The benefits of preventing pedestrian counter flow

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1 Introduction

The need to use pedestrian infrastructures to their full capacity is important given the limited space which is available in densely inhabited areas. This is particularly true for train stations as the demand in unequally spread over time and space. Similarly to road traffic, pedestrian traffic suffers from congestion with the corresponding negative effects. These can be increased travel time, poor level-of-service or excessive traveled distance. For vehicular traffic, many control and management strategies have been developed in order to counteract the negative effects. Nevertheless, the strategies themselves are not sufficient to improve the traffic dynamics. These must be integrated within a larger framework which is capable of evaluating the current traffic conditions and then applying the control strategies based on an evaluation of the current state. Such frameworks are called "Dynamic Traffic Management Systems", abbreviated DTMS (Mahmassani, 2001; Papageorgiou, 1990; Ben-Akiva et al., 2010).
Many different control strategies have been proposed for vehicular traffic. They can be either reactive or anticipative (or proactive). Strategies like the ALINEA ramp metering (Papageorgiou et al., 1991) or signalized intersection control (Diakaki et al., 2002; Hu and Mahmassani, 1997) are examples of reactive strategies. Anticipative strategies on the other hand predict the future state of the system and then take the best decision, an example is anticipative traffic lights (Lämmer et al., 2008) or (Lämmer and Helbing, 2008). 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.
The need for accurate, efficient and reliable pedestrian models for traffic management inside train stations is motivated in Dubroca-Voisin et al. (2019). 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. Therefore, in order to improve the usage and level-of-service of pedestrian infrastructures, we propose a DTMS for pedestrians and one pedestrian specific control strategy for improving the pedestrian dynamics. The goal of this control strategy is to separate the pedestrian flows by direction.

2 Methodology

The specificities of pedestrian traffic requires adaptations to a classical DTMS and a complete overhaul of the control and management strategies. These changes are detailed in the following sections. But first, we define a terminology regarding the control strategies to clarify the discussion. The difference between control and information is made with respect to compliance. Control strategies impose some actions, while information allows the individuals to decide whether to follow or not the guidance. Strategies can be reactive if they take decisions based on measurements or anticipative (or proactive) if they rely on an estimation of the future state of the system. Finally different subparts of a "control strategy" need to be defined. The control *devices* are the physical objects which are used to enforce the control strategy. They are updated based on the output from the control *policy* which takes the state of the system as input and returns the updated state of the devices.

2.1 DTMS for pedestrians

All dynamic traffic management systems rely on the traffic dynamics. The latter can be either real-world scenarios when the DTMS is applied in real situations, or a simulation when the objective is to explore the possible control strategies. Naturally, a DTMS focused on pedestrian traffic follows the same general rules. At this stage, we focus on the second option: using a simulation framework for testing and designing management strategies.

Pedestrian traffic Pedestrian traffic can be modeled using many different motion models. These can be macroscopic, mesoscopic or microscopic (Duives et al., 2013). Each category of model addresses the trade-off between computational time and the level of detail in different ways. The macroscopic models are generally fast to compute, but pedestrian specific information is not available. Microscopic models provide highly detailed information about the individual agents but can be very expensive to compute. And finally, mesoscopic models lie in-between: they provide some information regarding groups of individuals without the excessive computational time.
The choice of models depends on the scenario under investigation. If the scenario involves a compact infrastructure and the control strategies require disaggregate information, then a microscopic simulator would be better. On the other hand, very large scale infrastructures with strategies impacting pedestrians at an aggregate level do not require the agent-based models as they do not impact the individuals. This allows for faster motion models as the computational cost is lower. Nevertheless, no explicit rule can be defined. This decision relies strongly on the context.
Motion models as described previously are not sufficient for pedestrians to navigate around infrastructures. A route choice model is required to address the tactical decisions. There are multiple paradigms for modeling route choice. Graph-based (Kneidl et al., 2012) and potential-based (Guo et al., 2013) are two common approaches which can take into account congestion.

