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Publication date
2018

Document Version
Final published version

Published in
hEART 2018: 7th Symposium of the European Association for Research in Transportation, 5-7 September, Athens, Greece

Citation (APA)
Cats, O., Yap, M., van Oort, N., & Hoogendoorn, S. (2018). Controlling the propagation of passenger disruption impacts in multi-level public transport networks. In *hEART 2018: 7th Symposium of the European Association for Research in Transportation, 5-7 September, Athens, Greece*

CONTROLLING THE PROPAGATION OF PASSENGER DISRUPTION IMPACTS IN MULTI-LEVEL PUBLIC TRANSPORT NETWORKS

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Keywords: disruptions; holding; multi-level networks; public transport; simulation

Word count (excluding tables, figures and references): 1,312

1. STUDY OBJECTIVES

A passenger journey is often composed of trips using different public transport (PT) network levels: passengers for example use the (inter)regional train network level, and transfer to the urban tram or bus network level. A large, non-recurrent disruption on the train network level can impose delayed, rerouted or cancelled train services, which in turn can result in passengers arriving later than scheduled at the transfer location to the urban PT network, or passengers adapting their route choice and arriving at a different transfer location. Consequently, this can result in missed connections, longer travel times and higher crowding levels. The impact of a disruption on the train network level can thus propagate over the multi-level public transport network, via the transfer hub to the urban PT network. Hence, an optimal holding control decision for urban services at the transfer location should account for the impact of a disruption on another PT network level. Previous studies have focused on quantifying the impact of unreliability and disruptions on passengers (e.g. Cats et al. 2016; Cats and Jenelius, 2014; Ma et al. 2014; Van Oort, 2016; Yap et al. 2018) and real-time control strategies (e.g. Van Oort et al., 2010; Cats et al. 2011; Nesheli and Ceder, 2015). However, none of these studies accounted for the impact of disruptions occurring on another PT network level in the control decision for urban PT services. Due to the hierarchical relation between the different PT network levels, this means a control decision is triggered by services which are not subject to this same control decision.

We first quantify the passenger impacts of disruption propagation resulting from an exogenous train network disruption to the urban PT network level. Thereafter, we develop a rule-based controller for holding urban PT services while taking into account predicted passenger delays and rerouting from the train network level.

2. METHODOLOGY

Table 1 introduces the indices and sets, variables and parameters used in the control problem formulation.

Table 1. List of indices and sets, variables and parameters

Indices and sets:	
s, S	stop index, set
l, L	line index, set
j, J	passenger path index, set
S_l	set of stops on line l, $S_l \subseteq S$
S_t	set of transfer stops, $S_t \subseteq S$
$l = \{s_{l,1}, s_{l,2}, \dots, s_{l,\lvert l \rvert}\}$	line l is defined as ordered sequence of stops
$j = \{s_{j,1}, s_{j,2}, \dots, s_{j,\lvert j \rvert}\}$	passenger path j is defined as ordered sequence of stops
n, N	passenger index, set
r, R	run index, set
R_l	set of runs on line l, $R_l \subseteq R$
r^+	run index of the subsequent run after the vehicle assigned to run r
r^-	run index of the previous run before the vehicle assigned to run r
r_{is_t}	run inbound to transfer stop s_t
r_{os_t}	run outbound from transfer stop s_t
d	disruption scenario
Variables:	
$\tilde{t}^a_{rs}$	scheduled arrival time of run r at stop s
$\tilde{t}^d_{rs}$	scheduled departure time of run r from stop s
t^a_{rs}	arrival time of run r at stop s
t^d_{rs}	departure time of run r from stop s
t^h_{rs}	holding time of run r at stop s
$t^{ivt}_{rs_l}$	passenger in-vehicle time of run r from stop s_l to s_{l+1}

$t_{rs_l}^{ivt,p}$	perceived passenger in-vehicle time of run r from stop s_l to s_{l+1}
t_s^{wtt}	passenger waiting time at stop s
t_s^{wkt}	passenger transfer walking time at stop s
h_r	(backwards) headway between run r and run $r+1$
$\tilde{h}_r$	scheduled (backwards) headway between run r and run $r+1$
q_{rs}	number of passengers on-board run r on the segment between stop s and the subsequent stop
q_{rs}^{in}	number of passengers wishing to board run r at stop s (no transfer)
q_{rs}^{out}	number of passengers wishing to alight run r at stop s (no transfer)
$q_{r_i r_o s_t}^{trans}$	number of passengers transferring at stop s_t from run r_i to run r_o
$f_{r_o \mid q_{r_i s_t}^{out}}$	fraction of passengers alighting run r_i at stop s_t wishing to transfer to r_o
$f_{r_o \mid q_{r_o r_i s_t}^{out}}$	fraction of passengers wishing to transfer at stop s_t from run r_i to r_o who makes the connection
w	total monetized passenger welfare

