Two management strategies for improving passenger transfer experience in train stations

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Abstract

Exploiting the full potential of pedestrian infrastructures in order to satisfy the demand induced by public transport modes is key to achieving good level-of-service for passengers during transfers. High temporal variability in demand can lead to high congestion and possibly dangerous situations while the infrastructure is underused moments after. In order to improve the level-of-service experienced by pedestrians, two management strategies are investigated. Firstly, the utilization of gates to control the flows of passengers moving around the station is explored thanks to a PI control structure. Secondly, counter flow is minimized by dynamically adapting the space to the flows moving in opposing directions. This can be achieved by separating the corridor into two parts, one dedicated to each flow direction. The station of Lausanne, Switzerland is used as a case study for these strategies. Gating proved efficient to limit congestion without significantly increasings the travel time of passengers. The expected results when separating counter flow are similar: an increase in comfort without negatively impacting travel time. Finally, the implementation of efficient management strategies for pedestrians can significantly improve the transfer experience in transportation hubs by controlling the walking times between services.

Keywords

Pedestrian dynamics, management strategies, transportation hub

1 Introduction

With current trend of increasing the number and lengths of trains on the existing railway networks, the schedule adherence has become critical. The scope for delay is diminishing and delay propagation is a recurrent issue with saturated networks. One of the many possible sources for delay comes from excess time induced by pedestrian congestion inside the train stations (Hendren *et al.,* 2015). Indeed, sufficient time must be planned in order to guarantee that connecting passengers can catch their connections. As to minimize the risk of cascading delay induced by the wait for passengers to change services, the train operators need reliable estimations of the walking times between platforms.

The transfer times required for pedestrians to change platform depend on the dynamics taking place inside the station. High spatio-temporal variability in congestion occurs as the trains alight their passengers. On one hand, synchronizing the arrival of trains inside the station means any different connections are available, but on the other, when many trains arrive at the same time high pedestrian congestion occurs, hence leading to a decreased level of service and higher travel times and travel time variability. As an increase in the time between train arrivals will likely decrease the attractiveness of the train network, keeping an acceptable level-of-service during these highly congested times is desirable (Kanai *et al.,* 2011).

One direction for achieving an acceptable level-of-service is to influence the choices pedestrians make. This can be accomplished by implementing control and management strategies inside the infrastructure. As for vehicular traffic, various strategies can be conceived. They can influence different levels of decision-making (operational, tactical or strategical) (Hoogendoorn and Bovy, 2004), and be considered as soft strategies (like information or guidance) or hard ones (like physical barriers). In this paper, two possible strategies are investigated which are embedded into a framework capable of evaluating and simulating management strategies. The first strategy is the installation of gates which are controlled by a linear-quadratic regulator and the second is a mechanism for separating opposing flows, hence limiting counter-flow. The contribution to the improvement of the transfer experience for passengers is made by proposing efficient management strategies which exploit the specificities of pedestrian dynamics.

The following section presents the state-of-art literature regarding pedestrian management strategies and simulation frameworks for testing them. Then, section 3 details the proposed management strategies and the approach for evaluating them. Finally, section 4 provides an explanation of the planned case study and section 5 concludes this article.

