typically retimed, reordered or partially cancelled, while for freight trains it is important to reach their destination, possibly using an alternative path. Alternative paths for freight trains are generated using the k-shortest path algorithm. To solve the PF-TTAP, a mixed integer linear programming (MILP) problem is developed to simultaneously retime, reroute and cancel trains in the network. The model aims at minimizing deviations from the original timetable and in particular selecting alternative freight paths with the least turning activities and non-commercial stops. The model was tested on the Dutch national railway network. The PF-TTAP model successfully created an alternative hour pattern satisfying all the railway stakeholders.

Keywords— Railway, maintenance, possessions, timetable adjustment, freight, passenger, disruption, resilience

I. INTRODUCTION

THE desire to have clean and green environment is tangible in society nowadays. However, road congestion keeps increasing, for instance by 27% in the Netherlands in 2016 [1]. Shifting highway users to railways, for both people and freight, could decrease the congestion and also reduce the CO₂ emission. This will also lead to an increased need of planned infrastructure possessions, i.e., a track closed for traffic for a period of time to be able to do infrastructure maintenance and renewal. Therefore train services need to be adjusted to minimize the negative effects of infrastructure possessions. Currently, all stakeholders, the infrastructure manager (IM), the passenger train operator companies (POC), and freight train operator companies (FOC) have to sit together and discuss the best solution for every week's scheduled work possessions and coordinate their services accordingly. This paper addresses this problem and provides a mathematical model for the railway planners such that they

This project is a joint collaboration between the Delft University of Technology and ProRail, the infrastructure manager of the Dutch railway network.

N. Bešinović, B. Widarno and R.M.P. Goverde are with the Department of Transport and Planning, Delft University of Technology, Delft, The Netherlands, (e-mails: {n.besinovic, r.m.p.goverde}@tudelft.nl, bryanwidarno@gmail.com).

*Corresponding author.

can easily deal with the planned railway infrastructure possession, for both the passenger and freight trains together.

The timetable adjustments use the spare capacity as good as possible while rescheduling the scheduled passenger and freight trains. In this process, passenger trains stay as close as possible to the original routes, while for freight trains it is most important to reach their destination and thus planners have more flexibility to choose which route through the network to take. The result of this process is an adjusted timetable.

In this paper, we introduce the integrated Passenger and Freight Train Timetable Adjustment Problem (PF-TTAP) which handles both passenger as well as freight trains during infrastructure maintenance possessions. A new mixed integer linear programming (MILP) is developed to simultaneously retime, reroute and (partially) cancel trains in the network. The model minimizes deviations from the original timetable and in particular selects alternative freight paths with the least turns (changing direction) and non-commercial stops. In addition, an algorithm for creating a set of alternative routes is proposed. Interviews with experts helped to set up constraints, decisions and objective parameters when formulating the mathematical model. The model was tested on the Dutch national railway network.

The contribution of this paper is as follows:

1. New mathematical model for generating freight train adjustments during infrastructure possessions
2. New formulation for allowing global train rerouting
3. Experiments on a real-life case study

The remainder of the paper is organized as follows. Section II reviews the existing literature. The mathematical formulation of PF-TTAP is given in Section III. The case study is showcased in Section IV and the concluding remarks are in Section V.

II. LITERATURE REVIEW

To deal with possessions and in particular solving resulting conflicts with the traffic operations, three approaches can be found: 1. Given the fixed timetable for train services, adjust the schedule for doing the maintenance [2][3][4]; 2. Given the schedule for doing the maintenance, adjust the timetable of train services [5][6][7][8]; 3. Scheduling maintenance works and timetable simultaneously

to get the overall schedule [9][10][11][12]. In this project, the focus is on the second approach where the schedule for the railway infrastructure possession is one of the inputs and the model adjusts the timetable for both the passenger and freight train services. The reason for this decision is because specific possessions occur only a few times per year in certain locations, while the timetable is used daily. Therefore, it is more practical to introduce adjustments to the existing timetables only when this is really needed.