Parameters:	
τ_{rs}	minimum turnaround time for run r at stop s
λ_s	passenger arrival rate at stop s
β_1	weight of perceived passenger walking time
β_2	weight of perceived passenger waiting time
β_3	weight of perceived passenger in-vehicle time
β_4	weight of perceived time for each transfer
β_5	weight of perceived passenger in-vehicle time as function of load factor
β_6	weight of perceived passenger in-vehicle time as function of standing density
β_7	weight of perceived passenger waiting time in case of denied boarding
γ_s	crowding seat capacity in-vehicle time multiplier
γ_d	crowding standing density in-vehicle time multiplier
φ_r^s	seat capacity of run r
φ_r^c	crush capacity of run r
θ_r^c	surface available for standing on-board run r

2.1 Modelling framework

We develop a multi-level modelling framework to quantify the propagation of passenger disruption impacts between different network levels of the multi-level PT network (Figure 1). We assume a hierarchy, where control decisions are only applied in case disruptions occur on the same network level, or at a higher hierarchical network level. Urban control decisions can thus be taken following disruptions on the urban network level, or on the (inter)regional train network level. The system is illustrated in Figure 1 where an exogenous train network disruption causes rescheduling, rerouting and cancellation of train services, which can affect the arrival time, arrival platform and passenger flow transferring from train to urban PT network at each hub connecting these network levels. Incorporating transfer walking times at hubs between different train arrival platforms and urban PT departure platforms, results in different passenger transfer flows arriving at different locations and lines of the urban PT network. The urban controller incorporates the prediction of adjusted passenger transfer flows in the decision, aiming at minimizing passenger travel costs on the urban network.