2 Literature review

Many different control strategies have been proposed for vehicular traffic. They can be reactive strategies like the ALINEA ramp metering (Papageorgiou *et al.,* 1991) or signalized intersection control (Diakaki *et al.,* 2002, Hu and Mahmassani, 1997). Alternatively, strategies can be anticipative, meaning that they predict the future state of the system and then take the best decision, for example anticipative traffic lights (Lämmer *et al.,* 2008) or (LÃmmer and Helbing, 2008). The development of these strategies has taken place inside simulation environment at first, sometimes denoted as Dynamic Traffic Management Systems (DTMS). Two frameworks which have been extensively used and applied in practice are DYNAMIT (Ben-Akiva *et al.,* 2003) and DYNASMART (Mahmassani, 2001). Other simulation environments for evaluating control and management strategies have been proposed in (Jayakrishnan *et al.,* 1994, Papageorgiou, 1990, Yang and Koutsopoulos, 1996). Although many control strategies exist and have been deployed for vehicular traffic, control strategies for pedestrian traffic are still unexplored.
Recently, a framework for controlling LOS in a pedestrian infrastructure is presented in Zhang *et al.* (2016). The walkable space is represented in a bi-level way: a graph combined with cells. The same target density is enforced on each link by controlling the pedestrian's walking speed. This approach is difficult to apply in transportation hubs as the demand presents very high spatial and temporal fluctuations, making uniform density or speed not desirable. Similarly to the previous study, a macroscopic pedestrian movement model was used to assess and design the strategy for controlling the opening and closing times of access gates to metro stations (Bauer *et al.,* 2007). The scenarios were based on special events where the demand significantly exceeds the daily operation's demand. Nevertheless, although the authors use most of the components required in the design of a framework for the generation of management strategies, no complete framework is proposed, indeed, each component is used independently.
The effectiveness of some crowd management actions was observed in a real-life situation in (Campanella *et al.,* 2015), where a Brazilian metro stop offered very poor LOS and possibly dangerous situations during the new-year celebrations. Some management strategies had been planned and used to prevent critical situations while some reactive actions were also used. Qualitative observations where done and compared to operations from the previous years. The authors emphasize the need for an integrative framework including pedestrian simulations for evaluating various crowd management strategies.
When specific strategies are considered, most the attention has been guided towards reactive and offline strategies. The optimal configuration of traffic lights for signalized crosswalks has been studied for example Zhang *et al.* (2017). The authors propose a MILP to optimize the configuration of the green, orange and red phases to minimize the pedestrians delay while satisfying vehicular traffic constraints.

3 Methodology

Three main parts are included within the methodology section. Firstly, the framework used for simulating and evaluating management strategies is presented, secondly, both management strategies which are evaluated are explained, finally, the choice of metrics for evaluating the impact of the various strategies is motivated.
As to make the description of the various management strategies as clear as possible the following terminology is introduced. The first aspect concerns the action globally and is called the management *strategy*, while the second aspect refers to the actual operation of the given action and is called the management*policy*. The third is the measures used to physically apply the management policy and is called the management*devices*. As an illustrative example, let's consider gates used to control the flow of pedestrians. The management strategy is the position and number of gates. The operational aspects, i.e. the management policy specifies the flow rate allowed through the gates. Finally, the management devices are the gates themselves which enforce the management policy.

3.1 Framework

The framework which is detailed below can be considered as a pedestrian equivalent to the "plant" or "simulation laboratory" (Ben-Akiva *et al.,* 2003) commonly used in vehicular traffic. The objective of this environment is being able to reproduce and simulate the impact of various management strategies on the pedestrian dynamics. As presented in Figure 1, three main blocks are required to achieve the objective.
Firstly the pedestrian traffic itself must be understood and modelled. The interaction between the demand (pedestrians loading the infrastructure) and the supply (the space where pedestrians can walk made available by the infrastructure) is a dynamic user equilibrium problem. The pedestrians take two levels of decisions, tactical and operational, based on the current or future levels of congestion inside the infrastructure (Hoogendoorn and Bovy, 2004). These decisions in turn influence the congestion levels inside the infrastructure, which itself then influences the decisions of pedestrian. This iterative process is continuously in action. The tactical decisions which are taken by pedestrians concern the route inside the infrastructure as well as the set and sequence of activities to be performed. These can be impacted by management strategies, unlike the operational decisions which answer the question "in which direction should my next step be?".
The second core component of this framework is the traffic controller. This component evaluates the state of the pedestrians dynamics based on the measurement of some predefined set of key

performance indicators (KPIs) and takes the decisions regarding the state of the management devices. It can be seen as the “brain” of the system. From the controller’s perspective, it is irrelevant whether the data used to evaluate the KPIs comes from simulation or from reality. When a management strategy is implemented in "reality", the KPIs could be different. This would be due to technical limitations for example. Once the state of the system is evaluated, the KPIs are used to create the policy.

Finally, the third and last core component is composed of the control devices. Although the physical devices which are installed to enforce the management strategies are integrated into the infrastructure, they are presented separately since they have a strong link to the traffic controller and management strategies. The devices receive information from the traffic controller and will update their configuration accordingly, in turn influencing the pedestrian traffic. For example, gates can impact the routes that pedestrians choose, or floor markings can help separate counter flow.

