
Analysis and modelling of intra-hub pedestrian dynamics

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This report is based upon the work we performed in the context of the European project TRANS-FORM. At EPFL, our tasks mostly focused on intra-hub data analysis and modelling. Several members of the lab collaborated on the TRANS-FORM project: Riccardo Scarinci, Yuki Oyama, Nikola Obrenovic and Shadi Sharif Azadeh. The following academic and industrial partners were involved in the project:

- Delft University of Technology (Netherlands)
- Blekinge Institute of Technology (Sweden)
- Linköping University (Sweden)
- École Polytechnique Fédérale de Lausanne (Switzerland)
- IBM Research (Switzerland)
- ETRA (Spain)

1 Introduction

The TRANS-FORM project, carried out by a European consortium mixing research partners, industrial partners and stakeholders, was devoted to analysing and managing passenger transfer experience in public transport networks. It is common for passengers to transfer between different services when commuting to their work locations. Each time an individual leaves one public transport (PT) vehicle and gets on another, he uses a transfer location to change service. Transfer locations range in size from small bus stops to multi-story train stations. The larger transfer locations are called “hubs”. Hubs can typically include light rail and bus stops, regional train connections and even international train lines. Such hubs therefore act as connecting links between the different public transport modes and lines. Public transport networks can be divided into two levels. On one hand, urban networks provide public transport services inside a densely populated area. On the other hand, regional networks provide such services in between different densely populated areas. Nevertheless, in some cases a clear demarcation cannot be made and public transport services belong to both levels.

While the exchange hub lies in between the urban and regional levels when

a passenger's trip is considered, when dynamics are considered, the hub level boasts the fastest changing dynamics. The level-of-service inside a hub can significantly change within a matter of minutes. High spatial and temporal variations are observed in normal operating conditions. In case of disruptions or disturbances in the public transport network, consider an interruption of most of the trains inside a large station for example, negative effects like high congestion or missed connections can occur. In extreme cases, dangerous situations can occur if pedestrians enter the hub but cannot leave on their scheduled service. Therefore, measures must be taken to prevent such hazardous situations and poor level-of-service from occurring. Since the intra-hub conditions can be problematic, control and management strategies to mitigate the negative effects of PT disturbances/disruptions which consider both the public transport network and the intra-hub dynamics should be considered.

Prior to developing such risk mitigation strategies, the pedestrian dynamics taking place inside the hub must be understood. Furthermore, the interactions between the intra-hub pedestrian flows and the public transport services must also be explored. Therefore, regarding the hub level, the TRANS-FORM project aims at improving our understanding of pedestrian dynamics inside hubs and investigating the connections between public transport networks and hub pedestrian dynamics. With this report, we consider whether the inclusion of pedestrian dynamics in the decision process of scheduling or disturbance/disruption management has the potential to improve passenger welfare. This is achieved by exploiting pedestrian tracking data collected inside an existing infrastructure and by developing an integrated modelling scheme for hub dynamics and urban public transport networks.

This report is structured as follows. After this introduction, we present the relevant literature on multi-modal coordination in public transport networks. After that, we present some metrics dedicated to the monitoring of pedestrian dynamics. Following the theoretical considerations, we present the results from the analysis of the pedestrian tracking data. Next, the modelling assumptions and considerations are discussed and the results from the urban and hub integrated modelling are shown. Finally, we conclude this report and discuss some ideas for future work.

2 Literature review

Many different modelling schemes (microscopic, mesoscopic and macroscopic) exist and have been applied to a large variety of cases studies. Nevertheless, such models are scarcely used to include intra-hub dynamics into PT scheduling schemes. The following literature review presents the methods for including intra-hub dynamics in public transit models. This is done both for regular operations and in the case of disruptions or disturbances.

Transfer time is generally considered in railway scheduling and timetable synchronization problems. The coordinated railway scheduling problem is addressed in Cao et al. (2019). The authors propose a methodology for including variable transfer times in large scale problems. Although they relax the constraint where the transfer times are considered constant, the walking transfer time interval is considered independent from the pedestrian dynamics.

In Yap et al. (2019), the authors propose a methodology for reducing the complexity of the timetable synchronization problem by identifying which hubs should be prioritized when synchronization must be applied. The walking transfer time is integrated into the problem by using a low percentile of the walking speed and the walking distance as cut-off criteria. Although this approach improves the realism in the expected transfer time computation, extra travel caused by congestion is not considered.

A methodology for proposing public transit routes considering crowdedness inside hubs is proposed in Du et al. (2018). Nevertheless, the authors consider the median travel time per demand period. Although different demand periods are considered, a scalar is still used to report the walking transfer time and distance.

In the case of disruptions, transfer walking times are rarely considered. A review of metro (subway) disruption management strategies is presented in Zhang et al. (2021). Except from estimating the demand change when disruptions occur, the authors never mention any explicit consideration of walking transfer times inside the management strategies. They conclude that little research has been led on a multi-modal approach to public transport disruption management. Many disturbance and disruption management strategies aim at minimizing passenger waiting time, but don't consider realistic transfer walking times. Strong assumptions are made re-

garding time required by passengers to transfer on foot (Qu et al., 2015; ?). Identification of passenger transfers from smart card data provides valuable insight into the choices passengers make. Nevertheless, this is challenging since the operator has no a priori knowledge on the passenger’s origin or destination or trip purpose. Multiple methodologies exist for inferring these transfers based upon the data (Yap et al., 2017; ?). In general, the modelling assumptions made to propose a solvable formulation to the timetable synchronization problem include a fixed and static scalar value for the transfer walking time. Although the solution algorithms consider this walking transfer time, such an assumption is unrealistic in practice. The transfer time depends on the socio-economic characteristics of each passenger, the prevailing pedestrian traffic conditions inside the hub and other exogenous aspects like the weather for example (Wu et al., 2015). Maybe the most advanced methodology for considering passenger assignment in public transit networks and intra-hub dynamics can be found in HÄnseler et al. (2020). The authors include mesoscopic intra-hub models for each station in the network. The focus of this work is the description of in-vehicle congestion and platform usage. The authors emphasize that their methodology is tailored towards high-demand scenarios. Without being exhaustive in the literature review, we see that strong assumptions regarding the transfer times are generally made when solving the timetable synchronization problem or considering walking transfer times. The benefits for users of relaxing the assumptions by considering more realistic transfer times is yet underexplored. Before presenting the integration considerations between the hub and urban models, we discuss metrics for monitoring pedestrian dynamics and the results of the data analysis. By doing so, we expect to gain further understanding of the dynamics taking place inside transfer hubs.