State evaluation & controller policy The state of the system is monitored through various KPIs which can take into account different aspects of the pedestrian dynamics. This can be done with actual measurements from the system (density, flow, speed, etc) but predictions can also be incorporated to include information about the future (model predictive control Bellemans et al. (2006)). Data which comes from measurement devices is denoted as $\tilde{\cdot}$ and data coming from predictions is denoted $\cdot^{+}$.
The controller policy will then use the state estimation to take the required action based on the specific controller. Here, the policy can include an optimization process in order to improve the quality of the control. This can be a simulation-based optimization (SBO) framework for example. The challenge for real-time control is the computational effort of these methods.

Control devices The most significant difference between a DTMS for pedestrians and one for road traffic resides in the possible control strategies. Unlike vehicles, pedestrians (generally) are not constrained by lanes nor regulations. This means pedestrians have many more degrees of freedom. Therefore to control the pedestrian's movements, either completely new elements must be introduced (like gates, traffic lights, lanes) or strategies must "softly" influence the pedestrians. For example, soft strategies could attract the pedestrians to less crowded areas by using "points of

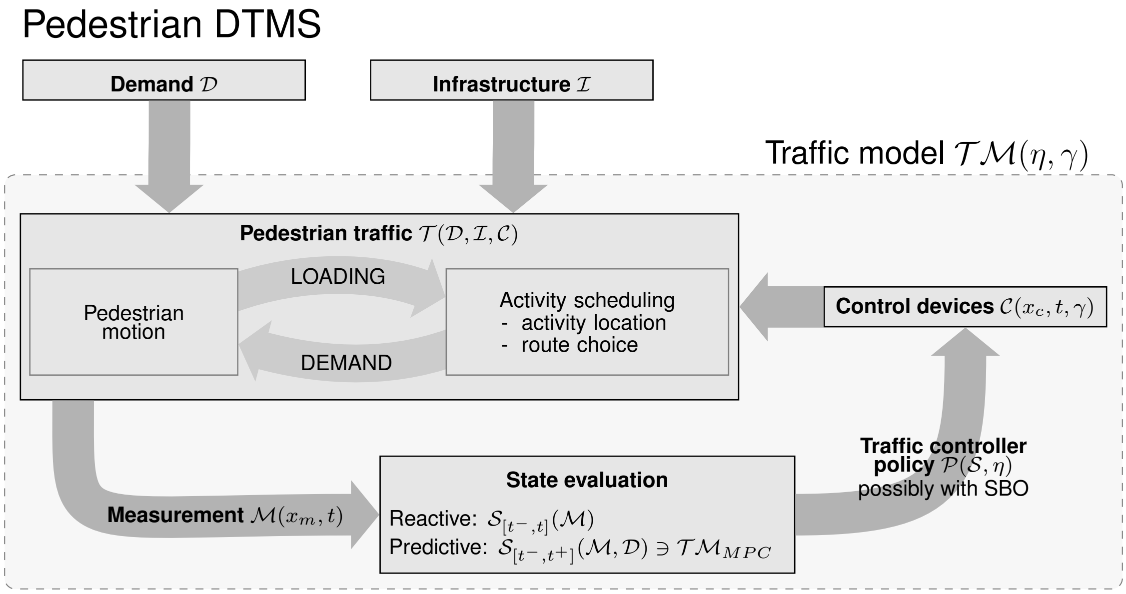


Figure 1: Dynamic traffic management system (DTMS) for pedestrians.

interest" or more directly by providing information. The major drawback and challenge regarding "soft" strategies is the pedestrian compliance. Some individuals will choose to follow the guidelines, while others won't.

2.2 Dynamic pedestrian flow separators

As experienced by many individuals and shown in studies Burstedde et al. (2001), counter flow in pedestrian traffic is responsible for a significant increase in travel time. This happens as people have to "slalom" between the people coming in the opposite direction. In order to prevent this, we propose a control strategy for preventing counter flow in corridors: flow separators. Counter flow can be prevented by splitting the corridors dynamically based on the pedestrian flows coming in each direction. Figure 2a presents a schematic setup where a flow separator is installed in a corridor.