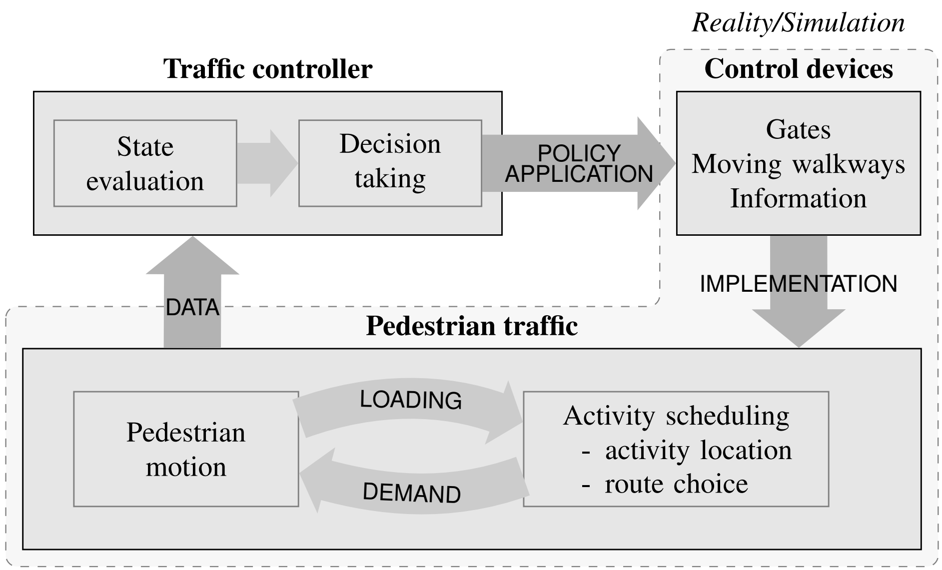

Figure 1: Interactions between the three main components in the framework. The dashed box surrounds the elements which can be either from “reality” or from a simulation. The pedestrian traffic is used by the controller in order to compute the KPIs. Based on these KPIs, the controller updates the configuration of the control devices which enforce the policy. The loop is closed as these devices will impact the decisions that pedestrians take, hence influencing the pedestrian dynamics.

3.2 Management strategies

Two management strategies which aim at improving the pedestrian dynamics are proposed. The first consists of gating, where physical barriers control the flow of pedestrians entering some predefined area. The second is flow separator which can be moved dynamically based on the expected flow of pedestrians.

3.3 Gating

The objective of gating is to prevent congestion in sensitive areas. The indicator chosen to measure congestion is pedestrian density. The control structure which is proposed is a discrete linear-quadratic regulator (DLQR). The development of the state-space model are similar to Keyvan-Ekbatani *et al.* (2012) where the authors developed a PI regulator for controlling the traffic flow inside a delimited region. We choose a DLQR for calibration purposes. The development of the state-space model relies on two assumptions which allow an explicit computation of the parameters of the model.
As with many systems, the conservation equation is central to the dynamics of the problem:

$$\dot{N}(t) = q_{in}(t) - q_{out}(t), \tag{1}$$

where N is the number of people inside the delimited area, q_{in} the inflow and q_{out} the outflow from the area. At this point the total inflow q_{in} can be split into two components, the controlled q_{con} and uncontrolled flows q_{un}. The density is linked to the number of pedestrians inside the area as follows:

$$\rho(t) = \frac{N(t)}{\omega_A} \Rightarrow N(t) = \rho(t) \cdot \omega_A, \tag{2}$$

where ω_A is the area of the cell. By inserting (2) into (1) and splitting the inflow into two components, one for the controlled inflow $q_{in,con}$ and one for the uncontrolled inflow $q_{in,unc}$ the conservation equation can be rewritten as:

$$\frac{d}{dt}\rho(t) \cdot \omega_A = q_{in,cont}(t) + q_{in,unc}(t) - q_{out}(t), \tag{3}$$

Assumption 1 *The pedestrian outflow from the area is linearly proportional to Edie's definition (van Wageningen-Kessels et al., 2014) of the generalized flow inside the delimited area.*

This assumption is verified empirically thanks to pedestrian tracking data collected in location chosen for the case study. This leads to the following:

$$q_{out}(t) = C_1 \cdot q_{e,gen}(t), \tag{4}$$

where $q_{e,gen}$ is the generalized flow inside the delimited area according to (van Wageningen-Kessels *et al.,* 2014). The constant C_1 is determined by linear regression on the empirical data.

