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Smart Cities  
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# D3.1: A toolbox of real-time strategies for smart transfers

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## Summary

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Organizing, financing and operating public transport service networks can be quite a challenge. The liberalization of the public transport sector within EU has introduced some additional challenges since the public transport systems nowadays more often consist of services operated by multiple organizations. When passengers move between public transport service networks that are operated by different organizations, the need for effective coordination become evident. The importance of effective coordination and the associated challenge to achieve this – independent of organizational structure - is the point of origin for the TRANS-FORM project. The project focuses on the development of an integrated passenger-focused management approach that takes advantage of multiple data sources and state-of-the-art scheduling support.

This document reports on the work performed in task 3.1 entitled “Real-time traffic management optimization” and task 3.2 entitled “Smart real-time strategies” of the TRANS-FORM project. These tasks were performed as part of work package 3 “Methods for Planning and Operating Robust Services”.

The work in the mentioned tasks focus on how to model an integrated passenger-focused management approach including developing strategies that enable improved coordination and smooth passenger transfers. This document contains a specification of the configuration of each modelled level (hub, urban and regional) and the proposed types of management strategies as well as the required information flow. A specification of the proposed integration of those three levels and their interaction is also presented.

## 1. Introduction

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In the previous work packages 1 and 2, the emphasis has been on understanding and modelling the passenger flow dynamics, including transfer activities, and defining relevant metrics to capture service quality from a passenger perspective primarily. In this third work package, WP3, more focus is on how to model an integrated passenger-focused management approach including developing management strategies that enable improved coordination and smooth passenger transfers.

Section 2 and 3 contains a specification of the configuration of each modelled level (hub, urban and regional) and the proposed types of management strategies. In section 4, the required information flow for each level is presented, as well as a conceptual model which integrates the three mentioned levels. In section 5, some concluding remarks with reference to the continued work in the project are provided.

## 2. Management optimization: Simulation and control

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This section introduces the decision-making processes for the different public transport system stakeholders (i.e. network managers, transport operators and travelers) for each modelling level.

The main part of this section shall outline the set-up of the controller and the simulator for each modelling level. For the urban and hub levels, there are separate controllers and simulators, which are described in section 2.1 and 2.2. In the regional level, the controller and simulator are integrated in an optimization model (mathematical program) which is presented in section 2.3 and 3.3.

## 2.1. Hub level

In order to improve the transfer dynamics inside transportation hubs, the framework which will be used is composed of two main parts: a pedestrian simulator and a controller. Figure 2.1.1: *Controller-simulator illustration for the hub model*. 2.1.1 below is an illustration of the setup. The pedestrian simulator takes care of both the pedestrian movement model and the activity scheduling model. The interaction between these components, which can be seen as a demand-supply interaction, is also handled here. The controller is the "brain" which decides how the management strategies should be applied. The required information flow is presented in more detail in later sections.

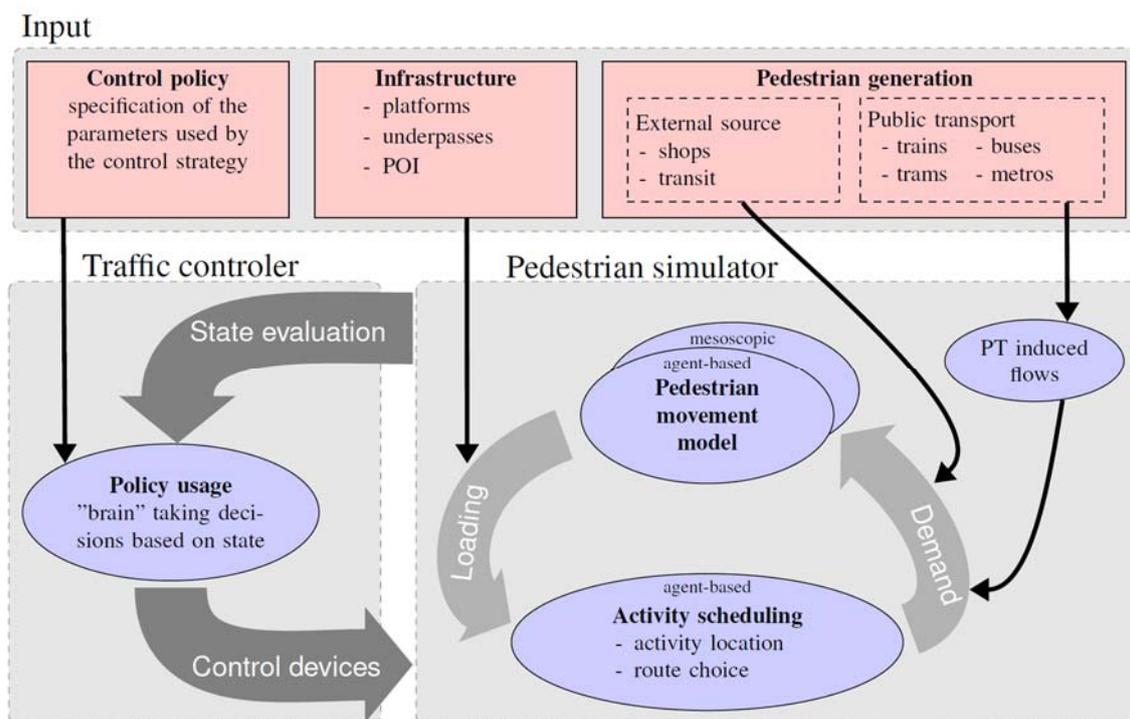


Figure 2.1.1: Controller-simulator illustration for the hub model.

The novelty of this approach is the development of management strategies as a controller, in a similar way to vehicular traffic, where controllers are developed for traffic flow management. Actions for controlling pedestrian movements will impact the pedestrians in different ways. By controlling which areas can be reached by pedestrians, with gates for example, pedestrians must update on short notice their route as their planned route might not be available for some time. Such updates will impact the pedestrian movement model and by propagation will also change the activity scheduling decisions of passengers. Strategic placement of ticket machines, for example, will make passengers plan ahead their routes and the order in which the activities are performed can be influenced. In this case, the activity scheduling is updated, which will in turn affect the pedestrian movement model.

In order to integrate the management strategies into the pedestrian simulator, a "feedback control" system must be designed. The objective is to conceive a simulator which can dynamically react to the level-of-service inside the hub. The concept of level-of-service can be made operational by defining metrics for quantifying the state of the system. In pedestrian modelling, some possibilities of the metrics are density or the difference between the desired walking speed and the effective walking speed.

The optimal control policy is identified using a simulation-based optimization approach. The controller runs the simulation with different control policies and evaluates the results. A heuristic

algorithm is used to investigate the solution space, i.e. the set of possible control policies. Different performance indicators may lead to the identification of different optimal policies. For example the minimization of congestion may be in contrast with the maximization of the number of passengers able to transfer. The trade-off curve among different performance indicators is explored, and the best control policy is chosen by the operator. Computation time is a limiting factor. Hence, in order to reduce computational time, a macroscopic version of the pedestrian simulator can be used to investigate the solution space.

## 2.2. Urban Level

The modelling approach adopted for analysing real-time strategies at the metropolitan public transport (urban) level consists of using a simulator and a controller. In the case of tactical decision-making, i.e. location of time point control stops (Cats et al. 2014), an optimization procedure calls the simulator with different specification of the decision variables and evolves from one solution to the other based on the output performance metrics generated by the simulator. In contrast, analysing real-time control strategies involves running the simulator as a testbed environment which then calls the controller at pre-defined control decision events. The set-up of the modelling environment is illustrated in Figure 2.2.1.

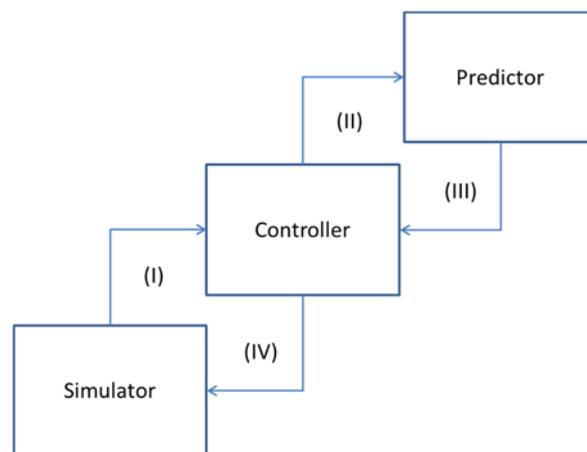


Figure 2.2.1: Set-up of the real-time strategies modelling environment in the urban level.

The modelling environment consists of the following components:

1. Simulator: mimicking real-world transit operations and passenger flows
2. Controller: determining the execution of real-time strategies
3. Predictor: generating predictions concerning future system states

The controller can be triggered by the simulator at various situations – when entering a public transport stop, determining riding speed or approaching a traffic signal - depending on the control strategies undertaken by the operator. Control decisions can be rule-based heuristics (e.g. equalize backward and forward headways) or full-fledged system optimization (e.g. minimizing expected delays). Since control decisions are taken with the aim to positively influence downstream conditions when compared to do-nothing (i.e. no control) scenario, they involve making predictions concerning future system states.