Most of the research on the second approach aim at passenger train services. In particular, [5], [6] focused on solving the Train Timetable Adjustment Problem (TTAP) without considering the freight trains using a mathematical model on a macroscopic level. The model focused on cancelling, retiming, and short-turning passenger trains at fixed locations. In addition, [6] presented flexible short-turning and network aggregation techniques for improving computation times to be able to adjust the timetable for the complete Dutch network.

Similarly, [8] worked on the adjustment of a train timetable during unplanned railway infrastructure maintenance activities using a microscopic representation. Their approach was applied to a corridor (Paris – Le Harve) and global rerouting is not possible. For large-scale networks, macroscopic models tend to be more suitable.

Currently, no research considers freight trains as one of the components in adjusting railway timetables of a large-scale railway network for given infrastructure possessions. In addition, recent studies suggest that more research is required to deal with both planned (i.e. possessions) and unplanned disruptions [13]. Our paper contributes to this gap and extends the previous research from the freight trains point of view. This paper defines the integrated Passenger and Freight Train Timetable Adjustment Problem (PF-TTAP), which is an extension of TTAP [5],[6].

III. MODEL DEVELOPMENT

To formulate the PF-TTAP model, we use the Periodic Event Scheduling Problem (PESP) [14], given that train timetables in the Netherlands are based on a basic hour pattern. Setting up the PF-TTAP can be expressed by a periodic directed graph $G = (E, A, T)$. The set E presents the train events such as arrivals, departures, and through events defined for each timetable point such as stations, open-track stops and junctions. The set A presents activities that link events and defines the constraints for the minimum and maximum allowable time duration between two events. These activities could connect two events of one train, i.e., running activities, dwell activities, and through activities, or two trains, i.e., transfers, turns and headways to ensure the safety requirements. The parameter T represents the period length of the timetable, which usually equals 60 minutes.

This section presents the required input data, pre-processing, the basic TTAP model and the new PF-TTAP model formulation.

A. Input Data

The inputs for the PF-TTAP model are the original timetable and the possessions. The original timetable, including events and activities, is extracted from the timetable planning tool called Donna. In addition, the headways are defined as the standard norms from the Network Statement of the Dutch IM ProRail [15].

A list of possessions is provided. According to the location, a possession can be classified either as a station track or open track. In this paper, we consider complete closures (i.e. all tracks between two timetable points) on open tracks and both complete and partial closures in stations.

B. Pre-processing

The preprocessing consists of two parts for the passenger trains and freight trains, respectively.

The preprocessing for passenger trains assigns short-turning activities to original passenger trains operating over tracks with possessions. Such trains are split into two parts, turning at the last possible station before the possession on either end. This step remains the same as in [5].

The preprocessing step for freight trains includes the cancellation of the original freight path and providing suitable alternative paths, i.e., global rerouting possibilities. If a train is affected by a possession, then alternative paths need to be generated. The alternative freight paths are generated using the k -shortest path algorithm [17] as described in Procedure 1. The costs for the k -shortest path algorithm are based on the lengths of the open track between two timetable points.

Procedure 1: Generating alternative freight paths

Input: topological network, distance matrix, list of possessions, cancelled freight paths, parameter k

Output: alternative freight paths for all cancelled freight paths

For all cancelled freight paths

1. Record the origin (O) and the destination (D) of the cancelled freight path
2. Find alternative routes based on the k -shortest paths algorithm
3. Save the best k solutions

End

These alternative paths are translated into events and activities. Additional information about tracks and platforms that might be used for each alternative path are provided and derived from the freight paths in the original timetable. Figure 1 illustrates the concept of global rerouting alternatives. In this figure, one can see that initially there is an original freight path with an origin and a destination represented by the blue color. Due to the cancelled freight path, new alternative freight paths are generated. The alternative paths that are generated by the algorithm are represented in different colors. The PF-TTAP model chooses

at most one of these alternative paths to be incorporated as an alternative freight path in the adjusted timetable.