This strategy is open-loop. There is no feedback from the controller to the policy. The width available for the pedestrians moving from A to B is function of the flows going from A to B and the flows going from B to A. These flows can either be measured (past or present) or predicted (future):

$$w_{AB} = f(\tilde{q}_{AB}, q^+_{AB}, \tilde{q}_{BA}, q^+_{BA}), \tag{1}$$

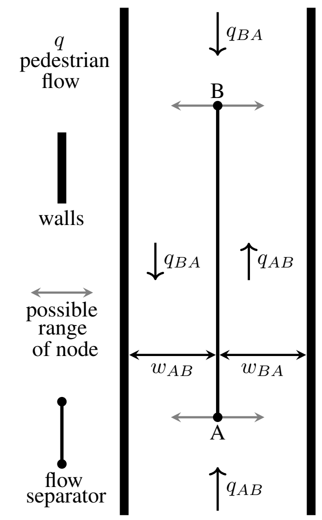
where w_{AB} is the width dedicated to pedestrians walking from A to B, $\tilde{q}_{AB}$ is the measured flow from A to B, q^+_{AB} is the predicted flow from A to B.

Making the strategy operational requires specifying the function f. Not only can the measured and predicted flows be combined in various ways, but the functional form can also change. In general, increasing the complexity of the functional form increases calibration complexity. Therefore to keep the calibration to a strict minimum, we propose a function which depends only on the measured flows at the current time:

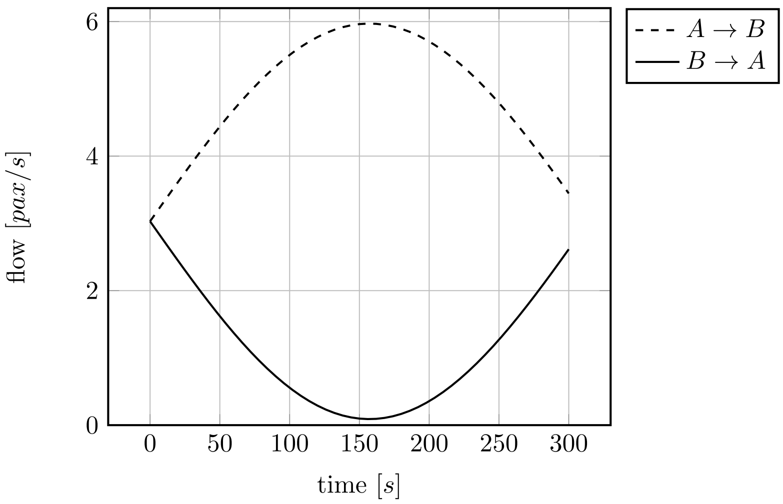
$$w_{AB}(t) = f(q_{AB}(t), q_{BA}(t)), \text{ with} \tag{2}$$

$$f(q_{AB}(t), q_{BA}(t)) = w \cdot \frac{q_{AB}}{q_{BA} + q_{BA}} \tag{3}$$

where w is the total corridor width. This way, the width dedicated to each direction is proportional to the flows. In order to prevent the width dedicated to a specific direction from becoming too small for pedestrians to move freely, there are lower and upper bounds on the widths. These bounds, denominated w^{min}_{AB} and w^{max}_{AB} correspond to the minimum width required by an individual to walk



(a) Dynamic flow separator.



(b) Demand pattern used to evaluate the flow separator.

Figure 2: Schematic presentation of the flow separator (left) and the demand pattern used to evaluate the effectiveness of the flow separators.

comfortably along a corridor (Weidmann, 1993). The full specification of the width, at time t, dedicated to pedestrian walking from A to B is therefore:

$$w_{AB}(t) = \begin{cases} w_{AB}^{min}, & \text{if } w \cdot \dfrac{q_{AB}}{q_{AB}+q_{BA}} \leq w_{AB}^{min} \\ w_{AB}^{max}, & \text{if } w \cdot \dfrac{q_{AB}}{q_{AB}+q_{BA}} \geq w_{AB}^{max} \\ w \cdot \dfrac{q_{AB}}{q_{AB}+q_{BA}}, & \text{otherwise} \end{cases} \tag{4}$$