Assumption 2 *An empirical aggregate fundamental diagram for pedestrian traffic exists.* Similarly to vehicular traffic, an aggregate (or macroscopic) can be shown to exist based on empirical data. This is the case for the data used in this research and also (Hoogendoorn *et al.,* 2017). With such an assumption, a relation between the generalized flow and density can be established:

$$q_{e,gen} = F[\rho(t)] + \varepsilon_1, \tag{5}$$

where ε_1 is the error term and F some general function. Now, by combining (4) and (5) into (3), a first order differential equation linking the density to the inflows into the sensitive area appears:

$$\frac{d}{dt}\rho(t) = \frac{1}{\omega_A}\left(q_{in}(t) + q_d(t) - C_1 \cdot F[\rho(t)]\right) \tag{6}$$

As a PID controller aims a keeping the process around a targeted steady state, this equation needs to be transformed into a discrete formulation. This can be achieved by exploiting the following:

$$\bar{q}_{in} + \bar{q}_d = \bar{q}_{out} \quad \text{and} \quad \bar{q}_{out} = C_1 \cdot \bar{q}_{e,gen},$$

where the bars indicate steady state variables. Furthermore, by linearizing the function F around the target steady state density $\bar{\rho}$, one gets:

$$\frac{d}{dt}\Delta\rho(t) = \frac{1}{\omega_A}\left[\Delta q_{in}(t) + \Delta q_d(t) - F' \cdot C_1 \cdot \Delta\rho(t)\right] \tag{7}$$

which is a first order differential equation. It can be solved in discrete time using standard procedures and written as:

$$\Delta\rho(k) = e^{-\frac{\Delta t \cdot F' \cdot C_1}{\omega_A}}\Delta\rho(k-1) + \frac{1}{F' \cdot C_1}(1 - e^{-\frac{\Delta t \cdot F' \cdot C_1}{\omega_A}}) \cdot \left[\Delta q_{in}(k-1) + \Delta q_d(k-1)\right] \tag{8}$$

Equation (8) is the exact solution to (7) at the sampling intervals under the assumption that Δq_{in} and Δq_d remain constant during the intervals (Seborg *et al.,* 2010). In order to find an optimal regulator, the discrete linear-quadratic regulator approach with integral action is considered (Dorato and Levis, 1971). The augmented state-space equation is then:

$$\begin{bmatrix} \Delta\rho(k) \\ q(k) \end{bmatrix} = \begin{bmatrix} e^{-\frac{\Delta t \cdot F' \cdot C_1}{\omega_A}} & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \Delta\rho(k-1) \\ q(k-1) \end{bmatrix} + \begin{bmatrix} \frac{1}{F' \cdot C_1}(1 - e^{-\frac{\Delta t \cdot F' \cdot C_1}{\omega_A}}) \\ 0 \end{bmatrix} \Delta q_{in}(k-1) \tag{9}$$

$$y(k) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\rho(k) \\ q(k) \end{bmatrix} \tag{10}$$

where $q(k)$ is the integral action. The gain matrix can be solved using any standard software with a discrete linear-quadratic regulator solver. Two weighting matrices must be provided to solve the LQR problem. At this stage, we chose to fix the relative weights to 100. This ratio will be refined in the future. The gain matrix is used as follows:

$$\Delta q_{in}(k) = \begin{bmatrix} 0.5421 & 0.0897 \end{bmatrix} \begin{bmatrix} \Delta\rho(k) \\ q(k) \end{bmatrix} \tag{11}$$

This regulator can then be used to control the pedestrian flow into the sensitive zones behind the gates.

3.4 Flow separator

The objective of flow separators is to prevent counter flow by directing opposing pedestrians flows in different parts of the corridors. Figure 2 shows an example of its application. This can be achieved dynamically by adjusting the width available to each opposing flow. Here, we assume that pedestrian comply with to the sub-corridor dedicated to their direction of travel. The width dedicated to each flow is proportional to the flow measured upstream of the flow separator's position. Based on the notation presented in Figure 2, the width dedicated to the flow moving from A to B is expressed as follows:

$$w_{AB} = \begin{cases} w \cdot f_{min,AB}, & \text{if } \dfrac{\sum q_{in,A}}{\sum q_{in,A} + \sum q_{in,B}} \leq f_{min,AB} \\ w \cdot f_{max,AB}, & \text{if } \dfrac{\sum q_{in,A}}{\sum q_{in,A} + \sum q_{in,B}} \geq f_{max,AB} \\ w \cdot \dfrac{\sum q_{in,A}}{\sum q_{in,A} + \sum q_{in,B}}, & \text{otherwise} \end{cases}$$

where w is the total width of the corridor, $f_{min,AB}$ and $f_{max,AB}$ respectively the lower and upper bounds of the fraction of corridor which can be occupied by the flows moving from A to B.