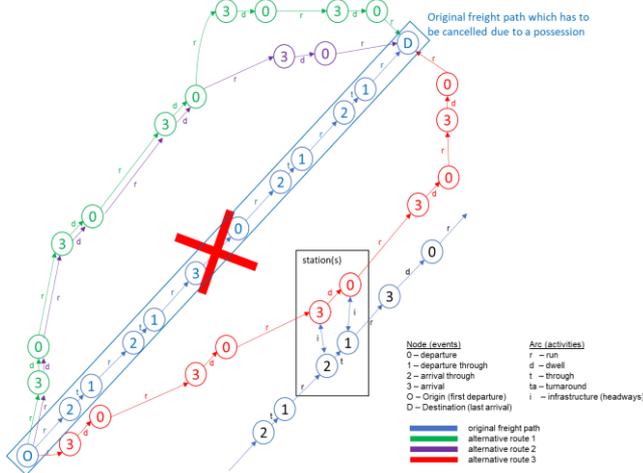


Fig. 1. Illustration of event-activity graph for global rerouting alternatives.

C. Basic TTAP Model

We introduce first the basics of the TTAP model developed in [5]. The TTAP model only considers passenger trains and introduces rescheduling measures such as cancelling and retiming. The main difference to PESP is that trains can be cancelled and therefore the events and constraints associated to a cancelled train should vanish. The constraints to accommodate cancellation for such trains are as follows:

$$l_{ij}(1 - X_m) \leq v_j - v_i + q_{ij}T \leq u_{ij}(1 - X_m) \quad \forall (i, j) \in A_{run}, \forall m \in M \quad (1)$$

$$v_j - v_i + q_{ij}T = dwell_m^s(1 - X_m) \quad \forall (i, j) \in A_{dwell}, \forall m \in M, \forall s \in S \quad (2)$$

$$l_{ij}(1 - X_m - X_n) \leq v_j - v_i + q_{ij}T \leq u_{ij}(1 - X_m - X_n) + (T - 1)(X_m + X_n) \quad \forall (i, j) \in A \setminus (A_{run} \cup A_{dwell}), \forall m, n \in M \quad (3)$$

Constraint (1) handles running activities, Constraint (2) is for dwell activities, and Constraint (3) is for other activities. Here, X_m is a binary variable stating whether train line m is cancelled, l_{ij} is the lower bound for an activity (i, j) , u_{ij} is the upper bound for an activity (i, j) , v_j is the event time of event j , q_{ij} is an integer variable for the order between two events, T is the period length of the timetable, $dwell_m^s$ is the scheduled dwell time of train line m at station s . An additional constraint to ensure that an event time becomes zero when the train m is cancelled is:

$$0 \leq v_j \leq (T - 1)X_m \quad \forall j \in E, \forall m \in M \quad (4)$$

Retiming of trains is treated using:

$$d_j^+ = v_j + T\alpha_j - \pi_j(1 - X_m) \quad \forall j \in E, \forall m \in M \quad (5)$$

$$0 \leq d_j^+ \leq dp_{max}^+ \quad \forall j \in E \quad (6)$$

Constraint (5) defines the delay of each event and constraint

(6) gives boundaries for the allowed maximum delay. Here, d_j^+ is the deviation from the original time for each train event j , α_j is a binary variable indicating whether the delay of event j crosses the time period border, π_j is the scheduled time of event j in the original timetable, dp_{max}^+ is the maximum deviation that is allowed for passenger trains. Also, the station capacity constraints from [5] remain in the PF-TTAP model.

The objective function of TTAP was to satisfy POCs only, i.e., minimize cancellation and delay of the passenger trains. In PF-TTAP this objective function is expanded such that the model could also choose good alternative paths for freight trains.

D. The PF-TTAP Model

Let us define the original freight paths $c \in C$ that need to be adjusted due to possessions and alternative freight paths $r \in R$ for each c . Set F is the set of events for all path in R , F_{OD} is the subset of the origin departure and destination arrival events, F_δ is the subset of events that allow changing directions, and A^{gr} is the set of the alternative freight paths activities.

