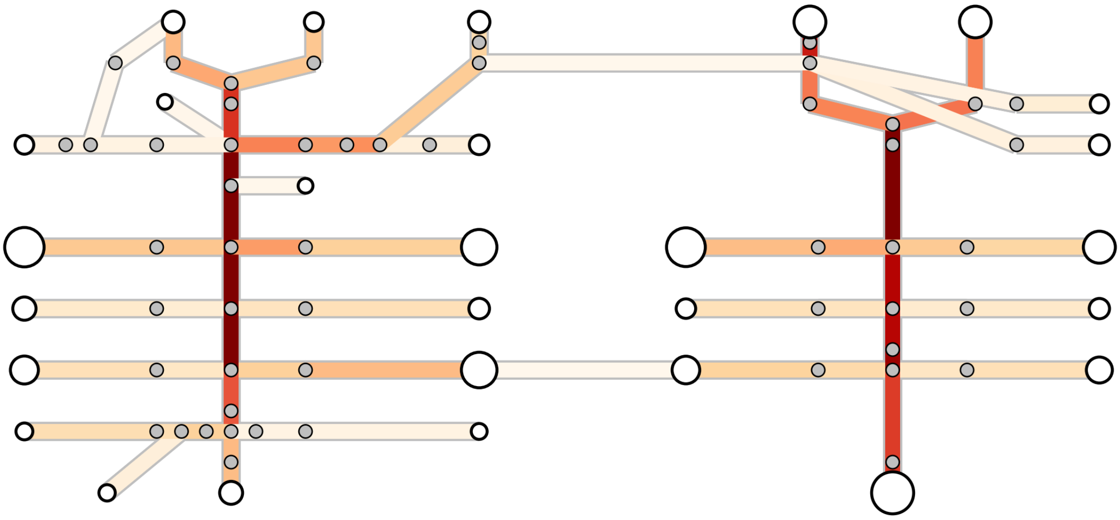


Modeling pedestrian flows in train stations: The example of Lausanne railway station

Flurin S. Hänseler

Michel Bierlaire

Nicholas A. Molyneaux

Riccardo Scarinci

Michaël Thémans

École polytechnique fédérale de Lausanne (EPFL)

April 2015

STRC

15th Swiss Transport Research Conference

Monte Verità / Ascona, April 15 – 17, 2015

Transport and Mobility Laboratory
School of Architecture, Civil and Environmental Engineering
EPFL – Ecole Polytechnique Fédérale de Lausanne

Modeling pedestrian flows in train stations: The example of Lausanne railway station

Flurin S. Hänseler, Michel Bierlaire, Nicholas A. Molyneaux, Riccardo Scarinci, Michaël Thémans

April 2, 2015

Abstract

In collaboration with the Swiss Federal Railways (SBB-CFF-FFS), various challenges associated with pedestrian flows in train stations are discussed at the example of Lausanne railway station. For this site, a rich set of data sources including travel surveys, pedestrian counts and trajectories has been collected.

The report is organized in three parts. First, an empirical analysis of the aforementioned data sources is provided. The main focus thereby lies on the identification of periodical movement patterns both in time and in space. Second, a methodology for estimating pedestrian origin-destination (OD) demand using various information sources including the train timetable is discussed. This methodology is applied to the case of Lausanne railway station, and results are provided for the morning peak period. Third, a pedestrian flow model is presented which, for a given OD demand, allows to estimate pedestrian travel times and density levels based on an empirical pedestrian fundamental diagram. This model is applied to study pedestrian movements in an underpass of Lausanne railway station, including an assessment of pedestrian level of service.

Instead of focusing on mathematical details, the present document provides a general overview of the problem of modeling pedestrian flows in railway stations that is accessible to practitioners. Suggestions for further literature are provided throughout the document.

v1.0

Keywords

pedestrian flows, public transportation, OD demand estimation, dynamic network loading, level-of-service assessment

1 Introduction

Every train trip starts and ends with a boarding and alighting process, causing pedestrian flows in train stations (see Fig. 1). For a long time, these flows have received relatively little attention by operators of railway systems. The growing occurrence of congestion in railway access facilities is provoking more interest, including that of train users. Today, capacity limits of pedestrian facilities in railway stations are regularly reached during peak periods, potentially impacting the safety, efficiency and comfort of passengers and the entire transportation system. For a discussion of these aspects from a research point of view, the reader is referred to Hänseler *et al.* (2015), who provide a recent review of the corresponding literature.