The modelling environment includes thus the following information flows (see Figure 2.2.1):

- I. Simulator → Controller: an event in the simulator triggers a control request along with information concerning system state variables, i.e. vehicle positions and passenger counts, the availability of which depends on the assumed availability of real-time information

- II. Controller → Predictor: the controller triggers a request for generating predictions concerning selected system variables such as downstream vehicle trajectories or passenger flows along with information concerning current state variables and control decision variables
- III. Predictor → Controller: the predictor provides the controller with expected future system variables for a given prediction horizon generated based on either analytical relations or running independent simulation instances
- IV. Controller → Simulator: the controller returns to the simulator the control decision which determines how the simulated operations of the controlled object will proceed

The focus in this project is on improving passenger transfer experience and passenger overall travel reliability and robustness. We therefore specifically investigate real-time control strategies that are designed to improve transfer synchronization in the event of service disturbances and disruptions. The holding of an urban vehicle will be determined using a multi-layer perspective by taking into consideration train rescheduling and transfer hub uncertainty in the formulation of the control decisions. The metropolitan public transport operations and passenger simulation model, BusMezzo, will be used. The controller will be triggered when an urban transit vehicle (i.e. bus, tram or light rail) enters a transfer hub. The holding control decision will depend on predictions concerning future vehicle and passenger flows generated by the predictor.

In the context of TRANS-FORM, vehicle holding control strategies will be formulated, implemented and tested. The formulation of the controller is presented in this deliverable (section 3.2). Information on the modelling of passenger flows in the simulator is available in D2.2 and predictions of passenger flows are developed in D3.2. Details on the implementation of the modelling environment and its interface with the other levels are given in D3.3, and model application to the case study of The Hague in the Netherlands is described in D4.1.

### 2.3. Regional level

The simulation of train traffic re-scheduling and public transport service coordination on a regional level and the impact assessment of alternative real-time decision-making strategies, uses an optimization-based delay management approach.

As described in D2.2, and illustrated by Figure 2.3.1, this delay management approach relies on:

- A model of the railway infrastructure, including network capacity restrictions and associated train traffic interaction constraints.
- A model of the public transport service network with associated timetables and train/bus service properties.
- A passenger transfer model, where passengers are assigned a specific route based on a pre-defined set of possible routes that only becomes available if the connections are successful.

Re-scheduling and delay management decisions taken for the transport services are related to:

- Re-timing of the trains and buses (i.e. adjusting the departure and arrival times of the PT services).
- Re-ordering of trains (i.e. changing the meet-pass plan in the railway traffic network).
- Local re-routing of trains (i.e. allowing changes of assigned platforms and tracks).

Which decisions that are taken, depend on (1) the management policies that are applied (e.g. when to hold services, when certain connections are jeopardized) and (2) the delay management objective that is selected. The objective used can be to e.g. minimize the sum of the train delays, minimize the total passenger delays, or minimizing a weighted combination of these two objectives.

The *passenger assignment and transfer model* serves to allocate passengers (a set of passenger groups, each with a known desired trip between an origin and a destination within a certain time period) to a sequence of transport service legs (including transfers) based on the re-scheduled timetables. The

result of the passenger assignment model is a specification of which train and bus services are used by each of the modelled passengers, i.e. their selected routes. The assignment and transfer model rely on good estimates of transfer times, specifying the minimum required transfer time from one platform to another in a given station. The minimum required transfer time from platform A to platform B, may be different from the required time to transfer from platform B to platform A. The models are described in more detail in section 3.3.

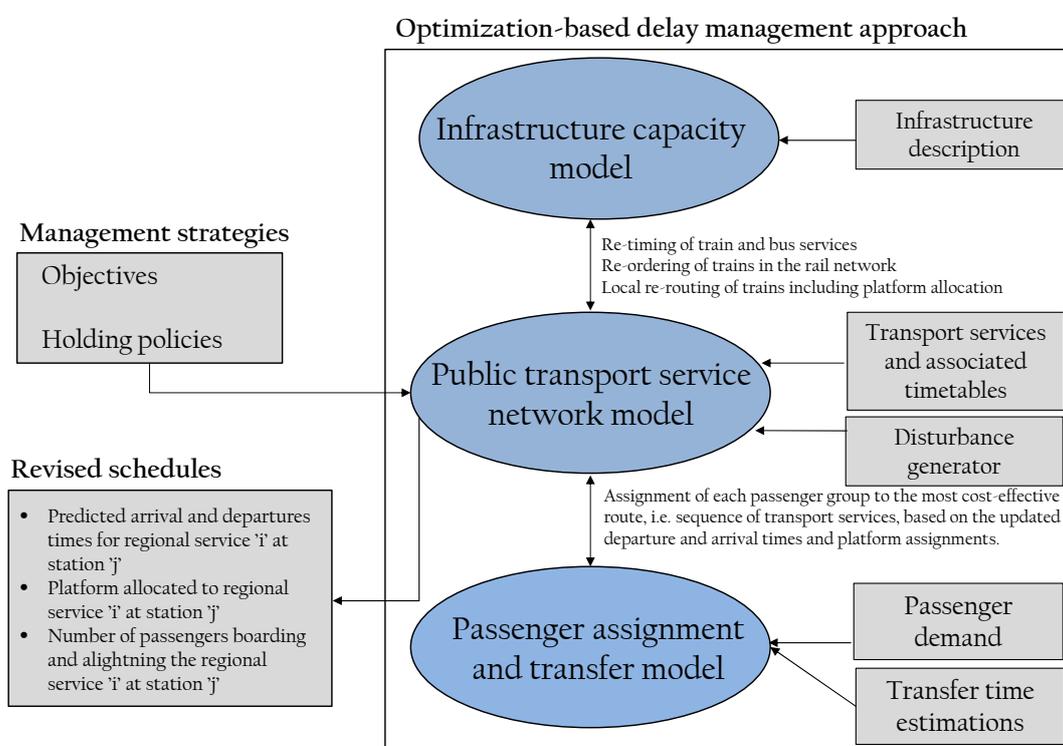


Figure 2.3.1. The optimization-based framework used to simulate and experimentally analyze the impact of selected management strategies for control and re-scheduling of regional transport services.

## 3. Control specification

For the modelling framework defined in Section 2 above, the mathematical formulations are outlined below.

### 3.1. Hub level

When discussing management strategies, a distinction must be made between three aspects. The first aspect concerns the design decisions, including what type of control can be taken, and is called the management/control strategy, while the second aspect refers to the actual operation of the given action and is called the management/control policy. The third is the actual devices used to apply the control policy and is called the management/control devices. As an example, let's consider gates controlling the access to a specific area. In this case, the control strategy is the number of gates and their location, while the control policy is the operational aspects: for how long should the gates be open, or what event triggers the opening or closing of the gates. The control policy represents the actual parameters over which the operator has control,

At this stage, the management strategy which is considered is the usage of gates. The objective is to control the pedestrian density inside critical areas. Critical areas can be entrances/exits, the junction between multiple corridors or the areas around service points. The objective is to limit the density at

an acceptable level. Naturally, the notion of "acceptable" depends on the context. To achieve this goal, gates can be located at strategic locations and control the inflow of pedestrian into the critical zones.

An adaptation of perimeter control for vehicular traffic is considered. The objective of perimeter control is to prevent the density of vehicles inside a delimited area (usually the city centre) to enter into the congested part of the fundamental diagram. The methodology for pedestrians is summarized in the following paragraphs. Assuming that congestion must be avoided in a specific area and the critical density is  $\hat{\rho}$ , then the pedestrian flow "allowed" into the area can be controlled using relation:

$$q(k) = q(k-1) + K_p[\rho(k) - \rho(k-1)] + K_I[\hat{\rho} - \rho(k)]$$

where  $q(k)$  is flow during time interval  $k$ , and  $\rho(k)$  is the density inside the delimited area during time interval  $k$ ,  $\hat{\rho}$  is the target density inside the area, and  $K_p$  and  $K_I$  are the parameters which need to be estimated. This function to control the inflow of pedestrians into the delimited area is commonly known as a PI controller. The derivation of this equation is deliberately left out as it is very technical. The objective of this controller is to prevent the density for going beyond the point of maximum flow (according to a fundamental diagram of pedestrian traffic). Hence the controller will only allow pedestrians to enter the zone if the density is below such target density  $\hat{\rho}$ . This is achieved by regularly evaluating, the density in the area, which is then used to compute the inflow to allow into the area.

The calibration of both parameters  $K_p$  and  $K_I$  requires empirical data. Based on the empirical observations of flow and density in the area under control, a least-squares approach is used to estimate the values of the parameters.

The controller has been discretized in order to make it usable in a simulation environment or even a real case study. If we image gates controlling the inflow of pedestrians into an area, these gates cannot open and close in a continuous manner. To make this strategy operational, the gates must remain in their specific state for some time otherwise pedestrians could be injured.

Alternative control strategies will also be considered. The two strategies which will be explored are moving walkways and the location of attractors. Moving walkways can be effective for managing pedestrian flows as both the direction and the speed of them can be controlled. The location of attractors can influence the activity sequence of pedestrians by changing the order and location of the performed activities.

## 3.2. Urban Level

### 3.2.1 Notation

In this section, the indices and sets, variables and parameters for the control algorithm are introduced.