The goal of the PF-TTAP model is to minimize the combined inconvenience of the POCs and FOCs. The objective function is developed based on interviews with planners. Passenger train-related terms are train delays at all stations and cancellations of train lines. Freight train-related terms are delays at the origin and destination, choosing the best alternative freight path (if none is selected, then it is cancelled), number of changing direction activities, number of commercial stops, and journey time. The objective function to solve the PF-TTAP is:

$$\min \left\{ \sum_{j \in E \cup F_{OD} \setminus E_{thru}} (w_j^{delay} d_j^+) + \sum_{m \in M} (w_m^{cancel} X_m) + \sum_{c \in C} \left(1 - \sum_{r \in R} Y_r^c \right) w_c^{cancel} + \sum_{r \in R} \sum_{j \in F} (\delta_{rj}^c w_{crj}^{CD} Y_r^c) + \sum_{r \in R} \sum_{j \in F} (w_{crj}^{ncS} Z_{rj}^c) + \sum_{r \in R} (\tau_{cr} w_{cr}^t Y_r^c) \right\} \quad (7)$$

Here, Y_r^c is a binary variable that determines whether an alternative path r for a cancelled freight path c is chosen or not, δ_{rj}^c is a parameter that indicates a change direction activity is required at event j of alternative path r of the freight path c , Z_{rj}^c is a binary variable that indicates whether event j corresponds to a dwell activity in alternative path r of freight path c . Finally, τ_{cr} describes the deviation of the journey time, which consists of running time and dwell time, between the cancelled freight path c and the alternative path r . The former is given by the timetable and the latter is computed as $\sum_{(i,j) \in A^{gr}} (v_j - v_i + q_{ij}T)$.

Each term has a weight: w_j^{delay} is the weight to penalize the deviation from the original time for each train event j , w_m^{cancel} serves as the weight to penalize cancellation of train line m , w_c^{cancel} is a penalty for not substituting freight path c by any alternative path, w_{rj}^{ncs} is the weight to penalize a non-commercial stop to event j , w_{cr}^{CD} is the weight to penalize changing direction in the global rerouting alternative path r caused by the cancelled freight train c , and w_{cr}^t is the weight to penalize the difference in journey time.

The model also controls the allowed maximum delay of the departure and arrival between the original freight path and the chosen alternative path by:

$$0 \leq d_j^+ \leq df_{max}^+ \quad \forall j \in F_{OD} \quad (8)$$

where df_{max}^+ is the allowed maximum delay for an alternative freight path. Train delays are tracked similarly as in (5):

$$d_j^+ = v_j + T\alpha_j - \pi_j(1 - Y_r^c) \quad \forall j \in F_{OD}, \forall m \in M \quad (5)$$

Additional sets of constraints are introduced for freight trains for selecting an alternative rerouting path and the corresponding activities. The model chooses at most one alternative r for each cancelled freight path c :

$$\sum_{r \in R} Y_r^c \leq 1, \quad \forall c \in C \quad (9)$$

In the following, constraints for non-commercial stop, run, pass through, headway and changing direction activities are given.

Non-commercial stop

$$l_{ij}Z_{rj}^c \leq v_j - v_i + q_{ij}T \leq u_{ij}Z_{rj}^c \quad \forall (i,j) \in A_{dwell}^{gr}, \forall j \in F_{dep}, \forall r \in R, \forall c \in C \quad (10)$$

$$Z_{rj}^c \leq Y_r^c \quad \forall j \in F, \forall r \in R, \forall c \in C \quad (11)$$

The model allows a possibility to dwell in certain stations (Constraint (10)). The lower and upper bounds l_{ij} and u_{ij} of a dwell activity (i,j) in the chosen alternative path ($Y_r^c = 1$) are activated only when it is necessary to dwell ($Z_{rj}^c = 1$). In addition, constraint (11) ensures that it eliminates the opportunity of the freight train to dwell when the alternative route is not chosen ($Y_r^c = 0$).