3 Pedestrian centric indicators

A prerequisite to modelling and understanding the pedestrian dynamics which take place inside walkable environments is having metrics to measure such dynamics. The existing methodologies for measuring service characteristics are evaluated in terms of their ability to reflect the actual (provided) level-of-service from a passenger’s perspective at the hub level.

When considering the variability and reliability of the performance of a hub, many different metrics and indicators of different complexity can be defined. The challenge lies in the identification of meaningful indicators which can be consistently evaluated and for which data is available. The following indicators are put forward.

Travel time The time pedestrians take to perform the origin-destination trip inside the hub is maybe the most critical indicator which can be identified. As an individual plans ahead the time required for reaching the platform from the entrance of the hub (for example), the variability of travel time is critical in assessing the performance of a hub. The distribution of travel times can change depending on different factors like congestion, construction work or even the users themselves.

Travel distance Similarly to travel time, the distance travelled by pedestrians inside the hub can provide valuable information on the variability of the system. If many individuals dwell in the highly used areas of the hub, then the passengers must extend their walking distance to avoid these “obstacles”. Likewise, many different situations can make a user divert from his ideal path to his objective, therefore inducing variability in his trip.

Pedestrian mean velocity Combining both previous quantities can be done to calculate mean velocity. The division of travel distance by travel time is defined as the pedestrian mean velocity. Pedestrians can be classified into different groups based on variables like age or trip purpose and these different behaviours will imply different free flow velocities.

Transfer reliability Missing a connecting train often leads to long travel time extensions. The transfer time between two platforms is critical when considering this aspect and any extra walking time between platforms can be problematic for pedestrians with short connection times. The transfer reliability can be computed by counting the fraction of people who managed to catch their connection. This approach allows a definition of transfer reliability for different spatial and temporal aggregations.

Pedestrian density Different methods for computing density exist in the literature. Pedestrian centric measures can be obtained by using Voronoi

tessellations. Classical average values can be obtained by counting the number of people inside a given area. Regardless of the method used to compute pedestrian density, it is critical to prevent excessive congestion from recurrently taking place since this can lead to dangerous situations. Furthermore, density is the most common method used to measure level-of-service (LOS) inside pedestrian infrastructure (Fruin, 1971).

These different metrics, travel time, travel distance or velocity for example, can be used to gain insight about daily or hourly variations of level-of-service inside the hub. Moreover, bottlenecks can be identified for a specific geographical place and a specific time inside the hub. This information can help planners to come up with better resolutions in case of a disruption or disturbance which may cause problems in the hub. Naturally, these indicators depend on the availability of the data. In some cases, all the indicators discussed previously cannot be evaluated as sufficient information is lacking.

Travel time, travelled distance and mean speed are properties of the pedestrians, while transfer reliability focuses more on the level of service of the infrastructure. Pedestrian density can be computed either per pedestrian, or per area. One common element to all indicators is the existence of variability, induced either by pedestrian specific factors (walking speed for example) or by external elements like the PT arrival times, weather, demand level, etc. In order to grasp this variability, distributions of the indicators need to be considered.

The different indicators presented above are now considered in light of the case study selected for the data analysis. The variability of the indicators is represented using histograms and other considerations relative to demand are presented.

4 Pedestrian tracking data analysis

Transportation hubs play an important role in modern cities, both for linking different public transport services but also as important infrastructures in the heart of cities. This is particularly true for the city of Lausanne (Switzerland) as the main train station serves as a link between the northern and southern parts of the city. Understanding the dynamics which

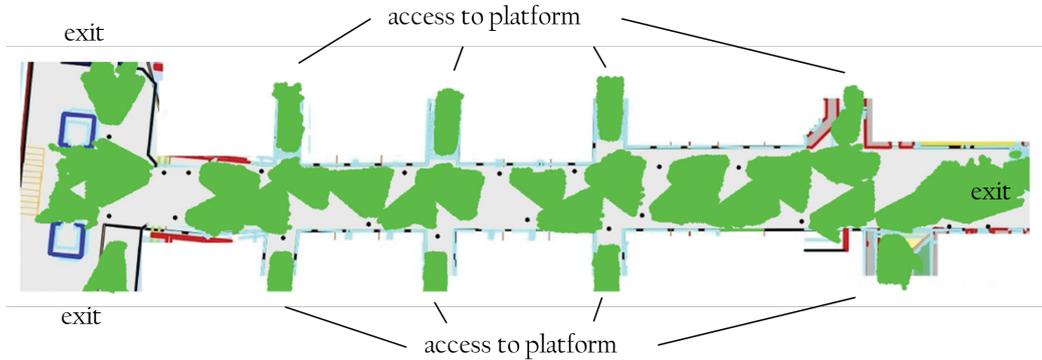


Figure 1: Geographical representation of a hub zone with tracking coverage from cameras.

take place inside a transportation hub is therefore a critical preliminary step towards integrated modelling. Many different aspects of the pedestrian dynamics can be considered. The current analysis focuses around three axes. First, the analysis of pedestrian density and the identification of the critical areas inside the hub is done. The critical areas can be entrances/exits, the junction between multiple corridors or the areas around service points. Secondly, the pedestrian flows inside the hub are explored. “Origin-destination” demand is analysed by using historical data and considering the flow’s source. Finally, pedestrian walking speed and travel time are summarized. The walking time distribution is critical when individuals transfer between different public transport services.

The analysis is carried out on pedestrian tracking data which has been collected inside both pedestrian underpasses of the station in Lausanne in 2013. Figure 1, taken from Lavadinho et al. (2013), shows the geographical representation of a zone in the hub. In this case, the zone is a pedestrian underpass (PU) connecting platforms and station exits in Lausanne train station. The areas marked in green indicate the field of view of the tracking sensors.