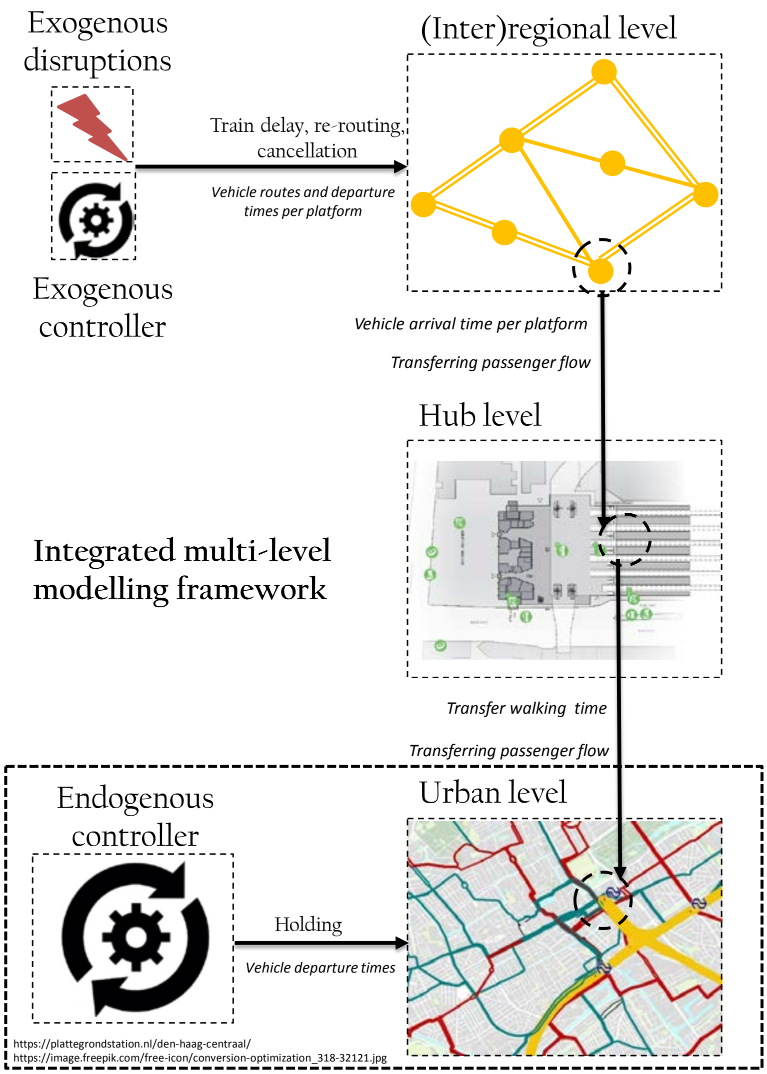

Figure 1. Integrated multi-level modelling framework

2.2 Scenario design

We quantify the total passenger welfare w_d for three different scenarios d, expressed as the generalized travel time over all passengers (Table 2). Equation 1 quantifies the passenger disruption propagation to the urban PT network in case no control decision is applied, whereas equation 2 quantifies the impact of the holding control strategy. Equation 3 describes the calculation of w_d.

Table 2. Overview of distinguished scenarios

Scenarios	*Control intervention*	
Disruption scenario	d_1 Undisrupted scenario No control intervention	
	d_2 Non-recurrent disruption scenario No control intervention	d_3 Non-recurrent disruption scenario Holding control intervention

$$\Delta w = w_{d_2} - w_{d_1} \tag{1}$$

$$\Delta w = w_{d_3} - w_{d_2} \tag{2}$$

$$w_d = \sum_{n \in N} \left(\left(\beta_1 * \sum_{s \in j} t_{s,n}^{wkt} \right) + \left(\beta_2 * \sum_{s \in j} t_{s,n}^{wtt} \right) + \left(\beta_3 * \sum_{s \in j \setminus s_{j,|j|}} t_{rs_l,n}^{ivt,p} \right) + \left(\beta_4 * \left| s_{t,n} \right| \right) \right) \tag{3}$$

2.3 Control problem description

The applied control strategy entails the decision whether to hold urban PT runs at multi-level transfer stops s_t for a certain holding time $t_{rs_t}^h$ in case a disruption occurs on the train network. The predicted welfare impacts on four different passenger segments are incorporated in this holding decision:

(i) Upstream boarding and downstream alighting (through) passengers;
(ii) Downstream boarding passengers;
(iii) Reverse downstream boarding passengers;
(iv) Transferring passengers at holding location.

A passenger-oriented decision rule (equation 5) is applied for the controller, where predicted costs of the control decision are deducted from the predicted control benefits (equation 4). Figure 2 shows the information flows for the short-term prediction algorithm for the urban network level.

$$z(t_{rs}^h) = w_d^{(i)}(t_{rs}^h) + w_d^{(ii)}(t_{rs}^h) + w_d^{(iii)}(t_{rs}^h) + w_d^{(iv)}(t_{rs}^h) - \Delta t_r^{ivt,p}(t_{rs}^h) \tag{4}$$

$$t_{rs}^h = \begin{cases} 0 & if\ z \leq 0 \\ argmax(z) & if\ z > 0 \end{cases} \tag{5}$$