#### Indices and sets:

$s, S$	stop index, set
$l, L$	line index, set
$S_l$	set of stops on line $l$ , $S_l \subseteq S$
$S_t$	set of transfer stops, $S_t \subseteq S$
$l = \{s_{l,1}, s_{l,2}, \dots, s_{l, l }\}$	line $l$ is defined as ordered sequence of stops
$r, R$	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 $s_t$

**Variables:**

$\tilde{t}_{rs}^a$	scheduled arrival time of run $r$ at stop $s$
$\tilde{t}_{rs}^d$	scheduled departure time of run $r$ from stop $s$
$t_{rs}^a$	arrival time of run $r$ at stop $s$
$t_{rs}^d$	departure time of run $r$ from stop $s$
$t_{rs}^h$	holding time of run $r$ at stop $s$
$t_{rs_l}^{ivt}$	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 $r_o$
$f_{r_o   q_{r_i s_t}^{out}}$	fraction of passengers alighting run $r_i$ at stop $s_t$ wishing to transfer to $r_o$
$f_{r_o   q_{r_o r_i s_t}^{out}}$	fraction of passengers wishing to transfer at stop $s_t$ from run $r_i$ to $r_o$ who makes the connection

**Parameters:**

$\tau_{rs}$	minimum turnaround time for run $r$ at stop $s$
$\lambda_s$	passenger arrival rate at stop $s$
$\beta_1$	weight of perceived passenger walking time
$\beta_2$	weight of perceived passenger waiting time
$\beta_{3m}$	weight of perceived passenger in-vehicle time in mode $m$
$\beta_4$	weight of perceived time for each transfer
$\beta_5$	weight of perceived passenger in-vehicle time as function of load factor
$\beta_6$	weight of perceived passenger in-vehicle time as function of standing density
$\beta_7$	weight of perceived passenger waiting time in case of denied boarding
$\gamma_s$	crowding seat capacity in-vehicle time multiplier
$\gamma_d$	crowding standing density in-vehicle time multiplier
$\varphi_r^s$	seat capacity of run $r$
$\varphi_r^c$	crush capacity of run $r$
$\theta_r^c$	surface available for standing of run $r$

**3.2.1. Control problem description**

The control strategy presented here relates to the decision whether to hold a certain run  $r \in R_l$  of line  $l \in L$  at a candidate transfer stop  $s_t \in S_t$  for a certain amount of time denoted by  $t_{rs}^h$ . The strategy applied by a controller targets public transport lines in the urban network. However, the control decision can be triggered by circumstances occurring on the urban network level as well as on other network levels (e.g. due to circumstances occurring on the regional or national public transport network level). Besides, when evaluating the expected effects of the control decision on the urban network, impacts on other network levels are incorporated as well. This means that a delay on the regional train network level can trigger a holding strategy at the urban network level at a multi-level transfer stop  $s$ , where  $s \in S_t$ . A strict hierarchy is assumed so that circumstances occurring on the heavy-rail network can trigger a holding strategy for urban light rail and bus services, but not vice-versa. Multi-level holding strategies are applied only at transfer stops,  $s \in S_t$ .

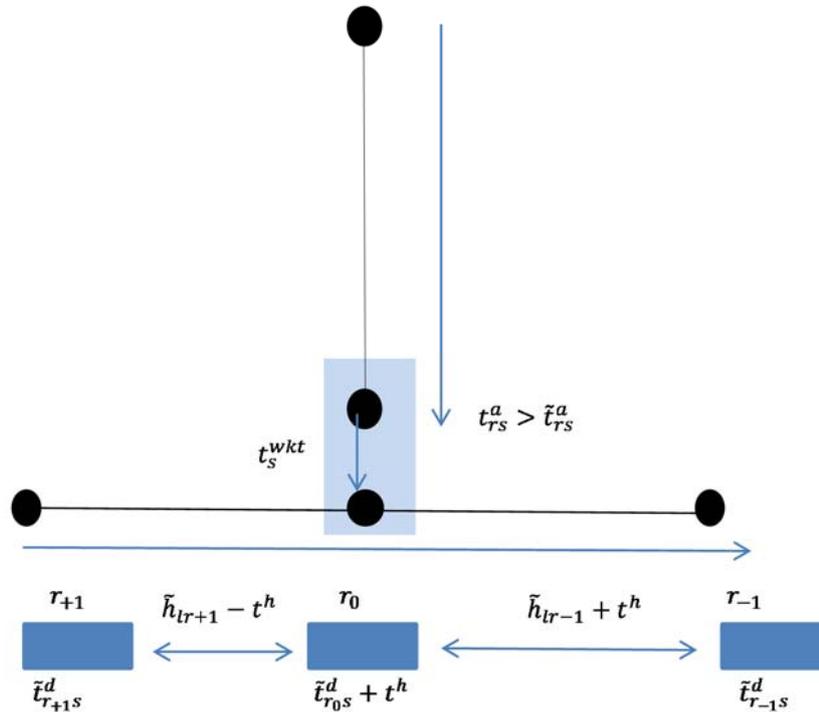


Figure 3.2.1. Illustration holding control strategy

Figure 3.2.1 illustrates the holding control setting at a multi-level transfer stop with the corresponding notations. In this illustration, an inbound regional train service run  $r \in R$  arrives with a certain delay at stop  $s \in S_t$ , resulting in a realized arrival time  $t_{rs}^a$  which is later than the scheduled arrival time  $\tilde{t}_{rs}^a$ . Given the expected transfer flow from this train service to an urban public transport service – amongst others influenced by the passenger transfer walking time  $t_s^{wkt}$  –, a control decision can be taken to hold the urban public transport service  $r \in R_l$  at stop  $s \in S_t$  for a certain holding time  $t_{rs}^h$  in order to increase the expected number of transferring passengers which make their connection. Assuming that urban services  $r, r^+, r^-$  operated according to schedule with departure time from holding stop  $t_{rs}^d$  being equal to the scheduled departure time from this stop  $\tilde{t}_{rs}^d$ , this holding strategy results in an increased headway  $h_{r^-} = \tilde{h}_{r^-} + t_{rs}^h$  between previous run  $r^-$  and run  $r$ . In case no holding is applied to subsequent run  $r^+$ , the holding strategy results in a decreased headway  $h_r = \tilde{h}_r - t_{rs}^h$  between the run  $r$  being held and the subsequent run  $r^+$ .

### 3.2.2. Impacted passenger segments

The impact of the holding control strategy is expected to influence different passenger segments. For each of these segments, the costs when applying this holding control strategy are formulated.

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

#### (i) Upstream boarding and downstream alighting (through) passengers

In case of holding, passengers who board upstream of the holding location and alight downstream of the holding location, will experience a direct extension of their in-vehicle time at the holding stop equal to the holding time  $t_{rs}^h$ . Besides, the holding will result in a larger number of boarding passengers at all downstream stops, since the headway  $h_{r^-}$  between run  $r$  and previous run  $r^-$  increases with  $t_{rs}^h$ . The larger number of passengers waiting at all stops downstream from the holding location results in

higher crowding levels in the run which has been held, resulting in higher perceived in-vehicle time for all on-board passengers. The possibly extended dwell time due to an increased number of boarding and alighting passengers  $q_{rs}^{in}$  and  $q_{rs}^{out}$  for all stops  $s_l \in S_l$  downstream  $s_t$  is not incorporated in the decision rule, given the expected marginal impact and many assumptions required regarding passenger boarding and alighting behaviour. The calculation of the costs of the direct extension of the in-vehicle time due to the holding strategy for passengers in the first category is shown below in Eq. 3.2.1. Eq. 3.2.6 shows the calculation of the costs of the increased perceived in-vehicle time due to increased crowding levels.

$$c_1 = \left( \sum_{s=1}^{t-1} q_{r,s}^{in} - \sum_{s=1}^t q_{r,s}^{out} \right) \cdot \beta_{3m} * t_{rs}^h \quad (\text{Eq. 3.2.1})$$

(ii) *Downstream boarding passengers*

Passengers waiting at a stop downstream of the holding location of line  $l = \{s_{l,t+1}, \dots, s_{l,|l|}\}$  also experience additional costs in case of holding. Their waiting time is directly extended with the holding time. Besides, the crowding level and therefore the perceived in-vehicle time increases due to the higher number of boarding passengers. The calculation of the costs of the direct prolongation of waiting time because of the holding strategy for passengers in the second category is shown below in Eq. 3.2.2. Eq. 3.2.6 shows the calculation of the costs of the increased perceived in-vehicle time due to increased crowding levels.

$$c_2 = \sum_{s=t}^{|l|-1} q_{rs}^{in} \cdot \beta_2 * t_{rs}^h \quad (\text{Eq. 3.2.2})$$

(iii) *Reverse downstream boarding passengers*

Passengers waiting at a stop downstream of the holding location in the reverse direction are only affected by the holding control strategy if the time between the realized arrival time at the final stop of the line,  $t_{r,s_{l,|l|}}^a$ , and the scheduled departure time from the terminal for the next run in the reverse direction  $\tilde{t}_{r,s_{l,1}}^d$  is smaller than the required minimum turnaround time  $\tau_{r,s_{l,|l|}}$ . In that case, there will be a longer waiting time for boarding passengers at all stops of the line in the reverse direction. When again neglecting possible dwell time extensions due to the higher number of boarding and alighting passengers, for passengers waiting at stops further downstream of the reversed line the additional waiting time equals the initial delay at the first stop, being the difference between  $t_{r,s_{l,1}}^d$  and  $\tilde{t}_{r,s_{l,1}}^d$ . Also, average crowding and the resulting perceived in-vehicle time increases between the boarding stop and alighting stop. The calculation of the costs of the direct increase in waiting time due to the holding strategy for passengers in the third category is shown below, whereas costs resulting from increased crowding levels are calculated using Eq. 3.2.6.

$$c_3 = \max \left\{ \sum_{s=1}^{|l|-1} q_{rs}^{in} \cdot \left( t_{rs}^h - \tau_{r,s_{l,|l|}} \right), 0 \right\} \quad (\text{Eq. 3.2.3})$$