3 Results

The control strategy presented in the previous section has been implemented in a pedestrian simulator. This simulator uses the pedestrian motion model from NOMAD (Campanella, 2016). First, the impact of the dynamic flow separator is compared to the "no strategy" situation and a static version of the flow separators. The static version is a fixed separator in the middle of the corridor. Secondly, the effectiveness of this control strategy is shown for different demand levels. Finally, a sensitivity analysis to the compliance (i.e. following the rules) is accomplished. The demand pattern shown in Figure 2b is used to evaluate the effectiveness of the dynamic flow separators. The demand various following two sine functions with a shift in the period. We chose such a pattern as this is a rough approximation of the flows which can occur inside a train station when trains alight their passengers. This demand pattern is used in all numerical experiments, except in some cases the amplitude is changed.

As the simulation is a stochastic process, multiple runs of the same setup must be performed to evaluate the stability of the process. From each of these simulations, one indicator is computed (either the median or the variance of the travel times), then we consider the mean of this indicator across simulations. Therefore we have either the mean of medians, or the mean of variances to consider.

Influence of dynamic flow separators

The flow separators are tested on the short section of corridor presented in Figure 2a. The objective is to decrease the travel time and also the variation in travel time of the pedestrians. The improvement is significant when comparing the "no separator" scenario to the "with separator" scenarios

(Figure 3). The number of simulations to perform has been determined by using Figure 4, where the mean square error (MSE) is computed using bootstrapping. This technique is used since no analytical solution exists for estimating the MSE of the medians. The number of simulations required to guarantee an acceptable MSE is fixed at 60. The MSE is already acceptable for our purpose and it decreases slowly after this point. For all subsequent simulations, we target 60 replications.

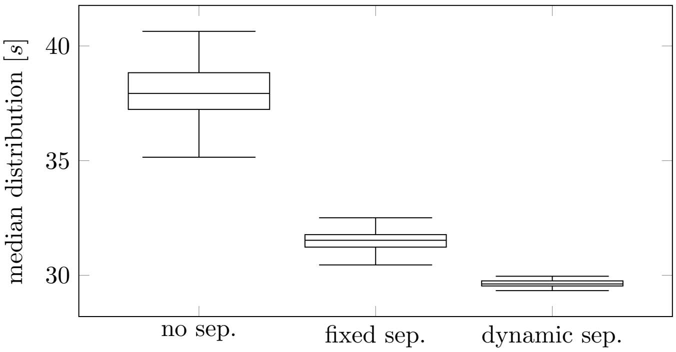


Figure 3: The pedestrian flow separators are very efficient for reducing the travel times. 100 simulations were performed, and for each simulation the median travel time is computed. The boxplots of the medians per scenario show that the travel time and variance in travel time are significantly reduced.

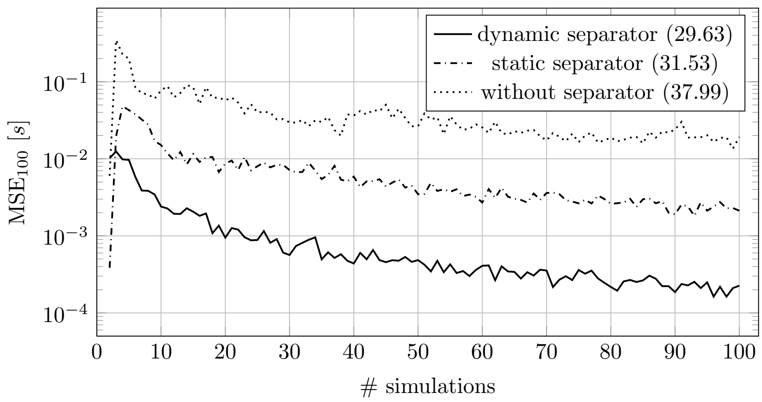
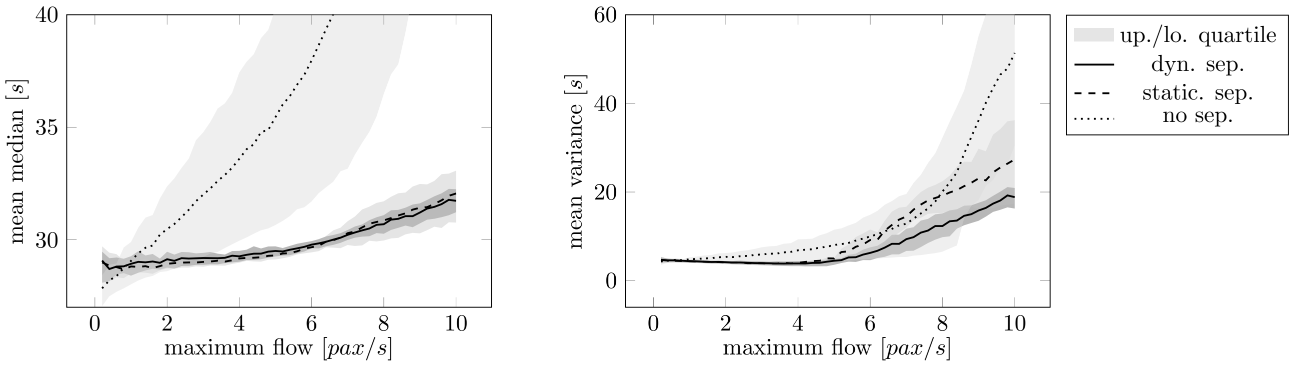