Figure 1: Commuters walking on platform #3/4 after leaving a train at Lausanne railway station. On the left, S4 from Allaman to Palézieux is visible; on the right, S1 from Yverdon-les-Bains to Villeneuve can be seen. (Photo: Sandro Campardo, ©SBB-CFF-FFS, Date: Tuesday, May 15, 2012)

To optimize the design and operation of railway access facilities, there is a general need to better understand pedestrian travel demand within train stations. Such demand is typically characterized by means of an origin-destination (OD) demand table, representing the number of people traveling between each pair of origin and destination. In a dynamic context, i.e., if travel demand fluctuates, time is usually discretized into intervals, and separate OD tables are calculated for each period. Pedestrians are then counted when they leave their destination.

Once the OD demand is known, pedestrian traffic conditions can be estimated, i.e., the ability of the infrastructure to cope with a certain demand. In that process, two steps are necessary. First, demand is assigned to 'routes'. The corresponding route fractions may be directly observed, or estimated using a route choice model. In the case of Lausanne railway station, between most OD pairs only a single route exists, and route choice is trivial. Second, the flows along routes are computed using a network loading model that describes the propagation of pedestrians through space and time.

As shown in Fig. 2, the estimation of demand and infrastructural supply considers various information sources, such as the train timetable, travel surveys, sales data, as well as pedestrian count and tracking data. In the presence of congestion, the traffic conditions are generally unknown, and a fixed-point problem arises between the demand estimator and the network loading model (Cascetta and Postorino, 2001). Otherwise, the interaction between demand and supply is negligible, and the two estimation problems can be considered independently. This is the case for Lausanne railway station (see Sec. 3).

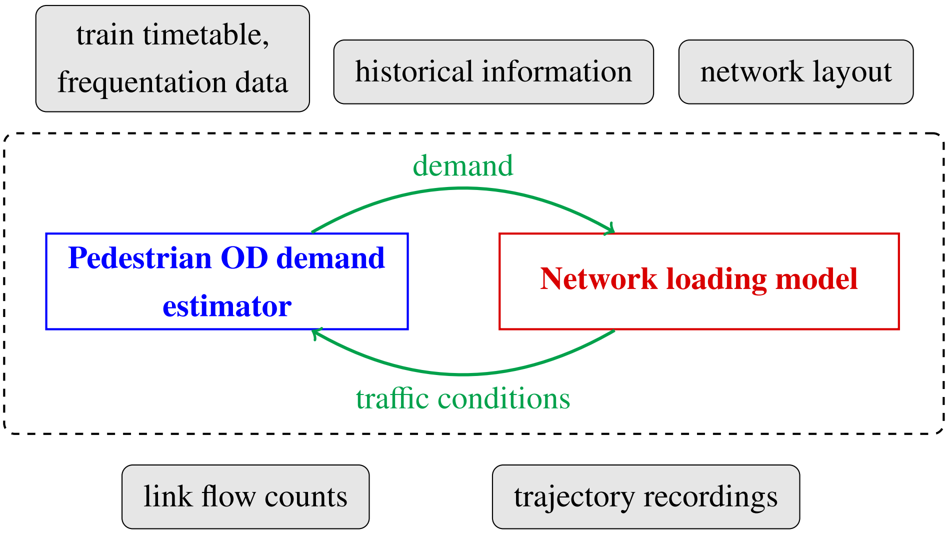


Figure 2: Scheme of a framework for estimating dynamic pedestrian OD demand and pedestrian traffic conditions in railway stations. Shaded rectangles represent data sources and the colored rectangles the actual demand estimator as well as the network loading model.

This report is structured as follows. First, a data-driven, exploratory case study analysis of Lausanne railway station is presented that is useful for model development and benchmarking. Second, a recently developed framework for estimating OD demand is applied to the same case study, providing dynamic OD trip tables for pedestrian flows within railway stations. Third, an aggregate network loading model is outlined, useful for the estimation of demand in the presence of congestion, or for assessing the level-of-service of pedestrian facilities in terms of density levels and walking times. This model is again applied to a case study involving

Lausanne railway station. The presented research has been conducted in collaboration with the Swiss Federal Railways, SBB-CFF-FFS, henceforth abbreviated as SBB.

2 Case study

Throughout this report, Lausanne railway station serves as case study illustrating various aspects of pedestrian flows in train stations. This choice is motivated by two reasons. First, due to its proximity to EPFL as well as previous studies in the framework of Léman 2030, a detailed knowledge of both infrastructural and operational aspects is available. Second, Lausanne represents a railway station of national importance in terms of passenger turnover and train movements. Fig. 3 shows an aerial view of Lausanne railway station. A corresponding schematic map is provided in Fig. 4.