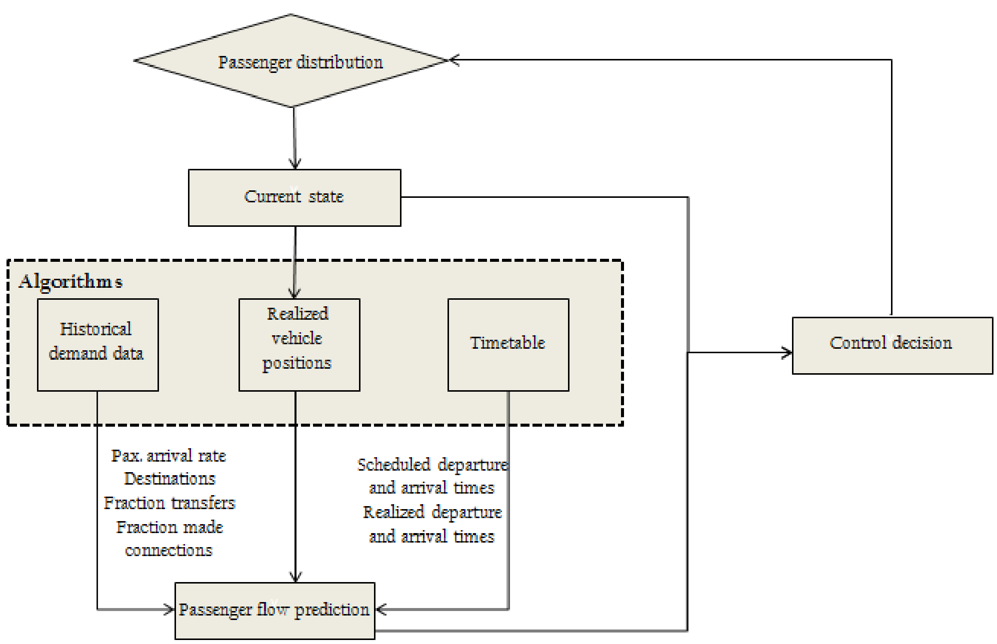

Figure 2. Information flow short-term passenger prediction algorithm

Eq. 6-9 formulate the total passenger effect of holding run r for t_{rs}^h on the four above-mentioned passenger segments, respectively. Eq. 6 is the direct extension of in-vehicle time at the holding stop of passengers who board upstream the holding location and alight downstream the holding location. The direct extension of waiting time of passengers waiting at a stop downstream the holding location is quantified using Eq. 7. Eq. 8 equals the longer waiting time for boarding passengers at all stops of the line in the reverse direction, in case the time between the realized arrival time at the final stop of the line, $t^a_{r,s_{l,|l|}}$, and the scheduled departure time from the terminal for the next run in the reverse direction $\tilde{t}^d_{r,s_{l,1}}$ is smaller than the required minimum turnaround time $\tau_{r,s_{l,|l|}}$. Eq. 9 is the reduced waiting time for passengers transferring at s_t due to the holding strategy, compared to having to wait for the next run. Eq. 10 calculates this passenger transfer flow as fraction of alighting passengers from the train network aiming for a transfer to the urban network, multiplied by the fraction making this connection given the required transfer walking time.

$$w_d^{(i)} = -((\sum_{s=1}^{t-1} q_{r,s}^{in} - \sum_{s=1}^{t} q_{r,s}^{out}) \cdot \beta_3 * t_{rs}^h) \tag{6}$$

$$w_d^{(ii)} = -(\sum_{s=t}^{|l|-1} q_{rs}^{in} \cdot \beta_2 * t_{rs}^h) \tag{7}$$

$$w_d^{(iii)} = \min\left\{\sum_{s=1}^{|l|-1} q_{rs}^{in} \cdot \left(\tau_{r,s_{l,|l|}} - t_{rs}^h\right), 0\right\} \tag{8}$$

$$w_d^{(iv)} = \sum_{r_i \in R_i} q_{r_i r_o s_t}^{trans} \cdot \left(t_{r^+s}^a - (t_{rs}^a + t_{rs}^h)\right) \tag{9}$$

$$q_{r_i r_o s_t}^{trans} = q_{r_i s}^{out} * f_{r_o|q_{r_i s_t}^{out}} * f_{r_o|q_{r_o r_i s_t}^{out}} \tag{10}$$

The holding strategy also affects the different passenger segments in terms of perceived in-vehicle time due to changed crowding levels. Due to the non-linear nature of perceived in-vehicle time as function of crowding, we quantify crowding effects over all passenger segments. Holding run r increases the headway between r^- and r with t_{rs}^h and increases the number of boarding passengers downstream. Eq. 11 calculates the perceived in-vehicle time for run r for each link downstream the potential holding location in case of holding (first term), minus the perceived in-vehicle time in case no holding would be applied (second term). Holding however also decreases the headway between run r and subsequent run r^+ with t_{rs}^h. This means crowding is expected to decrease in run r^+ due to the lower number of boarding passengers at each stop downstream the potential holding location. For a complete evaluation, the perceived in-vehicle time is calculated for run r^+ as well in case of holding (third term), minus the perceived in-vehicle time of run r^+ in case no holding would be applied (fourth term). To quantify the perceived in-vehicle time, the predicted occupancy q_{rs_t} is multiplied by the seat capacity multiplier γ_s (occupancy divided by the seat capacity φ_r^s: Eq. 12) and standing density crowding multiplier γ_d (standing passengers divided by the vehicle surface available for standing θ_r^c: Eq. 13).