Additional running time

$$l_{ij}Y_r^c + \mu_{acc}Z_{ri}^c + \mu_{dec}Z_{rj}^c \leq v_j - v_i + q_{ij}T \leq u_{ij}Y_r^c + \mu_{acc}Z_{ri}^c + \mu_{dec}Z_{rj}^c \quad \forall (i,j) \in A_{run}^{gr}, \forall i,j \in F, \forall r \in R, \forall c \in C \quad (12)$$

$$Z_{ri}^c = Z_{rj}^c \quad \forall i \in F_{arr}, j = \sigma(i), \forall r \in R, \forall c \in C \quad (13)$$

When an extra stop is necessary, a train needs to decelerate before a station and to accelerate afterwards. These actions affect the running time of a train. To include these actions in the running time activities, constraint (12) adds additional

acceleration time μ_{acc} and deceleration time μ_{dec} needed for freight trains after and before stopping to the lower bound l_{ij} and upper bound u_{ij} . Both additional times are valid only when an alternative freight path needs to stop towards arrival event i ($Z_{ri}^c = 1$). Constraint (13) defines the relation between the events at the station, i.e., an arrival event i and the successive departure event j .

Passing Through

$$l_{ij}Y_r^c \leq v_j - v_i + q_{ij}T \leq u_{ij}Y_r^c \quad \forall (i,j) \in A_{thru}^{gr}, \forall j \in F, \forall r \in R, \forall c \in C \quad (14)$$

$$Z_{ri}^c = 0 \quad \forall i \in F_{depthru} \cup F_{arrthru}, \forall r \in R, \forall c \in C \quad (15)$$

Constraint (14) states that the lower and the upper bound l_{ij} and u_{ij} in a passing through activity are active only if the alternative path r is chosen. In addition, constraint (15) defines that stopping at the passing through events is not possible (e.g. at bridges and junctions).

Headway

$$l_{ij}(Y_r^c - X_m) \leq v_j - v_i + q_{ij}T \leq u_{ij}(Y_r^c - X_m) + T(1 - Y_r^c + X_m) \quad \forall (i,j) \in A_{hw}^{gr}, \forall r \in R, \forall c \in C, \forall m, n \in M \quad (16)$$

Constraint (16) defines headways between alternative freight paths and passenger trains. It is valid only if an alternative path r is chosen ($Y_r^c = 1$) and the other train from the original timetable is not cancelled ($X_m = 0$). Otherwise, the lower bound l_{ij} and upper bound u_{ij} of an activity (i,j) between two events are relaxed.

Changing direction

When a changing direction occurs, a freight train needs additional time, e.g. at least 30 minutes. The constraint to ensure the train will stand still longer is the same as for dwell activity (10), only with different lower and upper bounds. The lower bound is set to 30 minutes and the upper bound is set to $T-1$. In addition, a freight train changing direction corresponds to a stop:

$$Z_{rj}^c = \delta_{rj}^c Y_r^c \quad \forall j \in F_{dep} \cap F_{\delta}, \forall r \in R, \forall c \in C \quad (17)$$

The following constraints characterize the type and domains of the variables.

$$v_j, q_{ij} \geq 0 \quad \forall i, j \in E \cup F \quad (18)$$

$$X_m \in \{0,1\} \quad \forall m \in M \quad (19)$$

$$Y_r^c \in \{0,1\} \quad \forall r \in R, \forall c \in C \quad (20)$$

$$Z_{rj}^c \in \{0,1\} \quad \forall j \in E \cup F, \forall r \in R, \forall c \in C \quad (21)$$

$$\alpha_j \in \{0,1\} \quad \forall j \in E \cup F \quad (22)$$

IV. COMPUTATIONAL EXPERIMENTS

The PF-TTAP model was demonstrated on a real-life case study in the Netherlands using the timetable 2018 of the

TABLE II
PARAMETERS USED FOR PF-TTAP

PARAMETER	VALUE
T [s]	3600
dp_{max}^+ [s]	180
df_{max}^+ [s]	($T-1$)
μ_{acc} [s]	30
μ_{dec} [s]	40
w_j^{delay}	2
w_m^{cancel}	10^6
w_c^{cancel}	10^6
w_{cr}^{CD}	5000
w_{rj}^{ncs}	1000
w_{cr}^r	1

Netherlands Railways with an open track possession in the western part of the country between Delft (Dt) and Schiedam Centrum (Sdm). This possession scenario is comparable to a real case of a week in 2018. The size of the network was reduced concentrating only on the affected part, approximately to half of its size, by removing the discarded events and activities. This resulted in a directed graph including 166 train lines, 5,093 events, 200 alternative events (summed over all alternative freight paths), 47,454 processes, and 161 timetable points.