Figure 3: Aerial view of Lausanne railway station

Lausanne railway station encompasses the passing tracks #1–9 and the dead end track #70. Track #2 is used by freight trains and through traffic only, as it is not accessible by any platform. Except for platforms #1 and #70, all platforms are accessible from the city solely through two pedestrian underpasses (PU), PU West and PU East. Platform #9 is only accessibly from PU West. Longitudinally, the train station is divided into sectors A-D, where the historical ordering

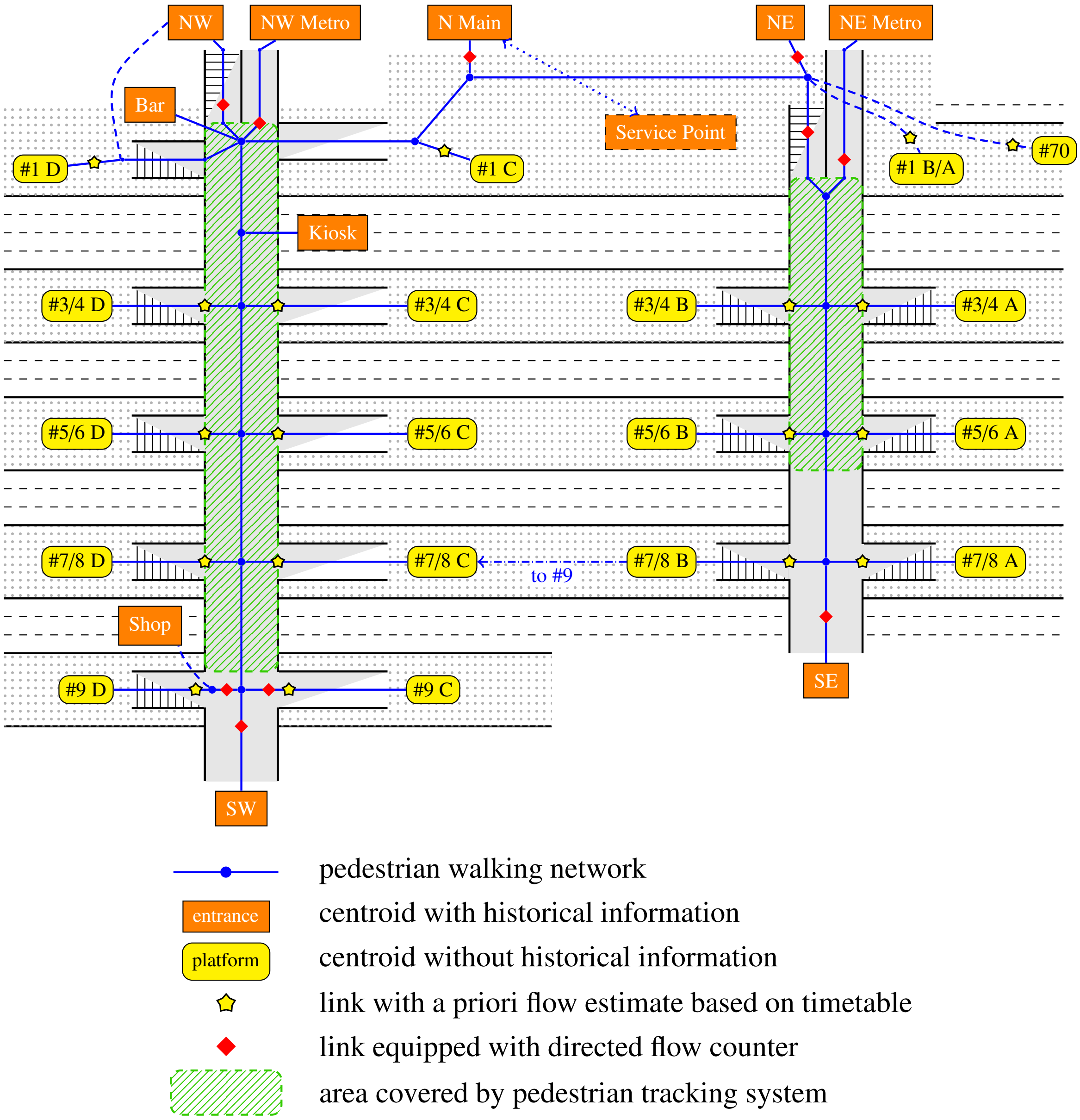


Figure 4: Schematic map of Lausanne railway station, encompassing ten tracks (#1–#9, #70) that are served by platforms #1, #3/4, #5/6, #7/8, #9 and #70. Platforms are connected by two pedestrian underpasses (PU) referred to as PU West and PU East, each partially covered by a pedestrian tracking system (corresponding areas are shaded in green). Dashed lines represent network links that cannot be directly shown on the scheme due to the chosen two-dimensional representation.

from East to West is adopted. The blue graph in Fig. 4 shows the corresponding walking network.