(iv) *Transferring passengers at holding location*

For transferring passengers at  $s_t$ , holding should result in benefits (negative costs) compared to the situation where no holding is applied. The direct benefit can be quantified as the reduced waiting time at  $s_t$  due to the holding strategy, compared to passengers having to wait for the next run. The holding benefit needs however to be corrected for the increased perceived in-vehicle time further downstream as a result of holding, since holding a certain run results in more waiting passengers and thus higher crowding levels. The calculation of the direct costs of the holding strategy for passengers in the fourth category is shown below by Eq. 3.2.4. Eq. 3.2.5 shows the determination of the number of transferring passengers between inbound run  $r_i$  to outbound run  $r_o$  at  $s_t$ . This value is equal to the number of passengers alighting from  $r_i$ , multiplied by the fraction of this group wishing to transfer to outbound run  $r_o$ , multiplied by the fraction of this group which makes the connection, given the required and available transfer walking time. Eq. 3.2.6 shows the quantification of the impact of crowding on perceived in-vehicle time.

$$c_4 = - \sum_{r_i \in R_i} q_{r_i r_o s_t}^{trans} \cdot (t_{r^+ s}^a - (t_{r s}^a + t_{r s}^h)) \quad (\text{Eq. 3.2.4})$$

$$q_{r_i r_o s_t}^{trans} = q_{r_i s}^{out} * f_{r_o | q_{r_i s_t}^{out}} * f_{r_o | q_{r_o s_t}^{out}} \quad (\text{Eq. 3.2.5})$$

### 3.2.3. Crowding

The costs of the holding strategy affects the different passenger segments in terms of perceived in-vehicle time due to changed crowding levels. In order to compare perceived in-vehicle times between the scenarios in which holding is, and is not, applied, we quantify crowding for each link downstream the holding location. Due to the non-linear nature of perceived in-vehicle time as function of crowding levels and in order to prevent double counts, we quantify crowding effects over all passenger segments together on a link level, instead of for each segment separately.

In the crowding calculation, the perceived in-vehicle time of run  $r$   $\Delta t_r^{ivt,p}$  for the run potentially being held, is quantified in case of a certain holding time  $t_{r s}^h$ . The perceived in-vehicle time for this same run  $r$  from the potential holding location downstream to the final stop of the line is also quantified in case no holding would be applied. This can be seen in Eq. 3.2.6 where the second part of the formula (expected perceived in-vehicle time of run  $r$ ) is deducted from the first part of the formula (expected perceived in-vehicle time of run  $r$  in case of holding). Holding run  $r$  for time  $t_{r s}^h$  increases the headway between  $r^-$  and  $r$  with  $t_{r s}^h$ , given a fixed passenger arrival rate  $\lambda_s$  at each downstream stop thus increasing the number of boarding passengers downstream. The headway between run  $r$  and subsequent run  $r^+$  is however decreased with  $t_{r s}^h$ . This means that crowding is expected to increase in run  $r$ , whereas crowding will decrease in run  $r^+$  due to the lower number of boarding passengers at each stop downstream of the potential holding location. For the sake of completeness, perceived in-vehicle times are also quantified for this run  $r^+$ : the fourth part of the formula (expected perceived in-vehicle time of run  $r^+$ ) is deducted from the third part of the formula (expected perceived in-vehicle time of run  $r^+$  in case of holding run  $r$ ). In case of holding run  $r$ , these two aspects together will usually result in a net lower perceived in-vehicle time in run  $r^+$  (the fourth component of Eq. 3.2.6 being larger than the third component), compared to the scenario in which run  $r$  is not being held.

$$\begin{aligned} \Delta t_r^{ivt,p} = & \sum_{s=t}^{|l|-1} \left( (q_{r s_{t-1}} - q_{r s}^{out} + ((t_{r s}^a - t_{r^- s}^a + t_{r s}^h) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o s}^{trans}) * (t_{r s_l}^{ivt} * (\gamma_s + \gamma_d)) \right) \\ & - \sum_{s=t}^{|l|-1} \left( (q_{r s_{t-1}} - q_{r s}^{out} + ((t_{r s}^a - t_{r^- s}^a) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o s}^{trans}) * (t_{r s_l}^{ivt} * (\gamma_s + \gamma_d)) \right) \\ & + \sum_{s=t}^{|l|-1} \left( (q_{r^+ s_{t-1}} - q_{r^+ s}^{out} + ((t_{r^+ s}^a - t_{r s}^a - t_{r s}^h) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o^+ s}^{trans}) * (t_{r^+ s_l}^{ivt} * (\gamma_s + \gamma_d)) \right) \\ & - \sum_{s=t}^{|l|-1} \left( (q_{r^+ s_{t-1}} - q_{r^+ s}^{out} + ((t_{r^+ s}^a - t_{r s}^a) * \lambda_s) + \sum_{r_i \in R_i} q_{r_i r_o^+ s}^{trans}) * (t_{r^+ s_l}^{ivt} * (\gamma_s + \gamma_d)) \right) \end{aligned} \quad (\text{Eq. 3.2.6})$$

To quantify perceived in-vehicle time from  $s_t$  to  $s_{t+1}$  (Eq. 3.2.7), the occupancy  $q_{s_{t-1}}$  on the previous link from  $s_{t-1}$  to  $s_t$  is required. This occupancy is the result of the total number of boarding passengers minus the total number of alighting passengers at all stops upstream the considered link. The number of boarding passengers can be calculated based on the realized headway between run  $r^-$  and  $r$ , given a fixed passenger arrival rate  $\lambda_s$  at a certain stop. The number of alighting passengers is the result of the passengers who board a certain run, given the destination of each boarded passenger. The crowding seat capacity multiplier  $\gamma_s$  (Eq. 3.2.8) can be calculated by dividing the occupancy  $q_{r s_t}$  by the seat capacity  $\varphi_r^s$  of run  $r$ , constrained by the interval  $[0,1]$ . This value can then be multiplied by its crowding parameter  $\beta_5$ . The crowding standing density multiplier  $\gamma_d$  (Eq. 3.2.9) is calculated by

dividing the number of standing passengers by the vehicle surface available for standing  $\theta_r^c$ . When assuming that passengers only stand if all seats are occupied, the number of standing passengers equals the occupancy  $q_{rs_t}$  minus the seat capacity  $\varphi_r^s$ . This value can then be multiplied by its crowding parameter  $\beta_6$ .

$$q_{rs_t} = \sum_{s=1}^t ((t_{rs}^d - t_{r^-s}^d) * \lambda_s) - \sum_{s=1}^t q_{rs}^{out} \quad (\text{Eq. 3.2.7})$$

$$\gamma_s = \min\left(\frac{q_{rs_t}}{\varphi_r^s}, 1\right) * \beta_5 \quad (\text{Eq. 3.2.8})$$

$$\gamma_d = \max\left(\frac{q_{rs_t} - \varphi_r^s}{\theta_r^c}, 0\right) * \beta_6 \quad (\text{Eq. 3.2.9})$$

### 3.2.4. Control decision rule

To determine whether, and to which extent, the holding control strategy should be applied, a passenger-oriented decision rule is applied. This means that the optimal holding duration is determined by maximizing the net societal benefits over all passenger segments. Eq. 3.2.10 shows this calculation, in which the expected costs for passenger segments (i), (ii), (iii) and expected crowding costs are deducted from the expected benefits for passenger segment (iv). The rule will be applied if the net societal costs for passengers due to holding are exceeded by the net societal benefits for the passenger segments benefitting from the holding strategy. In this case, the optimal holding time equals the maximum of function  $z$  (Eq. 3.2.10). In case the costs of holding exceed the benefits, the holding strategy will not be applied, and  $t_{rs}^h$  then equals zero. Maximizing  $z$  is therefore constrained by zero as lower bound (Eq. 3.2.11).

$$z = \left( \sum_{r_i \in R_i} q_{r_i r_o s_t}^{trans} \cdot (t_{r^+s}^a - (t_{rs}^a + t_{rs}^h)) \right) - \left( \left( \sum_{s=1}^{t-1} q_{r,s}^{in} - \sum_{s=1}^t q_{r,s}^{out} \right) * \beta_{3m} * t_{rs}^h \right) - \left( \sum_{s=t}^{|l|-1} q_{rs}^{in} \cdot \beta_2 * t_{rs}^h \right) - \max \left\{ \sum_{s=1}^{|l|-1} q_{rs}^{in} \cdot (t_{rs}^h - \tau_{r,s,l,|l|}), 0 \right\} - \Delta t_r^{ivt,p} \quad (\text{Eq. 3.2.10})$$

$$t_{rs}^h = \begin{cases} 0 & \text{if } z \leq 0 \\ \text{argmax}(z) & \text{if } z > 0 \end{cases} \quad (\text{Eq. 3.2.11})$$