The overall demand in Lausanne’s train station during the morning peak hour is summarized in Figure 2. The available dataset includes ten days of tracking data. Systematic differences are visible when comparing the demand in both underpasses. The western underpass is used by more

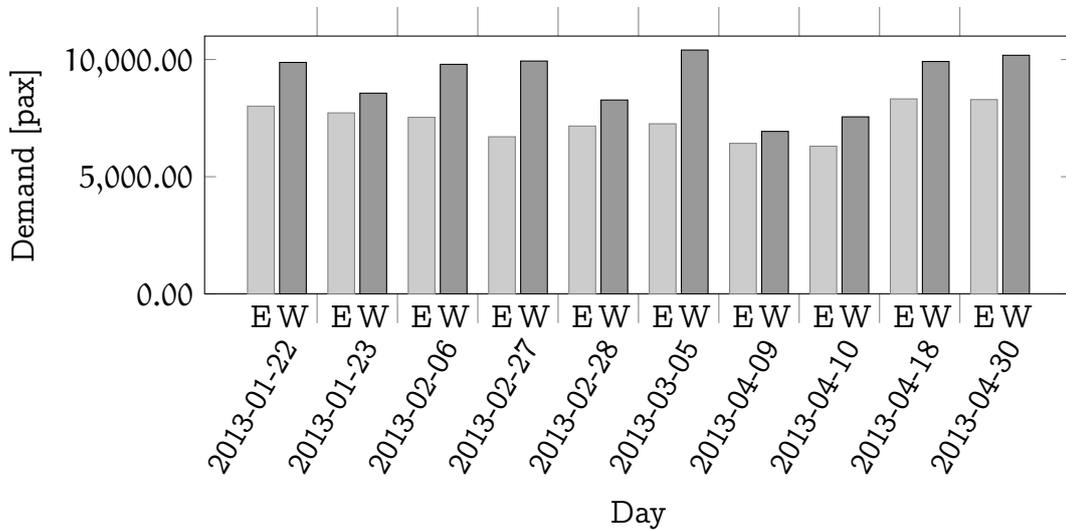


Figure 2: Daily demand in both pedestrian underpasses (East and West) during the morning peak hour (7:00 to 8:30).

individuals than the eastern underpass. The significant drop in pedestrian demand for the 9th and 10th April 2013 is certainly due to the easter school holidays which covered that week. Naturally, daily variations take place. Further analysis considering socio-economic characteristics was done in Lavadinho et al. (2013).

Flows To visualize the importance of the “transit” aspect of the station, a chord diagram is used (Hänseler et al., 2016). A chord diagram shows the distribution of pedestrian flows between different OD pairs in the station. Naturally, the train platforms attract most of the pedestrians, but people do come to the station for shopping (red bands) or simply traversing the station (North to South and vice-versa).

Another possibility for visualizing the pedestrian flows in the underpasses is by plotting each individual trajectory such that higher occupied zones become darker, as in a heat map. The exercise is done in Figure 4, where both underpasses are visible. With this trajectory heat map, it is possible to locate the areas of the underpasses which are most used, and qualitatively estimate which platforms attract the most passengers. When comparing both underpasses, the eastern underpass (bottom) appears to suffer

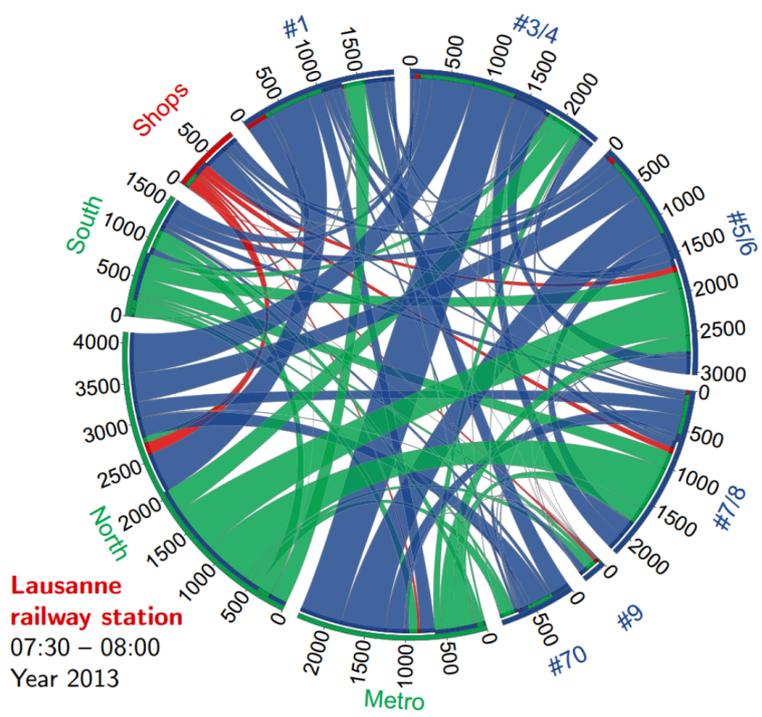


Figure 3: Chord diagram representing the flows at an origin/destination level inside the station.

less from high densities than the western underpass. This goes in the same direction as a socio-economic qualitative survey (Lavadinho et al., 2013), which indicates higher utilization of the western underpass. Furthermore, the fact that the northern exit (right in images) is more heavily used than the southern one is also visible. Finally, some artificial high density zones are created from the network of cameras. In PUE (bottom image), some polygonal areas appear through high density areas.