Figure 4: The mean square error computed using bootstrapping for the three scenarios. The usage of flow separators means the required number of simulations to reach a given error is significantly lower.

Naturally, flow separators will not be efficient for all scenarios and demand patterns. In order to explore the flow domains where the flow separators are efficient, the same demand pattern is used but the amplitude is changed. The results from this sensitivity analysis to demand are presented in Figure 5. For very low demand levels, the flow separators induce a small increase in travel time since the pedestrian must add a small walking distance to cross the corridor to the same side. This excess is quickly compensated as from a demand of 1.0 passengers per second the flow separators are beneficial when considering the medians of travel times (Figure 5a). If we consider only the medians, then dynamic flow separators have little benefit on the travel times compared to the static flow separators. Nevertheless, when considering the travel time variance per simulation, the dynamic flow separators are beneficial for the pedestrians. At high demand levels, the variance is significantly lower when dynamic flow separators are used instead of static ones (Figure 5b).

Sensitivity to compliance

As pedestrians are generally not restricted in their movements, nothing enforces the pedestrians to follow the rules. Therefore, the impact of compliance to the rules is explored in this section. The objective is to explore the cost induced by a small percentage (5% or 10%) of the pedestrians taking the sub-corridor dedicated to the opposite walking direction.
Figure 6 presents the travel time variance for full compliance, 5% and 10% of un-compliant pedestrians. Figure 7 shows the median travel time per direction for the three compliance scenarios. When considering Figure 6, it is clear that the case with 100% compliance shows the lowest variance in travel, which is expected. As already seen from Figure 5b, the dynamic flow separators present clear advantage as they keep the variance lower compared to a static separation of flows. This



(a) Mean of median travel times.

(b) Mean of travel time variance.

Figure 5: Travel time median and variance analysis for the different scenarios considered. The bands indicate the upper and lower quartiles of the distributions.

behaviour is also true for cases where a small percentage of pedestrians do not follow the rules. The dynamic flow separator keeps the travel time variance significantly lower than the static case, this is indicated by the gray lines being above the corresponding black lines from Figure 6.