### 3.2.5. Estimation of variables

In order to make a decision whether and for which duration to hold a certain run at a certain transfer stop, it is important to describe in what way the values for the variables of the abovementioned formulae are obtained. For the urban public transport network level, a stop-to-stop OD matrix can be inferred from AFC and AVL data. Applying a transfer inference algorithm to individual AFC transactions results in an OD matrix per time period (e.g. per hour). At each origin stop, the total number of boarding passengers per destination can be predicted based on a certain passenger arrival rate, assuming a random arrival pattern. To predict the number of transferring passengers from the (inter)urban train network (multi-level transfers) or from the urban PT network (single-level transfers) to the urban PT network at a transfer stop, Eq. 3.2.12 is applied. In case of multi-level transfers from the (inter)urban train network, the (inter)regional train model provides a prediction of the number of alighting train passengers at the multi-level stop, as well as the predicted arrival platform of the (inter)regional train service. In case of single-level urban network level transfers, the number of alighting passengers from an inbound urban PT run is predicted using the predicted number of boarding passengers at each run and historic origin-destination information obtained from AFC data.  $f_{r_o|q_{r_i s_t}^{out}}$ , the fraction of alighting passengers from an inbound PT service aiming to transfer to a

certain urban run  $r$ , is determined based on historical data. Historical AFC data and – specifically for the case study of The Hague – percentages based on integration of regional (NS) and urban (HTM) AFC data are used to determine this fraction. This allows the prediction of this value for both single-level and multi-level transfers to the urban network. Based on the time period of the day, day of the week and season, this fraction is predicted from the historically available data.  $f_{r_o|q_{r_o r_i s t}^{out}}$  is the fraction of transferring passengers from a certain inbound PT service to a certain outbound urban PT service, which makes this connection. This value is predicted, based on the predicted transfer walking time. The transfer walking distribution between each interurban PT platform and each urban PT platform, and between all urban PT platforms, is obtained from the hub level model, and can be specified for different periods of the day if crowding affects the distribution function. In the control decision,  $f_{r_o|q_{r_o r_i s t}^{out}}$  for a certain departure time of the urban PT service is predicted based on a probabilistic function using the expected value of the transfer walking time distribution, the predicted arrival time of the (inter)urban inbound PT service and thus the available transfer time.

$$q_{r_i r_o s t}^{trans} = q_{r_i s}^{out} \cdot f_{r_o|q_{r_i s t}^{out}} \cdot f_{r_o|q_{r_o r_i s t}^{out}} \quad (\text{Eq. 3.2.12})$$

By fusion of AFC and AVL data, vehicle occupancies can be directly obtained for the urban network level. This allows the quantification of the impact of holding on perceived in-vehicle times due to crowding. Values for vehicle capacities and standing surface for different vehicle types on the urban public transport network that are required to quantify the impact on perceived in-vehicle time, are obtained from data provided by the operator.

### 3.3. Regional level

As briefly mentioned in previous deliverables, the model of the regional public transport network management originates from an existing optimization model proposed by Törnquist and Persson (2007), which is an event-based model that does not explicitly include passenger flow variables. Without passenger flow variables in the model, passenger satisfaction objectives will be limited to objectives that can be expressed in terms of train movements. This implies that it is possible to use, for example, an objective function where the passenger delays associated with train arrivals are minimized, but this assumes that the passengers do not change their route during disturbances. Hence, there is no possibility for modelling passenger dynamic route choice, in case of disturbances leading to considerations of alternative itineraries. In order to allow the passengers to adapt their itinerary and complete their journey to the destination as fast as possible, the model needs to be modified. Furthermore, as the model focuses on real-time train traffic management, the existing model does not include alternative modes of public transport, such as regional buses. Also, in this aspect the model needs to be adjusted and extended.

#### 3.3.1. Basic notation and main constraints

The model by Törnquist and Persson (2007) is defined as the following. Let  $T$  be the set of trains,  $B$  the set of segments, defining the rail infrastructure, and  $E$  the set of events. An event can be seen as a time slot request by a train for a specific segment. The index  $i$  is associated with a specific train service, and the index  $j$  with a specific infrastructure segment, and  $k$  with the event. An event is connected both to an infrastructure segment and a train. The sets  $K_i \subseteq E$  are ordered sets of events for each train  $i$ , while  $L_j \subseteq E$  are ordered sets of events for each segment  $j$ .

Each event has a point of origin,  $o_k$ , which is used for determining a change in the direction of traffic on a specific track. Further, for each event there is a scheduled start time and an end time, denoted by  $b_k^{initial}$  and  $e_k^{initial}$ , which are given by the established timetable. The disturbance is modelled using parameters  $b_k^{static}$  and  $e_k^{static}$ , denoting the perturbed start and end time of the event.

There are two types of segments, modelling the infrastructure between stations and within stations. Each segment  $j$  has a number of parallel tracks, indicated by the sets  $P_j$  and each track requires a separation in time between its events (one train leaving the track and the next enters the same track). The length of a track  $t \in P_j$  is given by  $g_{jt}^{track}$  and the length of a train  $i \in T$  is given by  $g_i^{train}$ . The minimum time separation between trains on a segment is denoted by  $\Delta_j^M$  for trains that ride in the opposite direction, and  $\Delta_j^F$  for trains that follow each other; the separation is only required if the trains use the same track on that specific segment.

The parameter  $h_k$  indicates if event  $k$  includes a planned stop at the associated segment (i.e. it is then normally a station). The parameter  $d_k$  represents the minimum running time, pre-computed from the established schedule, if event  $k$  occurs on a line segment between stations. For station segments,  $d_k$  corresponds to the minimum dwell time of commercial stops, where transfers may be scheduled.

The variables in the model are either binary or continuous. The continuous variables describe the timing of the events and the delay, and the binary describe the discrete decisions to take in the model concerning the selection of a track on segments with multiple tracks or platforms, and the order of trains that want to occupy the same track and/or platform. The continuous, non-negative, variables are defined as follows:

$x_k^{begin}$  = start time of event  $k$ ,  $k \in E$ ,  
 $x_k^{end}$  = end time of event  $k$ ,  $k \in E$ ,  
 $z_k$  = delay of event  $k$ ,  $k \in E$  from the established schedule.

The  $x_k^{end}$  and  $x_k^{begin}$  model the resource allocation, where a resource is a rail segment, that is, part of a track. The arrival time at a specific segment is given by  $x_k^{begin}$  and the departure from a specific segment is given by  $x_k^{end}$  for a specific train. The binary variables are defined as:

$$q_{kt} = \begin{cases} 1, & \text{if event } k \text{ uses track } t, k \in L_j, t \in P_j, j \in B \\ 0, & \text{otherwise} \end{cases} \quad (\text{Eq. 3.3.1})$$

$$\gamma_{k\hat{k}} = \begin{cases} 1, & \text{if event } k \text{ occurs before event } \hat{k}, k \in L_j, j \in B: k < \hat{k} \\ 0, & \text{otherwise} \end{cases} \quad (\text{Eq. 3.3.2})$$

$$\lambda_{k\hat{k}} = \begin{cases} 1, & \text{if event } k \text{ is rescheduled to occur after event } \hat{k}, k \in L_j, j \in B: k < \hat{k} \\ 0, & \text{otherwise} \end{cases} \quad (\text{Eq. 3.3.3})$$

With the objective to minimize the sum of all delays for all trains, the objective function can be formulated as, where the parameter  $n_i$  for each train  $i \in T$  holds the final event of train  $i$ .

:

$$\min_z f := \sum_{i \in T} z_{n_i} \quad (\text{Eq. 3.3.4})$$

This objective function, or alternatives where the delay is weighted by for example the number of passenger, or where the delay penalty is formulated as a piecewise function, can be used subject to the following three blocks of constraints.

The first block of constraints concerns the timing of the events belonging to each train  $i$  and its sequence of events, defined by the event list  $K_i \subseteq E$ . These constraints define the relation between the initial schedule and the revised schedule, as an effect of the disturbance. Eq. 3.3.5f is used to compute the delay of each event.

$$x_k^{end} = x_{k+1}^{begin}, k \in K_i, i \in T: k \neq n_i \quad (\text{Eq. 3.3.5a})$$

$$x_k^{begin} = b_k^{static}, k \in E: b_k^{static} > 0 \quad (\text{Eq. 3.3.5b})$$

$$x_k^{end} = e_k^{static}, k \in E: e_k^{static} > 0 \quad (\text{Eq. 3.3.5c})$$

$$x_k^{end} \geq x_k^{begin} + d_k, k \in E \quad (\text{Eq. 3.3.5d})$$

$$x_k^{begin} \geq b_k^{initial}, k \in E: h_k = 1 \quad (\text{Eq. 3.3.5e})$$

$$x_k^{end} - e_k^{initial} \leq z_k, k \in E \quad (\text{Eq. 3.3.5f})$$

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

$$\sum_{t \in P_j} q_{kt} = 1, k \in L_j, j \in B \quad (\text{Eq. 3.3.6a})$$

$$q_{kt} + q_{\hat{k}t} - 1 \leq \lambda_{k\hat{k}} + \gamma_{k\hat{k}}, k, \hat{k} \in L_j, t \in P_j, j \in B: k < \hat{k} \quad (\text{Eq. 3.3.6b})$$

$$x_{\hat{k}}^{begin} - x_k^{end} \geq \Delta_j^M \gamma_{k\hat{k}} - M(1 - \gamma_{k\hat{k}}), k, \hat{k} \in L_j, j \in B: k < \hat{k}, o_{\hat{k}} \neq o_k \quad (\text{Eq. 3.3.6c})$$

$$x_{\hat{k}}^{begin} - x_k^{end} \geq \Delta_j^F \gamma_{k\hat{k}} - M(1 - \gamma_{k\hat{k}}), k, \hat{k} \in L_j, j \in B: k < \hat{k}, o_{\hat{k}} \neq o_k \quad (\text{Eq. 3.3.6d})$$