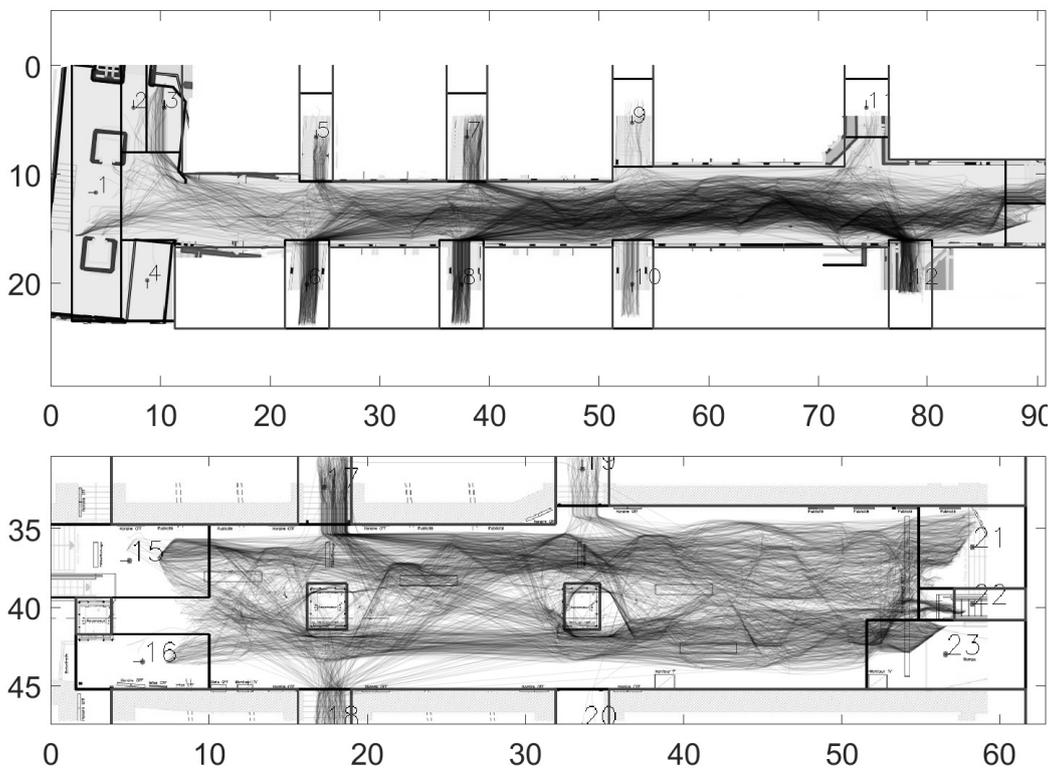


Figure 4: Subset of all trajectories for the main station in Lausanne. Only 1000 trajectories are shown and they have been smoothed using a moving-average algorithm of width 5. The axis labels are distance references in meters.

The last analysis focusing on the flows of pedestrians through the station is the location of the entrance and exit “stamps” for each individual. This is important in assessing the reliability of the data. In Figure 5 the blue dots represent entrance points while green dots represent exits. Not only

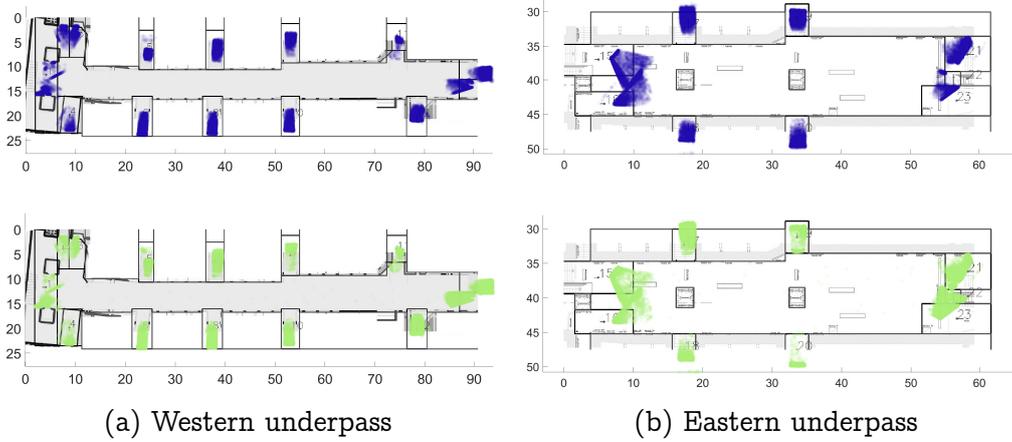


Figure 5: The entrance (top row) and exit (bottom row) points of each individual for all ten days are represented with dots.

are no points found far from the physical entrance locations (this could be the result of some filtering), but very few exit stamps are located in the middle of the underpasses (indicating the tracking system lost someone). This is encouraging as the available data set appears robust or has been filtered.

Velocities & travel time Using finite difference approximations, the velocity of each pedestrian can be calculated throughout his trip in the underpasses. The distribution of the mean speed of each pedestrian is shown in Figures 6a and 6b, for both underpasses. Although a small difference in the distributions is visible, they both have the same mean and globally share the same shape. The mean is located at approximately 1.1m/s. On the other hand, when considering the distributions of travel times in both underpasses, one significant difference stands out (Figures 6c and 6d). For the western underpass, the travel time follows a normal-like distribution, while the eastern underpass yields a truncated distribution. Although the left tail seems to be normal-like, the right tail appears truncated at travel times of 60 seconds. The cause for this behaviour is not known for sure, one possible explanation would be the variety of length of all possible trips. In PUW, there is enough diversity in the trip lengths to create a full distribution, while PUE does not contain longer trips.