The PF-TTAP model is implemented in MATLAB and solved using a standard optimization solver CPLEX 12.8.0. The computational experiments are conducted using an Intel core i5-7300U (2.60 GHz) processor and 8GB RAM. The list of parameters for the PF-TTAP are given in Table II.

A. Results for Case Study Dt-Sdm

In this assessment, the focus is on the impact of freight train paths. The possession on Dt-Sdm results in cancelling one freight train path, BVK10, in the original timetable. In the pre-processing step for freight trains, the user can choose the number of alternatives that should be generated by the k -shortest path algorithm. We selected $k = 2$ to be able to track model performance and verify the model behaviour. The k -shortest path algorithm used in this research assumes all timetable points are equal and thus all allow changing directions.

The first alternative path requires two changing direction activities, in Den Haag Centraal (Gvc) and Moordrecht aansluiting zuid (Mdaz). The second generated alternative is the same as the one in the *Corridorbook* [16], a guideline that the planners use to create the alternative rerouting path for BVK10 in the alternative hour pattern.

The result of the PF-TTAP model showed that except for the partial cancellations of passenger trains in the pre-processing step, there are no additional trains cancelled within the optimization. Some delays for passenger trains are needed to respect headway constraints. After a more detailed analysis, it was revealed that the original timetable was designed intrinsically with these headway conflicts which were then resolved in PF-TTAP.

The PF-TTAP model chose the second alternative freight path as the alternative rerouting path for BVK10 during the possession in Dt-Sdm. The computation time was two minutes and 18 seconds. Table III gives the results of the

chosen alternative path by the PF-TTAP model and compares it with the cancelled freight path and the alternative path from the planners. It presents cancellations, total delays, number of changing direction activities, number of non-commercial stops, adjusted departure and arrival times and total journey time. As stated, PF-TTAP selected the same route as the planners did. However, some differences in the paths occurred. First, our solution has no non-commercial stops, as opposed to 2 in the planner's version. Second, the model delayed the departure only slightly (32s), while the other solution has almost 30 min (1620 s) delay. Third, the journey time of the model's solution is more than 30 min shorter (8220-6264=1956s), and thus comparable with the original one. In can be concluded that PF-TTAP selected a better alternative freight path in terms of journey time and delay at the origin.

Figure 2 plots the time-distance diagram of the adjusted timetable and highlights the chosen alternative path. The time on the horizontal axis represents the period length of the timetable $T=3600$ seconds, while the vertical axis shows the subsequent timetable points for a given corridor. The distance between two timetable points on the vertical axis is