$$x_k^{begin} - x_{\hat{k}}^{end} \geq \Delta_j^M \lambda_{k\hat{k}} - M(1 - \lambda_{k\hat{k}}), k, \hat{k} \in L_j, j \in B: k < \hat{k}, o_{\hat{k}} \neq o_k \quad (\text{Eq. 3.3.6e})$$

$$x_k^{begin} - x_{\hat{k}}^{end} \geq \Delta_j^F \lambda_{k\hat{k}} - M(1 - \lambda_{k\hat{k}}), k, \hat{k} \in L_j, j \in B: k < \hat{k}, o_{\hat{k}} \neq o_k \quad (\text{Eq. 3.3.6f})$$

$$\lambda_{k\hat{k}} + \gamma_{k\hat{k}} \leq 1, k, \hat{k} \in L_j, j \in B: k < \hat{k} \quad (\text{Eq. 3.3.6g})$$

$$g_i^{train} q_{kt} \leq g_{jt}^{track}, k \in (K_i \cap L_j), t \in P_j, j \in B, i \in T \quad (\text{Eq. 3.3.6h})$$

$$x_k^{begin}, x_k^{end}, z_k \geq 0, k \in E \quad (\text{Eq. 3.3.7a})$$

$$\gamma_{k\hat{k}}, \lambda_{k\hat{k}} \in \{0,1\}, \hat{k} \in L_j, j \in B: k < \hat{k} \quad (\text{Eq. 3.3.7b})$$

$$q_{kt} \in \{0,1\}, k \in L_j, t \in P_j, j \in B \quad (\text{Eq. 3.3.7c})$$

The above three blocks of constraints provide flexibility in the train ordering and the use of tracks. If considering a specific strategy when adapting to the disturbance situation, additional constraints need to be added to the model. These are discussed in the next section.

### 3.3.2. Extending the existing model with passenger flow route choice

Even if the model presented in Törnquist and Persson (2007) allows for weighting of the delay by, for example, the number of passengers in the trains, the model is not trivial to extend with passenger behaviour at the time of a disturbance. In order to model reactions from travellers to disturbances, the notion of passenger routes needs to be added to the model. Furthermore, alternative public transport services, in addition to passenger trains, should be included to enable realistic dynamic route choice.

Therefore we need to introduce the set  $V$ , which includes all trains in the selected train traffic network (i.e.  $T \subseteq V$ ) and also all alternative relevant public transport services, such as regional buses. Consequently, we now want to use index  $i$  to represent any transport service in the set  $V$  (i.e.  $i \in V$ ). We thus now also extend the definition of the events sets,  $K_i$  and Eq. 3.3.5a needs to be modified (after revision it is denoted Eq. 3.3.5a\* below):

$$x_k^{end} = x_{k+1}^{begin}, k \in K_i, i \in V: k \neq n_i \quad (\text{Eq. 3.3.5a*})$$

Note though, that it is still only trains that need to respect the infrastructure capacity restrictions outlined in the associated above constraints (Equations 3.3.6a-6h). Also, only the events belonging to a train event list are included in the sets  $L_j$ .

In order to now better capture passenger flow dynamics and route choice in our model, we introduce groups of passengers in a similar manner as proposed by Binder et al. (2017). We define a set of

passenger groups  $G$ , where any passenger group  $g$  is characterized by the triplet  $(o_g, d_g, t_g)$  where  $o_g$  is the origin,  $d_g$  is the destination, and  $t_g$  is the desired departure time from the origin. The parameter  $n_g$  specifies the number of passengers. For each group of passengers, the model takes a set of routes, denoted  $R_g$ , from the origin to the destination within a relevant time period, as input. In a transport service network with low frequency of services, the practical route set will be relatively small.

As in the model by Binder et.al. (2017), a generalized cost function is defined for each route. For now, this generalized cost function is defined as the travel time to the final destination. Further, we assume that all passengers in the group either select the route (or, one of the routes) with the lowest travel time. The cost (travel time) functions will primarily depend on  $x_k^{end}, k \in K_i$ , and specifically of the final event on in the route (dependent of the transport service used by the passenger group). The cost functions can be defined together with the route set as an input to the model formulation. The computation of the generalized cost, based on the event times, will be relatively involved, and may need a number of relations/constraints to be realized.

A route  $r$  (where  $r \in R_g$ ) is defined as an ordered sequence of events (denoted  $R_g^r$ ) where those events are station events, where the passenger group is boarding and alighting the corresponding transport services  $i$ , where  $i \in V$ .  $R_g^r$  always contains an even number of events but minimum two events (the event associated with the service that is boarded, and the event of the same service when alighting). Two events means a direct trip without transfers.

Exactly one route  $r \in R_g$  must be selected by passenger group  $g$ . We use the binary variable  $\phi_{g,r}$  to denote if passenger group  $g$  has selected route  $r$  (=1) or not (=0). A route can only be selected if all of its transfers are successful (i.e. the service connections are decided to be kept by the traffic and transport control management). Let us use the example below to illustrate the model of route choice.

### *Example*

A typical disruption is illustrated in the graphical timetable in Figure 3.3.1: *Graphical time table*. Train 1 is represented by the black line, and its updated time after the delay is the dashed black line. Screen shot from <http://n7.se/train/index.html> 3.3.1. In the figure, four train services are illustrated,  $i = \{1,2,3,4\}$ . A group of passengers,  $g=1$ , is travelling from Karlskrona to Kalmar. Train 1 from Karlskrona departs on time and the passengers on this train travelling to Kalmar are identified from tap-ins on the trains (or by paper tickets). This trip involves a transfer at the station Emmaboda with only six minutes of changeover time (incoming train 1 arriving at 08:24 and connecting train 2 departing at 08:30). The minimum transfer time, denoted  $d_{ir}$  here is four minutes. We assume in this simple example that no coordination of the trains is forced in the model. That is, train 2, departing from Emmaboda at 8:30, does not necessarily wait for train 1 from Karlskrona if it is delayed.

The three train departures in Emmaboda are illustrated by the two grey lines and the red line in the graph and they constitute the three modelled options. If train 1 from Karlskrona gets delayed (dashed line), and train 2 (scheduled to depart 8:30 from Emmaboda) does not wait, the group will need to wait for one of the next trains departing at 08:58 (train 3) and at 09:29 (train 4). The planned arrival time for Train 2 and group  $g$  in Kalmar is 08:59. If their connection is missed, and the next train is boarded and it runs on time, the arrival time of group  $g$  at Kalmar will instead be 09:35. If the third train is used, and it runs on time, the arrival time will be at 10:01. Therefore, in case of a disturbance causing the connection to be missed, the passengers will suffer from a delay. The size of the delay depends on which train they will board and the on-time performance of that particular train.

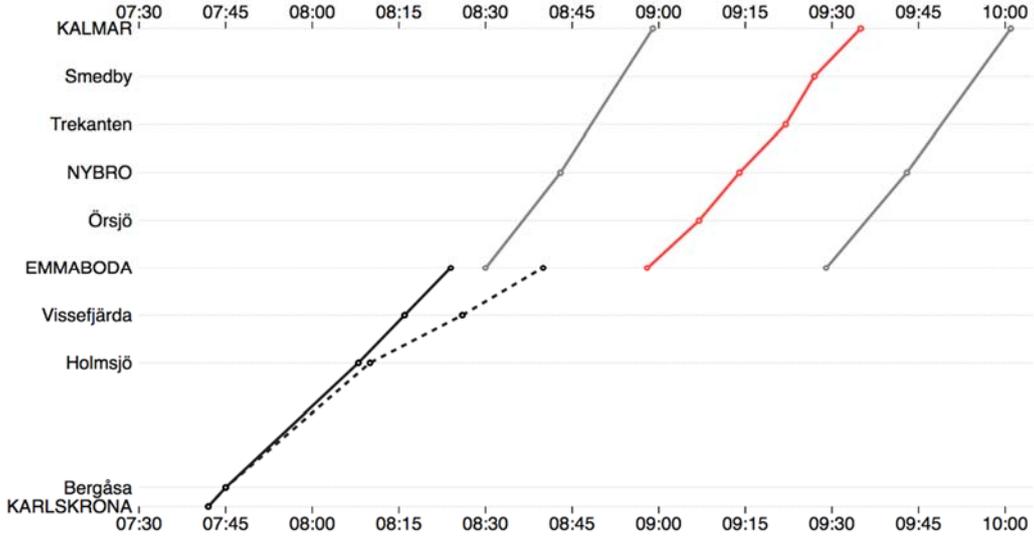


Figure 3.3.1: Graphical time table. Train 1 is represented by the black line, and its updated time after the delay is the dashed black line. Screen shot from <http://n7.se/train/index.html>

In the model, the passenger group has thus three alternative routes,  $r = \{1, 2, 3\}$ . Route 1 ( $r=1$ ) is defined as taking train 1 from Karlskrona to Emmaboda and then taking train 2 from Emmaboda at 08:30 to Kalmar. This means that route 1 consists of the following sequence of events:  $R_1^1 = \{\text{train 1's event at Karlskrona, train 1's event at Emmaboda, train 2's event at Emmaboda, train 2's event at Kalmar}\}$ .

Route 2 is defined as taking train 1 from Karlskrona to Emmaboda and then taking train 3 to Kalmar at 08:58 while route 3 is defined as taking train 1 from Karlskrona to Emmaboda and boarding train 4 towards Kalmar at 09:29. The sequence of events for routes 2 and 3 follow the same structure as explained for route 1 above.