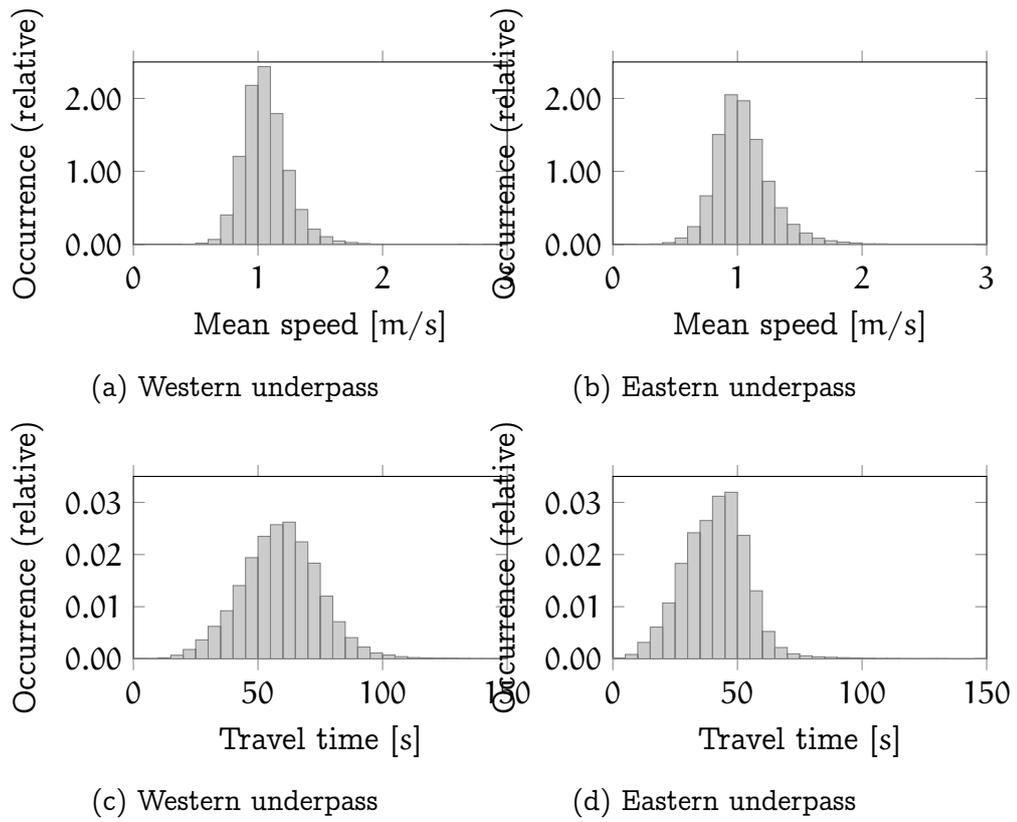


Figure 6: The distribution of mean velocities and travel times for both pedestrian underpasses.

Velocity & accumulation When combining the velocity of each individual with an estimation (approximation) of density in the underpasses, an aggregate speed-density diagram can be created. To simplify the computation and obtain an aggregate estimate of density, the accumulation of pedestrians inside an underpass is used. This is simply the count of the number of pedestrians inside an underpass at a given moment. In Figure 7, the accumulation of pedestrians inside PUW is plotted for the 22nd of January 2013. It is clear that very large variations induced by trains arriving in the station occur and one can easily image congestion taking place. In only a couple of minutes it varies from less than 50 to over 300 people. When considering the link between velocity and accumulation as in Figure 8, an interesting pattern appears. As the accumulation increases, the variability of mean pedestrian speed decreases. This converging velocity phenomenon can be explained by the pressure of the surrounding people. Individuals wishing to walk slower or faster than the average speed of the crowd cannot and are forced to follow everyone else. We can observe that for high accumulations (high density), the velocity values converge towards 1m/s.

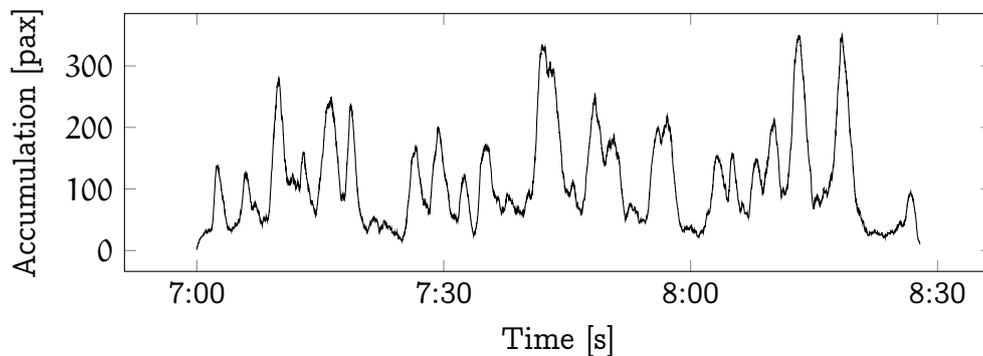


Figure 7: The accumulation of pedestrian in each underpass is highly variable.

The different indicators analysed in this section emphasized the variability in the pedestrian dynamics which take place. The demand shows significant spatial and temporal variations. Understanding the source of these variations is important in the context of disruption management and rescheduling strategies. For example, the significant variations in pedestrian accumulation inside the station is strongly linked to the arrival of

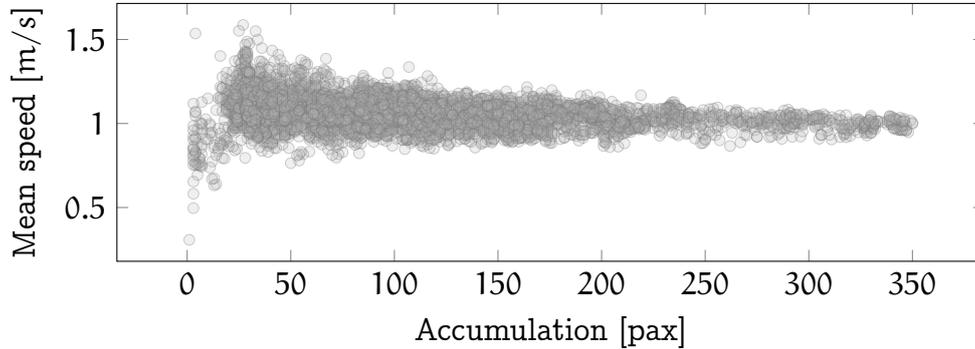


Figure 8: Each point represents the mean velocity of all pedestrians inside the infrastructure for a given interval and the corresponding accumulation in the station at that time.

trains. The integrated modelling approach will exploit this connection.

5 Hub and urban integrated modelling

As previously stated, the modelling objective of the TRANS-FORM project is to propose an integrated approach which considers both urban public transport dynamics and intra-hub dynamics. To achieve this, we first discuss the interactions which take place between these two levels. Then, we discuss some modelling assumptions which must be made at the pedestrian level.

Naturally, the pedestrian dynamics taking place inside a hub are strongly influenced by the public transport services which are alighting passengers into the infrastructure. Such pedestrian demand is endogenous to the public transport network. The demand can also be exogenous if the pedestrians arrive on foot to the hub. A pedestrian inside a hub can either take a PT service or leave the infrastructure on foot.

Although embarking pedestrians must board a PT vehicle, the PT services are not strongly constrained by the pedestrian dynamics. The vehicles can leave the hub according to the schedule regardless of the dynamics taking place inside the hub. Nevertheless, passengers could strongly benefit if the PT operators consider the prevailing intra-hub dynamics. For example, the operator can ignore the excess walking time of a transferring passenger induced by congestion inside the hub. Such a decision can lead to the

passenger missing his connection. On the other hand, if the operator integrates prevailing conditions into the decision process, then measures can be taken to allow the passengers to catch their connection.