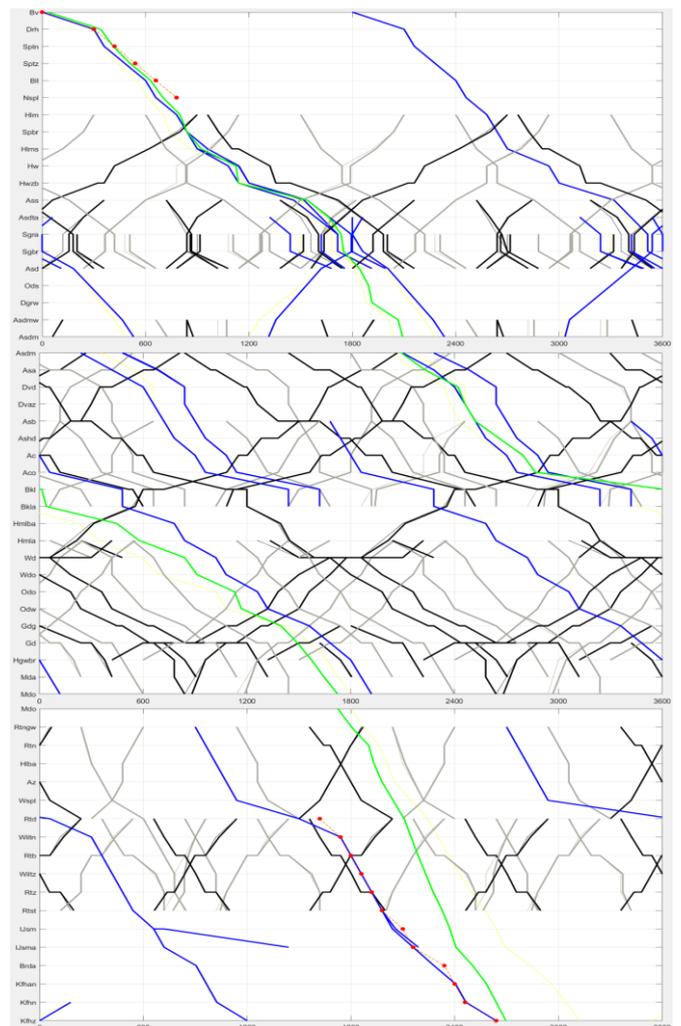


Fig. 2. The chosen alternative path (green) of BVK10 from Bv to Kfhz due to the possession in Dt-Sdm.

equidistant and does not represent the real-life distances. Different train types can be distinguished: intercity (grey line), local (black), the freight paths in the original timetable (blue), the freight train that was cancelled and needed to be rerouted (dashed-dotted red line), and the computed alternative path by PF-TTAP (green line). Note that the constraints on running activities assured that the speed is between 55 km/h to 90 km/h (the planned freight train speed).

To conclude, the chosen alternative path happens to be the same as the one picked by the planners, but better aligned. This result demonstrates two points: 1. the k -shortest path algorithm generates alternatives that are relevant to practice, and 2. FR-TTAP inserted the preferable alternative path even better than the planners have done.

V. CONCLUSIONS

In this paper, we introduced the PF-TTAP model to generate alternative timetables for passenger and freight trains during planned possessions. The PF-TTAP model could generate an optimal solution that causes only limited impact to the original timetable, such as limited cancellation of trains and insignificant delay for passenger trains in the original timetable. Furthermore, the activities specific to freight trains, like changing direction and non-commercial stops, are minimized by the PF-TTAP model. Additional experiments showed that the solutions often provided equal departure and arrival times as in the original cancelled freight path. This demonstrates that the PF-TTAP model could help and give insights to the railway planners to design better alternative paths for freight trains.

Further development of the PF-TTAP model may focus on reducing computational time. One option is to reduce the network size by incorporating several aggregation measures as introduced in [6]. The PF-TTAP model may also consider adding commercial stops, such as for changing the driver or (un)loading goods in intermediate stations. A microscopic model would be a useful counterpart to analyze solutions in more detail and ensure timetable feasibility [19]. Together, these models will achieve a more efficient timetable for planned possessions that minimizes the disadvantages of passenger and freight train operator companies.

TABLE III
COMPARISON BETWEEN THE ORIGINAL AND ADJUSTED TIMETABLE (AUP)

	Original	AUP Railway Planners	AUP Integrated PF-TTAP Model
Cancellation	0	0	0
Delays (seconds)	0	n/a	403
Changing direction	0	0	0
Non-commercial stop	1	2	0
Departure – Bv (at seconds to)	0	1620	32
Arrival – Kfhz (at seconds to)	2640	2640	2696
Journey time (seconds)	6240	8220	6264

ACKNOWLEDGMENT

This research was conducted as a joint project between Delft University of Technology and ProRail. We thank all people involved for their contribution, in particular, Niels van der Glas, Johannes Lok and Dennis Wittenberg for helping with data collection, sharing knowledge, and examining the result. Also, we thank Jasper Engel from NS for his support and practical feedback.