Let the arrival time of train 1 to Emmaboda be given by  $x_{k^1}^{begin}$  (i.e. the time the train begins to occupy the station Emmaboda) and the departure times from Emmaboda for train 2, 3 and 4 be denoted  $x_{k^2}^{end}$ ,  $x_{k^3}^{end}$  and  $x_{k^4}^{end}$ , respectively. Since only one of the routes can be used by the passenger, the restriction below must hold:

$$\phi_{1,1} + \phi_{1,2} + \phi_{1,3} = 1 \quad (\text{Eq. 3.3.8})$$

However, a route which includes transfer(s) can only be selected if all its transfers are successful, which can be expressed in a simplified way below for the example.  $M$  is a large constant and  $d_{tr}$  is the transfer time required for a passenger to make the connection at Emmaboda - independent of the platform allocations in this case. Equation 3.3.9 ensures that a route can only be selected if the associated train connections are successful, i.e. the time between the incoming train and the outgoing train is sufficiently large to enable a transfer.

$$x_{k^2}^{end} - x_{k^1}^{begin} - d_{tr} \geq M(\phi_{1,1} - 1) \quad (\text{Eq. 3.3.9a})$$

$$x_{k^3}^{end} - x_{k^1}^{begin} - d_{tr} \geq M(\phi_{1,2} - 1) \quad (\text{Eq. 3.3.9b})$$

$$x_{k^4}^{end} - x_{k^1}^{begin} - d_{tr} \geq M(\phi_{1,3} - 1) \quad (\text{Eq. 3.3.9c})$$

We introduce  $x_g^{paxArrival}$  as the arrival time at Kalmar for this group of passengers. The arrival time is computed using the following restrictions where  $x_{k^{2'}}^{end}$ ,  $x_{k^{3'}}^{end}$  and  $x_{k^{4'}}^{end}$  refers to the arrival time at Kalmar for train 2, 3 and 4, respectively.

$$x_g^{arrival} \geq x_{k^{2'}}^{start} - M(1 - \phi_{1,1}) \quad (\text{Eq. 3.3.10a})$$

$$x_g^{arrival} \geq x_{k^{3'}}^{start} - M(1 - \phi_{1,2}) \quad (\text{Eq. 3.3.10b})$$

$$x_g^{arrival} \geq x_{k^{4'}}^{start} - M(1 - \phi_{1,3}) \quad (\text{Eq. 3.3.10c})$$

Given the time for the first departure for this group of passengers and the arrival time, the total travel time can be computed. The total travel time, or the delay, is used in the computation of the generalized travel cost, which will be minimized by the passengers.

The proposed modelling approach allows for several alternative control strategies based on holding and train re-ordering policies. That is, in the proposed model, the re-scheduling adjustments from the optimization will make use of arrival and departure time adjustments as well as train re-ordering, for the cases where this is beneficial for the stated objective.

If, for example, holding shall not be allowed in the model, this is modelled using the parameter  $e_k^{static}$  for the specific train or bus event, as shown in the first block of restrictions (Equations 3.2.5a-f). The possibility for one train to depart before another train, that is, in the established timetable it is planned to depart after, can e.g. be removed by adding restrictions on the  $\lambda_{k\hat{k}}$  variables.

The proposed model does currently not include the possibility to cancel a train or add a train on demand. Such controls will not be included in the case study experiments with the basic proposed model. Which controls that shall be allowed for in the specific case study will be defined in a later deliverable.

## 4. Model integration and information flow requirements

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The three models outlined in section 2 and 3, describe three different parts of a larger public transport system - inside which passengers need to navigate. These models can be used in isolation from each other, to study phenomenon concerning for example the design and throughput of a particular station, or the effect of certain holding strategies for an urban, or regional transport service system. Therefore we describe the required input of information for each of the three different models, as well as the expected output. In Figure 4.1 below, we also illustrate the proposed integration of these three levels and corresponding models. The interaction between the urban, hub and regional levels occurs primarily via the flow of passengers and their transfers between the (inter)regional and the urban public transport service network. The infrastructure and associated constraints are modelled with different granularities in the different levels and no resources are modelled jointly. That is, the urban model includes constraints concerning the main capacity restrictions for the transport services including the effect of crowding when boarding and alighting during peak hours, while it is the hub model that explicitly models the transfer movements within stations and includes the station capacity constraints for the pedestrians. Capacity constraints associated with the traffic and infrastructure, e.g. track and platform length in relation to the length of the train set, are included in the model of the (inter)regional railway transport system.

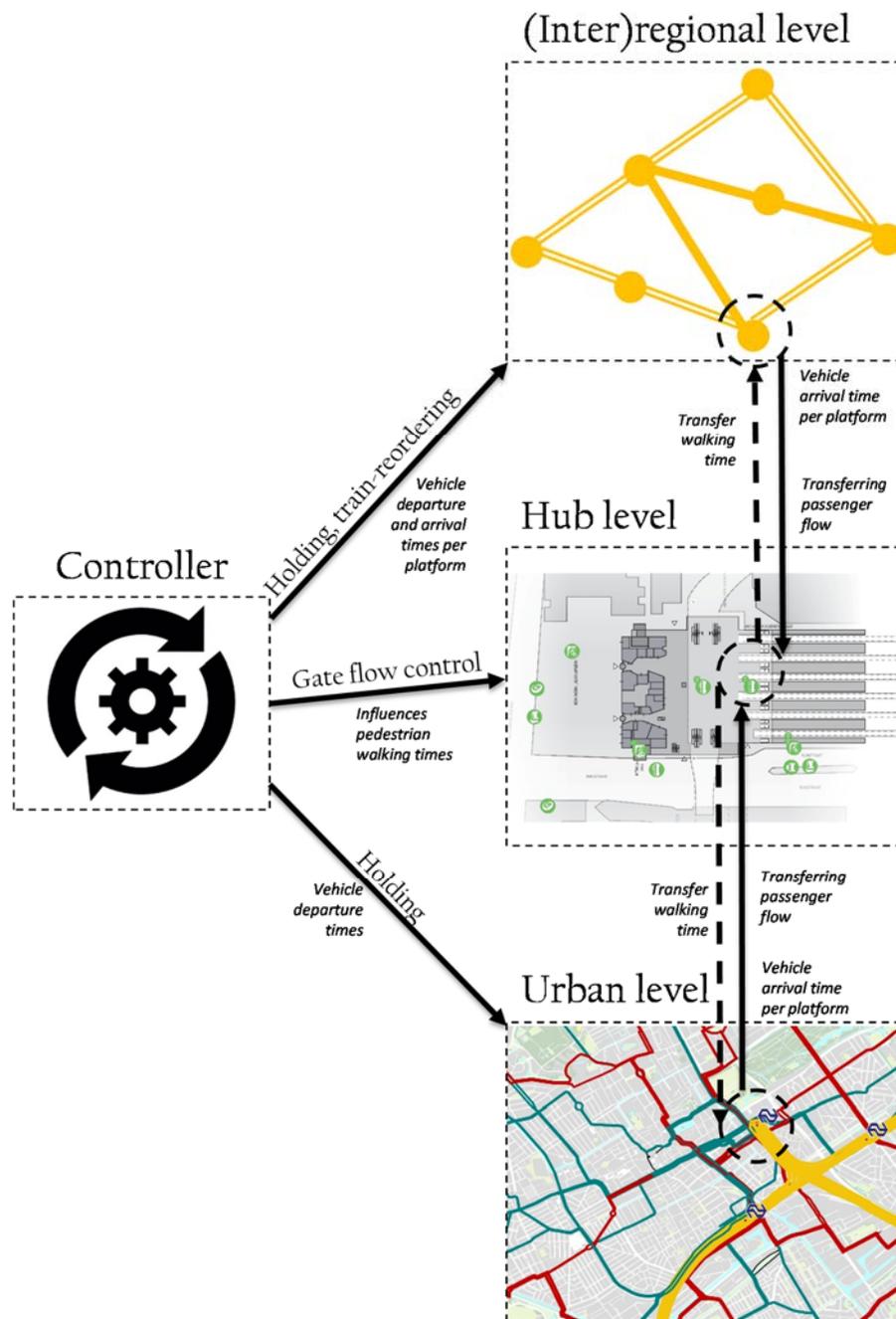


Figure 4.1. Illustration of the integrated model framework. The illustration includes figures found at <https://plattegrondstation.nl/den-haag-centraal/> and [https://image.freepik.com/free-icon/conversion-optimization\\_318-32121.jpg](https://image.freepik.com/free-icon/conversion-optimization_318-32121.jpg).

#### 4.1. Hub level

The prerequisites for running the hub model are multiple. Firstly, the specification of the infrastructure is needed. This can be built based on CAD plans of the infrastructure. The set of walls delimiting the walkable space for pedestrians must be coded as lines (one start point and one end point). They should be connected to each other and make a single closed area. Based on this walkable area, a network is used for representing the different routes pedestrians can choose. Each vertex of the graph has an associated zone. The zones located at the end vertices are used for generating pedestrians and also making them “leave” the system. The second element which is required is the public transport schedule. Depending on the hub, this can be simply the train timetable, or more complicated. For

example, metros, buses, trams and trains can be combined to make up the schedule. Finally, the pedestrian flows between each PT service are needed. Furthermore, the pedestrian flows which are not concerned by the PT services (for example individuals only shopping in the hub) are also required. These requirements can be summarized as follows:

- CAD file to build infrastructure
- Public transport schedule
- Pedestrian flows between all combinations of trains and external sources

The model can be used in two different ways: either to produce pre-computed solutions or online (on demand). The data requirements are the same in both cases. When pre-computed, simulations are needed either for computational speed, or because the number of combinations is too large, the hub model can produce offline results.