$$\begin{aligned}
\Delta t_r^{ivt,p} = &\sum_{s=t}^{|l|-1}\left((q_{rs_{t-1}} - q_{rs}^{out} + ((t_{rs}^a - t_{r^-s}^a + t_{rs}^h) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o s}^{trans}) * (t_{rs_l}^{ivt} * (\gamma_s + \gamma_d))\right) \\
&- \sum_{s=t}^{|l|-1}\left((q_{rs_{t-1}} - q_{rs}^{out} + ((t_{rs}^a - t_{r^-s}^a) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o s}^{trans}) * (t_{rs_l}^{ivt} * (\gamma_s + \gamma_d))\right) \\
&+ \sum_{s=t}^{|l|-1}\left((q_{r^+s_{t-1}} - q_{r^+s}^{out} + ((t_{r^+s}^a - t_{rs}^a - t_{rs}^h) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o^+ s}^{trans}) * (t_{r^+s_l}^{ivt} * (\gamma_s + \gamma_d))\right) \\
&- \sum_{s=t}^{|l|-1}\left((q_{r^+s_{t-1}} - q_{r^+s}^{out} + ((t_{r^+s}^a - t_{rs}^a) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o^+ s}^{trans}) * (t_{r^+s_l}^{ivt} * (\gamma_s + \gamma_d))\right)
\end{aligned} \tag{11}$$

$$\gamma_s = \min\left(\frac{q_{rs_t}}{\varphi_r^s}, 1\right) * \beta_5 \quad (12)$$

$$\gamma_d = \max\left(\frac{q_{rs_t} - \varphi_r^s}{\theta_r^c}, 0\right) * \beta_6 \quad (13)$$

3. APPLICATION AND OUTLOOK

We apply our methodology to the multi-level PT network of The Hague, the Netherlands. We consider the full urban PT network of The Hague of 12 tram lines and 8 bus lines. Besides, all train services to/from The Hague from the directions Leiden, Gouda and Rotterdam are considered (Figure 3). We use BusMezzo, an agent-based dynamic simulation model for PT operations and passenger assignment, as evaluation tool to simulate a disruption on the train network between stations The Hague Central and Laan van NOI (Cats and Jenelius, 2014).

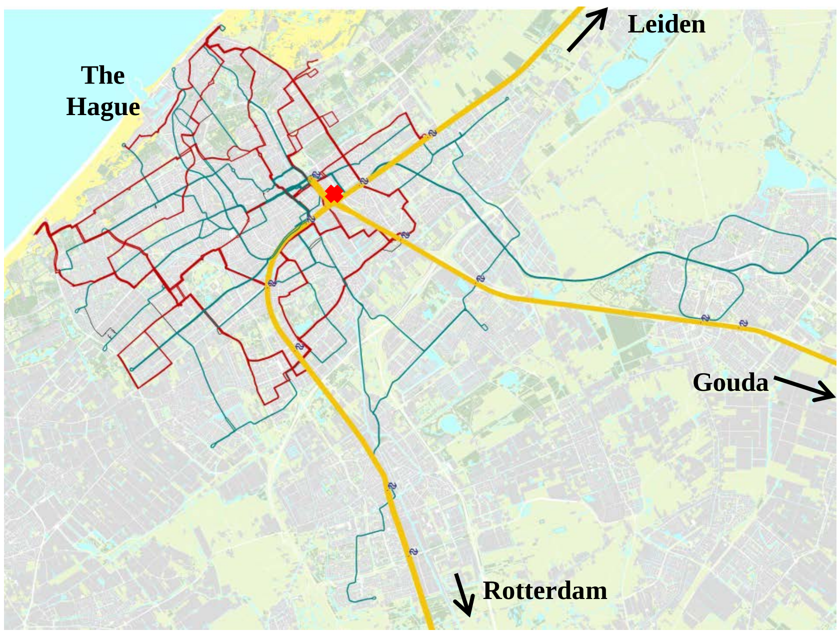

Figure 3. Case study public transport network (yellow: train services / green: tram services / red: bus services). The red cross indicates the location of the simulated disruption.

The scenario analysis is performed as part of an on-going work. For each scenario (Table 2) the total passenger welfare is calculated to show the propagation of disruption impacts from the train network to the urban network level, and to evaluate the impact of the holding control intervention for the simulated train network disruption. The analysis will include comparison of assignment results and the performance of the proposed controller. Conclusions, study implications and recommendations for future research will be shared in the conference presentation.

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