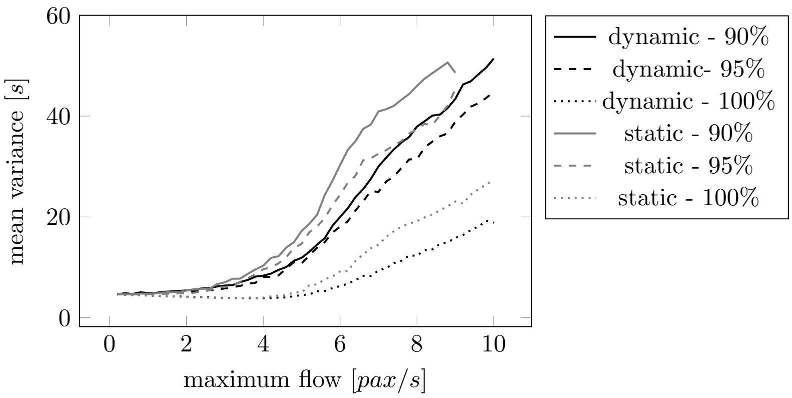
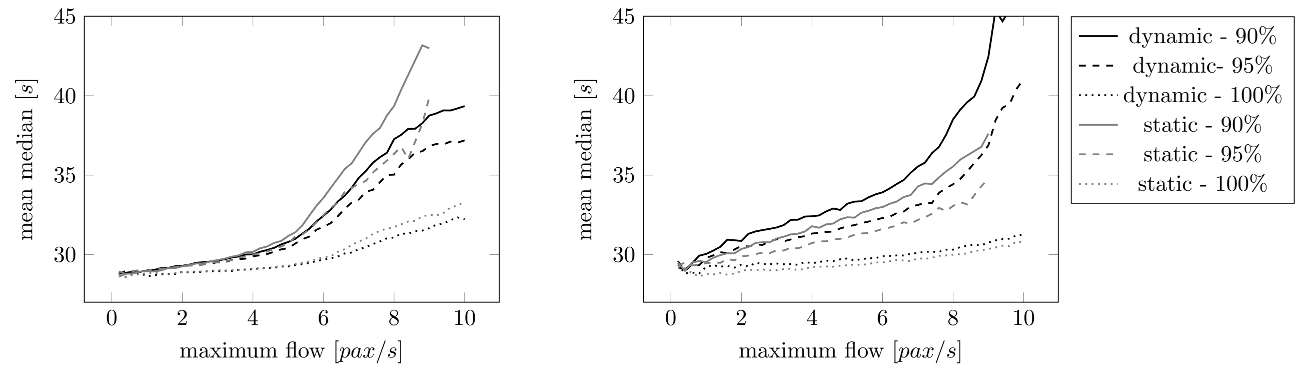


Figure 6: Comparison of the travel time variance between the static flow separators and the dynamic ones for different compliance levels. The dynamic flow separators effectively reduce the variance in travel time for higher demand levels.

By analyzing the travel time medians per direction, we can see two opposite situations. The pedestrian flow going from A to B is the dominant flow, while the opposite flow from B to A is the dominated one (i.e. a small group of people moving against a larger group). First of all, the general behaviour of the dynamic flow separator is to give more space to the larger flow. This means that the dominant flow will generally benefit from this strategy, while the dominated flow will see it's reserved space decrease. Hence it is generally penalized by this approach. The impact on the travel times will therefore reflect this idea, as seen in Figure 7. When comparing the dynamic to the static flow separator for the dominant flow (Figure 7a), the dynamic flow separator is beneficial for this group. On the other hand, for the dominated flow (Figure 7b) the opposite is true: the dynamic version increases the travel times of the pedestrians. This happens because this group has less space to move around in, hence creating higher congestion.



(a) Pedestrians moving from $A \to B$.

(b) Pedestrians moving from $B \to A$.

Figure 7: Travel time comparison for the opposing directions with different compliance levels. The dynamic flow separators are useful for reducing the impact of the uncompliant pedestrians.

4 Conclusion

The DTMS framework can effectively be used to control the movements of pedestrians inside a proof-of-concept case study. The separation of pedestrian flows dynamically is efficient for decreasing travel time and travel time variations. Both the static and dynamic variations are very efficient compared to the "no control" scenario. We showed that the dynamic aspect is beneficial for preventing the degradation of travel time when all pedestrians are not compliant. The other important benefit for pedestrians is the reduction in variance in travel time. This is important when pedestrians need to reach their destination at a precise time (for example to catch a train). Having a reliable travel time can be more important than a slightly faster trip.
The next steps include the evaluation of the control strategy in a more complex environment, like a subpart from a train station. This opens the question about a coordinated version of these flow separators. Secondly, a more realistic demand pattern can be used. Finally, different control strategies like gating or moving walkways can be investigated.

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