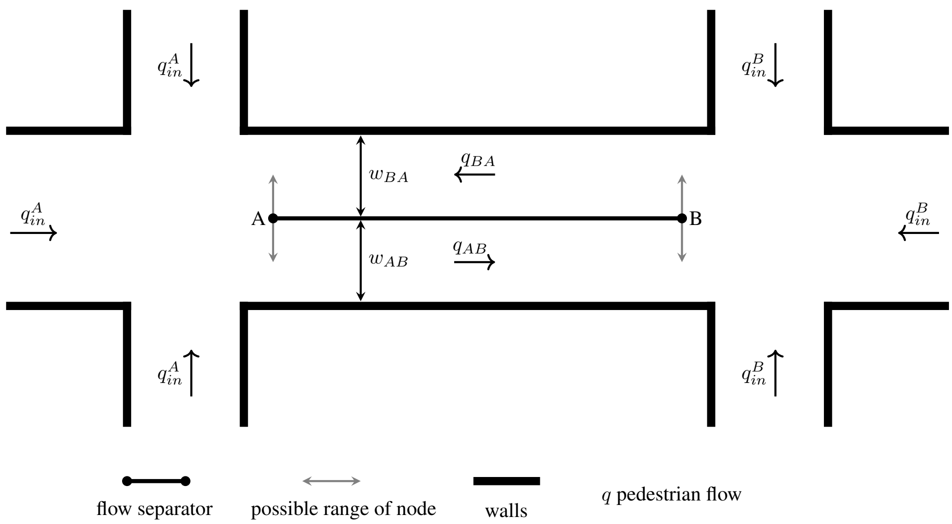

Figure 2: Schematic presentation of the devices used to separate the opposing flows. The inflow at each end determines the width available to each directed flow.

3.5 Measuring effectiveness

Measuring the impact of a given management strategy requires a comprehensive view of the objective of each the strategy and a thorough understanding of the dynamics at work. The objective of the management strategies presented in the previous section is the reduction of travel time and travel time variability, hence the indicators used to measure the effectiveness must reflect this. The most significant source of variability comes from congestion (Moussaid *et al.,* 2012), which is spatio-temporally dependent. As inter-pedestrian variations in walking speed cannot be controlled, the action of the strategies must be to manage the density in a positive way. Although somewhat counter-intuitive, a decrease in travel time variability could be achieved by allowing densit to increase in some areas of the station.

Trips with similar nominal distances can be grouped together when computing the indicators.

This way, all pedestrians, independently from the origin or destination are taking into account. This implies that there is no spatial dependency. To measure the variability of travel time over time, pedestrians are grouped by departure time and similar OD lengths. Therefore for a fixed time interval, each pedestrian belongs to one interval. Then, the mean travel time per interval is computed. Finally, to obtain an index which can be compared over different simulation runs (or days for empirical data) the mean and variance of the departure-time means are computed. The management strategy's objectives can then be quantified by minimizing this mean and variance computed over multiple runs as the process is stochastic.

4 Expected results

The management strategies are implemented inside a discrete event simulator. The pedestrian motion model which is used is the NOMAD model (Campanella *et al.,* 2014). The shortest path algorithm is used for modelling route choice. The case study used to evaluate the two strategies is one of the pedestrian underpasses of the current train station in Lausanne, Switzerland. Pedestrian tracking data has been collected in 2013. This data is used to validate the pedestrian simulator and provides a realistic demand for the evaluation of the effectiveness of the strategies.

5 Conclusion

Two management strategies for controlling pedestrian flows in train stations are proposed. These strategies should improve the pedestrian dynamics by preventing excessive congestion from occurring and by separating opposing flows. These strategies can be used not only in transportation hubs but various infrastructures where high density occurs, like conference centers or airports.

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