For an online application, a simulation of the whole time frame of interest is performed. This means that there is no possibility to update the PT schedule during the simulation. Nevertheless, the conditions for using the hub model in an online situation is the short computational time. Therefore, when an update of the schedule is done, for rescheduling after an incident for example, a new simulation is performed with the updated schedule. This approach means the inputs are the same for offline and online situations.

Input data:

- Infrastructure: specification of the walls delimiting the walkable area (each wall is modelled as a line), accompanied by the specification of a graph used for computing route choice.
- Demand: public transport timetable accompanied by the pedestrian flows generating from / arriving to trains. Secondly, the pedestrian flows not linked to public transport modes are also required.

Output data:

- Transfer times: for each OD pair in the system, a statistical distribution of the walking times is provided. This is computed based on the walking times of each individual in the system. If, for some reason, no pedestrian uses a specific OD, then either a "ghost" pedestrian is added as to generate some data for that OD, or the travel time is estimated based on the shortest distance required to perform that trip.

## 4.2. Urban Level

This section describes the ingoing and outgoing information flows to/from the urban public transport model. Input for the urban public transport assignment model consists of the following aspects:

- Network. This contains an infrastructure description of all transit nodes, links and stops with their corresponding coordinates, as well as walking links which allow single-level and multi-level transfers between public transport services, and which allow walking to/from different stops (e.g. in case of disruptions). It also consists of the definition of public transport lines, being defined as an ordered sequence of links, over the network. This information can be provided based on shapefiles of the case study public transport network.
- Supply. This contains the urban public transport network timetable: for each line, and for each run, the scheduled departure and arrival time at each stop is defined, based on which the scheduled running time and dwell time can be inferred. This information is obtained based on GTFS / AVL data of the case study public transport network. Based on historical AVL data, it is also possible to deduce a running time distribution based on realized running times per leg, per line and per time period.
- Demand. This contains information about the passenger origin-destination (OD) matrix, per time period (e.g. per hour). This information is obtained based on raw AFC transaction data provided by the PT operator, based on which – by applying a transfer inference algorithm which uses AFC and AVL data – journeys are inferred.

- Transfer walking time. In order to model the impact of holding strategies, the (distribution of) transfer walking time at the considered multi-level hub between each departure/arrival location of the regional train network level and the urban tram/bus network level needs to be known. This information results as output from the **hub model**.
- Arrival and departure times of regional trains. In order to model transfer flows between the regional train network level and the urban tram/bus network level, both the scheduled and realized departure and arrival times of all regional train runs at the multi-level transfer hub are required. This information results from the **(inter)regional train model**: the scheduled arrival/departure times are input for the (inter)regional train model, whereas the realized arrival/departure times are output from the (inter)regional train model.
- Arrival and departure platform of regional trains. In order to model the transfer walking times of transferring passengers, the scheduled and realized departure / arrival platforms of the (inter)regional trains at the multi-level transfer hub are required. Scheduled platforms are input for the **(inter)regional train model** based on the schedule, whereas realized platforms are output from the (inter)regional train model.
- The number of passengers wishing to transfer from each arriving (inter)regional train run to each urban PT line is required to quantify transfer flows and to quantify the percentage of this group which do make their connection given a certain (expected) transfer walking time. This information is output from the assignment module of the **(inter)regional train model**.
- Disruption information. In order to model disruptions, information about the disruption location, duration and adjusted urban PT supply is required. This is provided externally and by the urban PT operator.

Information output of the urban public transport assignment model can be categorized as follows:

- Output to the **hub model** and **(inter)regional train model**: number of passengers wishing to transfer from each arriving urban PT line to each departing regional train;
- Output to both the **hub model** and **(inter)regional train model**: scheduled and realized arrival and departure time of each urban PT service at transfer. The scheduled times are input for the urban PT model, whereas the realized times are output resulting from the urban PT model;
- Output of the urban model: passenger route choice → passenger loads (per run, per line, per link), including crowding levels;
- Output of the urban model: passenger travel costs (nominal and perceived travel times, generalized travel costs);
- Output of the urban model: number of boarding / alighting / transferring passengers per stop.

Figure 4.2.1 below summarizes the incoming and outgoing information for the urban public transport passenger assignment model.

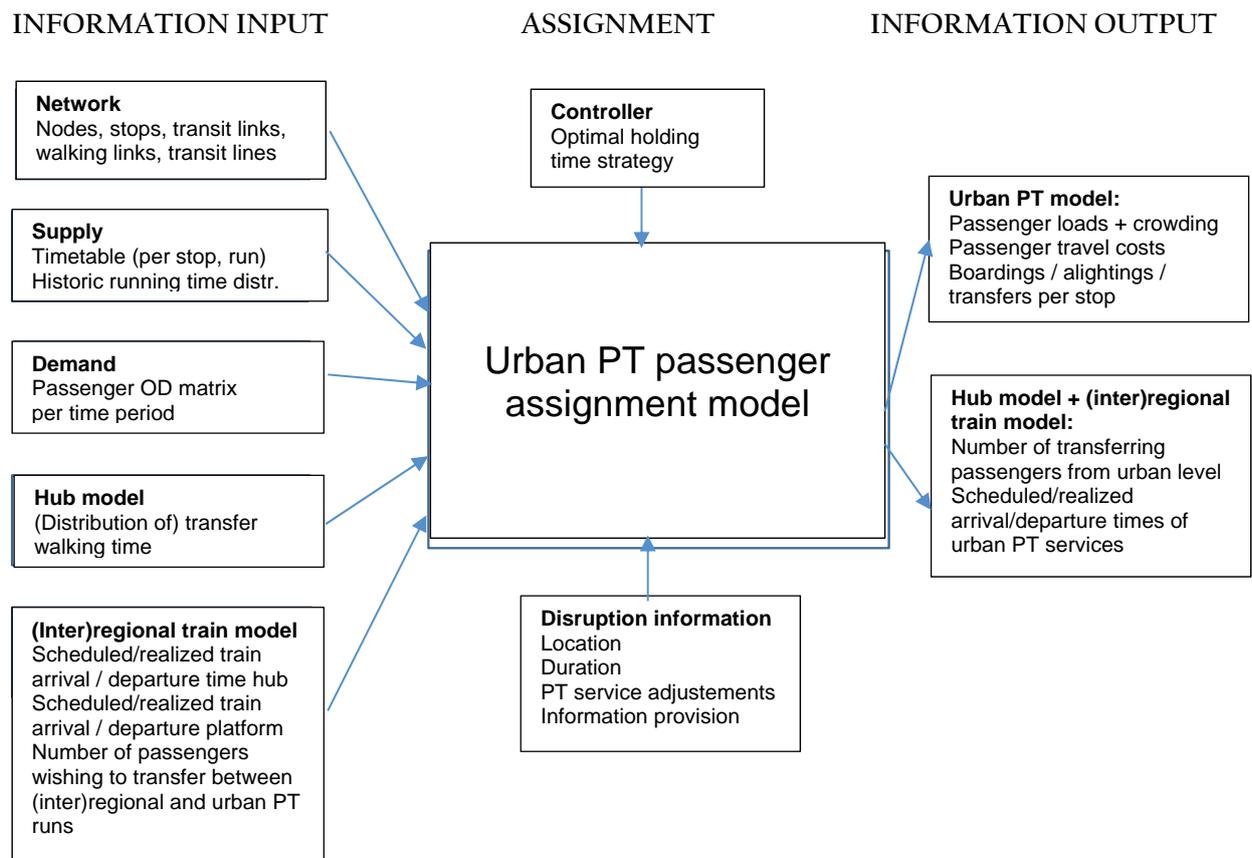


Figure 4.2.1 Information flow to/from urban public transport passenger assignment model

### 4.3. Regional level

As illustrated by Figure 2.3.1, the output from the optimization-based delay management approach for regional public transport are revised schedules (i.e. updated arrival and departures times as well as platform allocations) and routes selected by the defined passenger groups, including the expected arrival time at final destination within the regional network.

The input required from the hub level model is “transfer walking time”, which correspond to the parameter  $d_{tr}$  in the mathematical model in section 3.3 (i.e. the minimum transfer time required for a passenger to make the connection, which is depending on the length of the path between the platforms of the connecting services). If these times are assumed to not be affected by crowding at a particular station hub, these times are static and can be pre-computed for all directed pairs of platforms for that hub.

The urban and regional level interact via the transfer of passengers from one level to another, using the hubs as transfer points. The passengers that enter the regional level via a specific hub are associated with the departure of a particular regional PT service at the corresponding station (hub) platform. The passengers that leave the regional system enters the urban level via the arrival of specific regional services at specific platforms in the associated hub. The input to the urban level is therefore the revised regional PT service arrival and departures times and associated platform assignments and passenger flows (i.e. alighting passengers). The input from the urban level is the number of passengers boarding a specific regional service at a specific hub and their final destination within the regional network.

## 5. Conclusions and Prospects

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The work in tasks 3.1 and 3.2 have focused on development of three models that are suitable to analyse the effect of selected public transport system management strategies on different levels as well as in combination, with a multi-level perspective in mind. Figure 4.1 above illustrates the proposed integrated passenger-focused modelling approach. This integrated modelling approach will be further developed and implemented as a tool for evaluating relevant management strategies within task 3.4 and later applied in the following work package 4 entitled “Application and Demonstration of Smart Transfer Strategies” with focus on the Dutch case study.

## 6. References

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