The relationship between the hub dynamics and the PT services is therefore asymmetrical. Although the intra-hub demand and PT demand influence each other, PT operators can take actions which directly impact the transfer experience of passengers. Nevertheless, the measures which can be considered depend on the type of service. High frequency buses and international trains cannot be managed the same way. When passengers use a high frequency service, they don't systematically check the schedule before going to the bus stop. Therefore, if a passenger misses a connection he will need to wait only a short time until another vehicle from the same service arrives. On the other hand, for low frequency services, passengers take care to plan their trips such as to reduce the chance of missing the connection. In this case, a passenger who has missed his connection will suffer from a significantly longer journey time since he must wait a long time until the next service arrives.

The passenger's welfare is therefore significantly impacted by the prevailing pedestrian dynamics and the PT operator's decisions. Hence, we see the importance of understanding and integrating the intra-hub dynamics into the PT operator decision making process. Next, we discuss how an intra-hub model can provide insight about the prevailing dynamics to the PT network.

The objective of the exchange hub modelling is to provide insight to the other levels (urban and regional) about the pedestrian dynamics taking place inside the walkable environment. Therefore, a pedestrian simulator which can accurately model pedestrian congestion and route choice is required. The pedestrian demand comes from two sources: public transport vehicles and on-foot individuals. Therefore, the model must be able to accommodate this. Considering the different constraints and wishing to have flexibility, we choose to use a microscopic pedestrian simulator based upon the NOMAD pedestrian model (Campanella, 2016). Although the computational cost is higher for disaggregate simulators compared to mesoscopic or macroscopic simulators, the ability to model pedestrians individually outweighs the excessive calculation time. For example, this flexibility allows us to accurately compute OD specific statistics even for OD pairs with few users. Another advantage of using a microscopic simulator is the co-

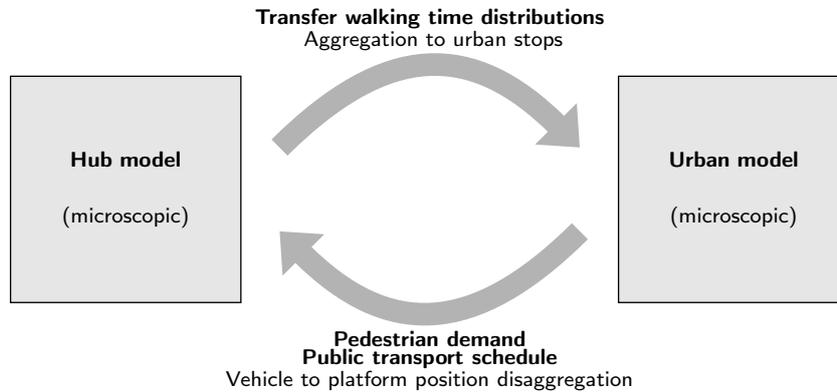


Figure 9: Hub model and urban model data exchange.

herence with the urban PT model which is used. The urban PT model is BusMezzo (Cats et al., 2010) which is an agent based model. Maybe the most critical information which is useful for the PT operators concerning the internal hub dynamics is the time required for passengers, which become pedestrians inside the infrastructure, to reach their connecting service. This transfer walking time is not a deterministic quantity since individuals walk at different speeds or have different aversion to congestion for example. The prevailing dynamics also impact the time taken to reach a given destination. In order to take into account such stochasticity of the transfer time, the walking times are provided to the PT services as distributions. The walking times between all origin and destinations are given to the PT network model. By doing so, the PT operator has quantifiable information about the prevailing dynamics inside the hub. Figure 9 summarizes the data exchange between both models.

Further modelling decisions must be made to build an operational pedestrian simulator. One critical question in the current context is route choice. Many aspects such as what information is available to the pedestrians and the subsequent user-optimal choice equilibrium are discussed in Hoogenboom and Bovy (2004). In practice, pedestrians dynamically update their route based upon the prevailing traffic conditions. Inside a simulation environment, this behaviour generates a fixed-point problem which must be solved. This is usually called the traffic assignment problem. The pedestrian assignment isn't the only fixed-point problem which takes place inside the simulation environment. Recall that the pedestrian de-

mand originates partly from public transport vehicles. On one hand, transferring passengers leave one vehicle and must walk to catch their destination vehicle. On the other hand, the number of passengers which are able to catch their connection depends on the pedestrian demand inside the infrastructure. Therefore, the demand of the public transport services depends on the pedestrian dynamics taking place inside the hub, and the pedestrian demand depends on the public transport network. This induces a second equilibrium problem between the PT networks and the pedestrian dynamics. To address this fixed-point problem, we choose to perform several sequential runs of each model. The runs of the hub model and urban model are alternated and the data transferred between them updated at each iteration. The equilibrium is reached once the exchanged data is the same between iterations.

Only a partial view of all the elements required to build an intra-hub pedestrian simulator have been discussed here. More aspects must be considered to design a functional model (Campanella, 2016). Next, we present the numerical results from the integrated modelling.

6 Hub and urban integration results

The scenario analysed for exploring the mutual influence of the hub model and the urban PT model is presented here. The exact scenario is the following successive runs of each model: Urban -> Hub -> Urban -> Hub -> Urban (UHUHU). With this setup, the influence of the hub model on the transfer location choice can be analysed. The sensitivity of the pedestrian travel times inside the hub as a function of the PT demand can also be considered. The first iteration of the urban model uses physical distance to infer transfer times. The subsequent iterations include walking time distributions from the hub model, as discussed in the previous section. The urban network of Den Haag (Netherlands) is used as a case study. The urban network covers the city and the hub considered is Den Haag central station. The pedestrian infrastructure is visible in Figure 10.