REFERENCES

- [1] TrafficQuest, *Traffic in the Netherlands 2016*. Den Haag, The Netherlands: Essencia Communicatie, 2016.
- [2] A. Higgins, "Scheduling of Railway Track Maintenance Activities and Crews," *J. Operational Res. Society*, 49, pp. 1026-1033, 1998.
- [3] G. Budai, D. Huisman, and R. Dekker, "Scheduling Preventive Railway Maintenance Activities," in *Systems, Man and Cybernetics, 2004 IEEE International Conference, vol. 5*, 2004, pp. 4171-4176.
- [4] T. Liden and M. Joborn, "Maintenance Windows for Railway Infrastructure Maintenance: An Assessment and Dimensioning Model for the Study of Traffic Impact and Maintenance Cost," *Conference on Advanced Systems in Public Transport (CASPT2015)*, Rotterdam, The Netherlands, 2015.
- [5] S. van Aken, N. Besinovic, and R.M.P. Goverde, "Designing Alternative Railway Timetables under Infrastructure Maintenance Possessions," *Transp. Res. Part B Methodol.*, 98, pp. 224-238, 2017.
- [6] S. van Aken, N. Besinovic, and R.M.P. Goverde, "Solving Large-Scale Train Timetable Adjustment Problems under Infrastructure Maintenance Possessions," *Journal of Rail Transport Planning & Management*, 7(3), pp. 141-156, 2017.
- [7] P. Looij, "Adjusting Train Routing in case of Planned Infrastructure Maintenance," MSc thesis, Delft University of Technology, Delft, The Netherlands, 2017.
- [8] D. Arenas, P. Pellegrini, S. Hanafi, and J. Rodriguez, "Timetable Optimization during Railway Infrastructure Maintenance," *7th International Conference on Railway Operations Modelling and Analysis - Rail Lille*, Lille, France, 2017.
- [9] A. Albrecht, D. Panton, and D. Lee, "Rescheduling Rail Networks with Maintenance Disruptions using Problem Space Search," *Computers & Operations Research*, 40(3), pp. 703-712, 2013.
- [10] M. Forsgren, M. Aronsson, and S. Gestrelus, "Maintaining Tracks and Traffic Flow at the Same Time," *Journal of Rail Transport Planning & Management*, 3(3), pp. 111-123, 2013.
- [11] R. Gedik, H. Medal, C. Rainwater, E. A. Pohl, and S. J. Mason, (2014). "Vulnerability Assessment and Re-routing of Freight Trains under Disruptions: A Coal Supply Chain Network Application," *Transportation Research Part E*, 71, pp. 45-57, 2014.
- [12] M. Bababeik, M. M. Nasiri, N. Khademi, and A. Chen, "Vulnerability Evaluation of Freight Railway Networks using a Heuristic Routing and Scheduling Optimization Model," *Transportation*, 46, pp. 1143-1170, 2017.
- [13] N. Bešinović, "Resilience in railway transport systems: a literature review and research agenda," *Transport Reviews*, 2020, DOI: 10.1080/01441647.2020.1728419
- [14] P. Serafini and W. Ukovich, "A Mathematical Model for Periodic Scheduling Problems," *SIAM J. Discrete Math.*, 2(4), pp. 550-581, 1989.
- [15] *Network Statement 2018*, ProRail, Utrecht, The Netherlands, 2016.
- [16] *Corridorboek*, ProRail, Utrecht, The Netherlands, 2016.
- [17] J. Y. Yen, "Finding the K shortest loopless paths in a network," *Management Science*, 17, pp. 712-716, 1971.
- [18] B. Widarno, "Integrated Passenger and Freight Train Timetable Adjustment Problem (PF-TTAP) during Infrastructure Work Possessions", MSc thesis, Delft University of Technology, Delft, The Netherlands, 2018.
- [19] Goverde, R. M. P., Besinovic, N., Binder, A., Cacchiani, V., Quaglietta, E., Roberti, R., & Toth, P. (2016). A three-level framework for performance-based railway timetabling. *Transportation Research Part C: Emerging Technologies*, 67(June), 62-83.