Figure 11 presents the change in median walking time between the two hub model iterations. The first observation is the absence of significant changes in demand for any given OD pair. This is visible since all points are located along the diagonal of the figure. The changes are relatively more

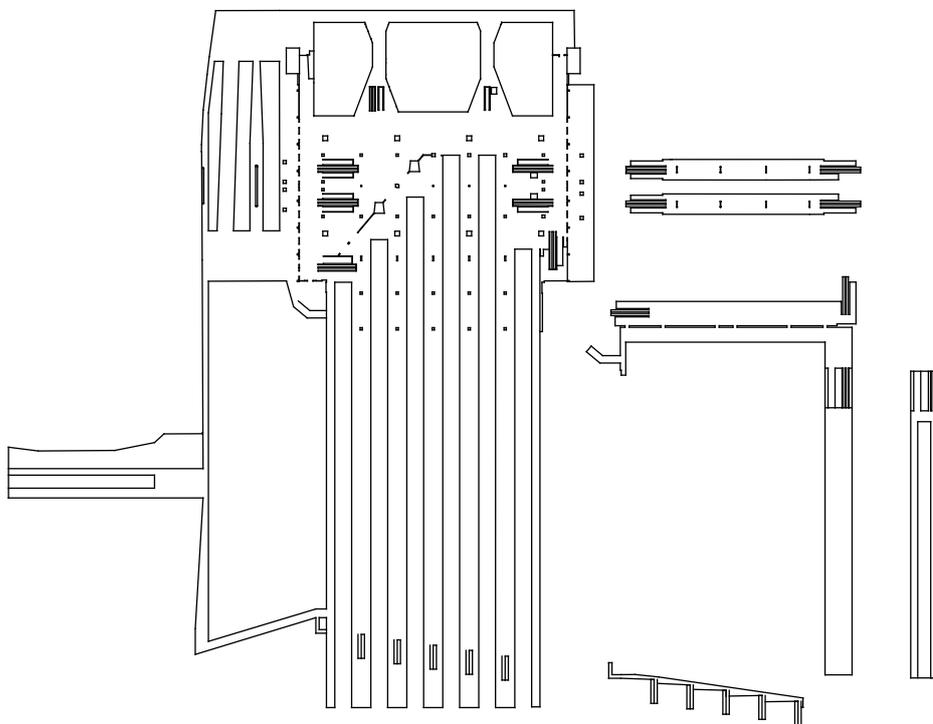


Figure 10: Den Haag pedestrian infrastructure.

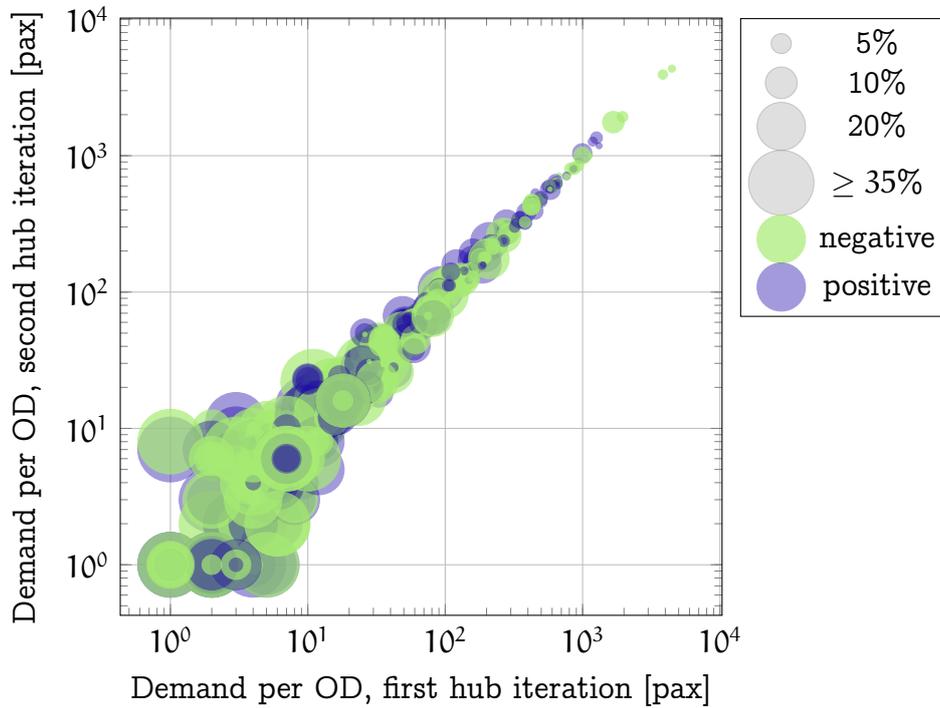


Figure 11: Change in median travel time for each origin-destination pair in the hub for two successive iterations of the hub and urban network simulations.

important for OD pairs with low demand, which is expected considering the stochastic nature of the hub model. The change in median travel time is significant for OD pairs with very low demand. This is caused by the very few pedestrians taken into account for computing this indicator. The statistical validity is questionable for these cases. On the other hand, when hundreds or thousands of pedestrians use a specific OD, then the results have stronger statistical significance. For the higher demand cases, the changes in travel time are between 0% and 10%. No systematic pattern is visible regarding an increase or decrease as a function of the demand levels. Considering these results, we can assume that most of the variations are induced from the stochasticity of the simulator.

The effect of including the distributions of transfer times in the urban model provided limited added value. There are 52 public transit lines considered in the case study. Out of these 52 lines, only 4 of them show a change larger than 10% in the number of boardings occurring. Further-

more, these 4 lines are used by less than 20 passengers. On the other hand, lines with many boarding passengers show very little change (less than 2%) in relative boardings. The change in number of passengers using Den Haag as a transfer location is small (approx. 1%), hence few passengers are affected by the inclusion of transfer time distributions.

An explanation for the limited influence of incorporating a walking time distribution can be found in the relative limited crowding levels at this particular station. Combined with the lack of narrow spaces at this specific station, this results in limited differences when using a walking time distribution compared to assuming an average walking speed. However, it can be hypothesized that more substantial differences might be found if demand levels would increase and/or this method would be applied to a station having more confined spaces.

7 Discussion & practical recommendations

The analysis of the empirical tracking data emphasized the pedestrian dynamics variability. Such results highlight the strong assumptions which are made when operators consider a fixed time for the passenger's transfer between services. Therefore, PT operators should invest effort in developing methodologies which consider transfer time variability. Considering the mean or median transfer time cannot be considered acceptable since 50% of the users would miss their connection under such assumption. A first step would be developing time dependant transfer times. During the peak hours, travel time is generally increased due to congestion. Therefore, pre-computing transfer times for different periods of the day is a manageable approach to introduce more realistic walking transfer times. Developing real-time solutions requires more complex modelling techniques and real-time data collection hardware. Regardless of whether online or offline solutions are used, exploiting transfer time distributions should ideally become the norm for PT operators when considering intra-hubs transfer times.

Integrating the urban PT model with the intra-hub pedestrian model increased the realism of each model by improving the quality of the input data. On one hand, the hub model had access to reliable and precise data regarding the origins, destinations and alighting times of each pedestrian. On the other hand, the urban model received detailed transfer time dis-

tributions for each origin-destination pair. This iterative process emphasized the low levels of congestion which take place inside the hub, hence most passengers experience free flow travel times inside the infrastructure. Therefore, the walking transfer times do not depend on the urban network. For the case study presented here, the integrated modelling provided benefit in terms of realism and detail, but the iterative process presented no benefit.

In environments with significant congestion, the results would certainly be different. In cases where the fastest route changes depending on the demand levels, the transfer times will also change. Therefore, in such conditions, integrating the intra-hub dynamics into the decision process of the urban network would significantly improve the passenger's transfer experience. The benefit comes from the accurate representation of the walking transfer times.

The approach of integrating the urban and intra-hub models was limited to developing an exchange interface for the data. The effect of the intra-hub congestion on the user's route planning at the PT network level was addressed by the iterative procedure previously described. Nevertheless, this aspect should be improved by building a comprehensive model including all aspects. This direction has been explored recently in HÄnseler et al. (2020).

8 Conclusion

Thanks to the analysis of the pedestrian tracking data, we were able to understand some of the dynamics taking place inside the train station of Lausanne (Switzerland). In general, pedestrians experience low levels of congestion. The integration of the urban and intra-hub models gave us insight towards understanding the interactions which take place between the different levels. This process provided more accurate walking transfer times and detailed demand data for the intra-hub model. The near absence of congestion inside the Den Haag train station explains the lack of reciprocal influence between the hub and urban levels. Although the integrated modelling did not provide the expected benefits in the current case study, we expect the results would be different for case studies suffering from higher congestion.

In the future, case study selection should depend not only on the size or complexity of the hub, but also on the congestion experienced by users. Development of truly multi-modal models should also be pursued. When integrating different models, taking into account aspects like route choice across several PT lines and hubs is often impossible since the models do not allow for this. Therefore, by developing models which simultaneously consider the hub dynamics and the PT networks, the user's strategic and tactical decisions can be modelled.

The TRANS-FORM project has emphasized the need for more elaborate multi-modal decision processes. Although the benefit for the passengers is clear when disruptions or disturbances occur in the PT networks, during daily operations, the integrated approach did not provide the expected added value for the selected case study. Therefore, another approach is recommended for improving the transfer experience of passengers during daily operations: intra-hub pedestrian flow management and control. During daily operations, operators can influence the intra-hub dynamics by using control and information strategies. Moreover, the spatial and temporal consistency of the dynamics can also be addressed by using intra-hub measures. This can be achieved by providing the pedestrians with information or by guiding them using control strategies.

References

- Campanella, M. C. (2016). Microscopic modelling of walking behaviour.
- Cao, Z., Ceder, A., Li, D. and Zhang, S. (2019). Optimal synchronization and coordination of actual passenger-rail timetables, *Journal of Intelligent Transportation Systems* **23**(3): 231–249.
URL: <https://doi.org/10.1080/15472450.2018.1488132>
- Cats, O., Burghout, W., Toledo, T. and Koutsopoulos, H. N. (2010). Mesoscopic modeling of bus public transportation, *Transportation Research Record* **2188**(1): 9–18.
- Du, B., Cui, Y., Fu, Y., Zhong, R. and Xiong, H. (2018). Smarttransfer: Modeling the spatiotemporal dynamics of passenger transfers for crowdedness-aware route recommendations, *ACM Trans. Intell.*

Syst. Technol. **9**(6).

URL: <https://doi.org/10.1145/3232229>

Fruin, J. J. (1971). *Designing for pedestrians: A level-of-service concept*, number HS-011 999.

Hänseler, F. S., Bierlaire, M. and Scarinci, R. (2016). Assessing the usage and level-of-service of pedestrian facilities in train stations: A swiss case study, *Transportation Research Part A: Policy and Practice* **89**: 106–123.

Hoogendoorn, S. P. and Bovy, P. H. L. (2004). Pedestrian route-choice and activity scheduling theory and models, *Transportation Research Part B: Methodological* **38**(2): 169–190.

URL: <https://www.sciencedirect.com/science/article/pii/S0191261503000079>

Hänseler, F. S., van den Heuvel, J. P. A., Cats, O., Daamen, W. and Hoogendoorn, S. P. (2020). A passenger-pedestrian model to assess platform and train usage from automated data, *Transportation Research Part A: Policy and Practice* **132**: 948–968.

URL: <https://www.sciencedirect.com/science/article/pii/S0965856418307420>

Lavadinho, S., Alahi, A. and Bagnato, L. (2013). Analysis of pedestrian flows: Underground pedestrian walkways of lausanne train station, *Technical report*, Internal report (unpublished), VisioSafe SA, Switzerland.

Qu, W., Corman, F. and Lodewijks, G. (2015). A review of real time railway traffic management during disturbances, *International Conference on Computational Logistics*, Springer, pp. 658–672.

Wu, J., Liu, M., Sun, H., Li, T., Gao, Z. and Wang, D. Z. W. (2015). Equity-based timetable synchronization optimization in urban subway network, *Transportation Research Part C: Emerging Technologies* **51**: 1–18.

URL: <https://www.sciencedirect.com/science/article/pii/S0968090X14003179>

Yap, M. D., Cats, O., van Oort, N. and Hoogendoorn, S. P. (2017). A robust transfer inference algorithm for public transport journeys during disruptions, *Transportation Research Procedia* **27**: 1042–1049. 20th

EURO Working Group on Transportation Meeting, EWGT 2017, 4-6
September 2017, Budapest, Hungary.

URL: <https://www.sciencedirect.com/science/article/pii/S2352146517309961>

Yap, M. D., Luo, D., Cats, O., van Oort, N. and Hoogendoorn, S. P.
(2019). Where shall we sync? Clustering passenger flows to identify
urban public transport hubs and their key synchronization priorities,
Transportation Research Part C: Emerging Technologies 98: 433–
448.

URL: <https://www.sciencedirect.com/science/article/pii/S0968090X18303826>

Zhang, S., Lo, H. K., Ng, K. F. and Chen, G. (2021). Metro system dis-
ruption management and substitute bus service: a systematic review
and future directions, *Transport Reviews* 41(2): 230–251.

URL: <https://doi.org/10.1080/01441647.2020.1834468>