Several data sources are available for Lausanne railway station. These include pedestrian trajectories covering the pedestrian underpasses (provided by VisioSafe, Lausanne, Switzerland), directed pedestrian counts at several exit ways (provided by ASE GmbH, Zürich, Switzerland), as well as various historical surveys and sales data. The VisioSafe data set containing pedestrian trajectories has been collected explicitly for the present study, representing a particularly useful resource for analysis and model development.

3 Data analysis

A detailed exploratory analysis of the aforementioned data sources associated with Lausanne railway station has been conducted. The analysis is largely based on the morning peak period between 07:00 and 08:30 of ten 'normal' working days, spread out between January and April 2013. Specifically, these days include January 22 and 23, February 6, 27 and 28, March 5, as well as April 9, 10, 18 and 30. They represent typical weekdays (Tuesday, Wednesday, Thursday) with a low level of delay. The selection has been made by SBB based on the actual train timetable data and is referred to as '10-day reference set'.

3.1 Periodic flow patterns

Pedestrian flows in railway stations show strongly recurrent patterns, which are among other factors induced by the cyclic train timetable and the day/night or working day/weekend rhythm. In the following, periodic patterns during the course of a week, a typical working day, as well as the morning peak hour are considered.

Fig. 5 shows the periodicity of demand over a typical working week. The period between February 25 and May 19, 2013, is used for this analysis. April 1 and 2 are excluded, as no tracking data is available on these days.

The total number of pedestrian visits in the two pedestrian underpasses of Lausanne railway station (PU West and East) is slightly below 120,000 ped/day. On Fridays, Lausanne railway station is busier than during the week due to weekly commuters returning to their principal place of residence, as well as due to weekend travelers.

In Fig. 6, the periodicity of demand over a typical day is shown. The evening and morning peak hours stand out with an hourly demand of around 14,000 ped/h, which is several times larger than the average hourly demand. While the morning peak period is relatively short, the evening peak period spreads over almost four hours. Though not visible from the shown graph, the busiest 60-minute period in Lausanne railway station is between 07:30 and 08:30. In the subsequent analysis, this period is mainly used as case study.

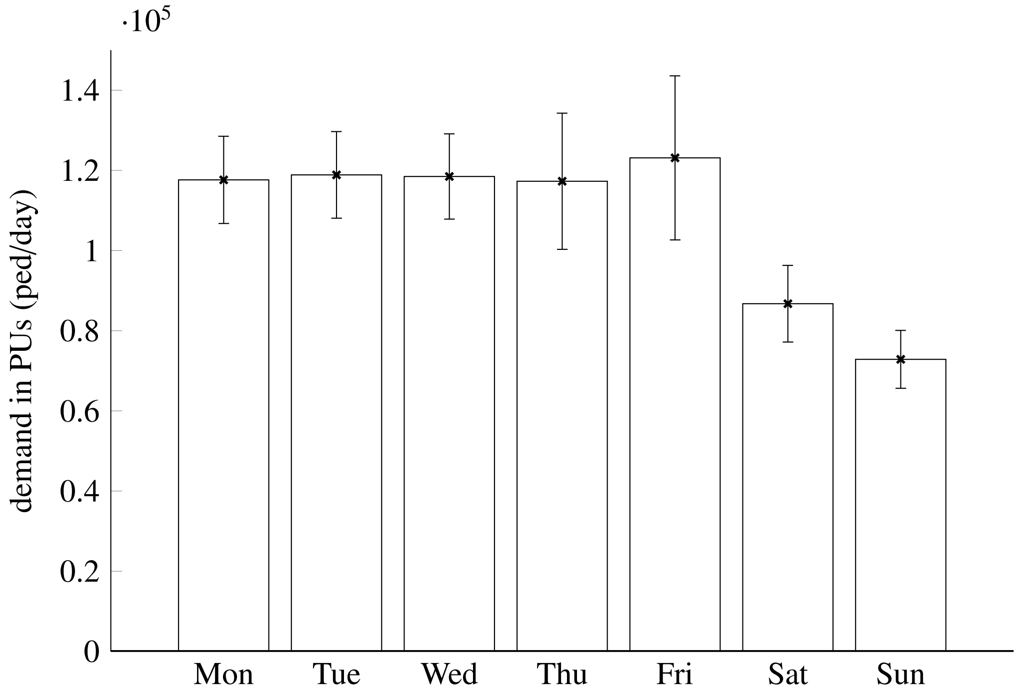


Figure 5: Mean daily pedestrian demand over a week in the pedestrian underpasses of Lausanne railway station (PU West and PU East). Results obtained for a period of 12 weeks (February 25 to May 19, 2013 without April 1 – 2, 2013 due to lack of data) as provided by VisioSafe. Standard deviations are around $\pm 15,000$ pedestrians for a typical working day.

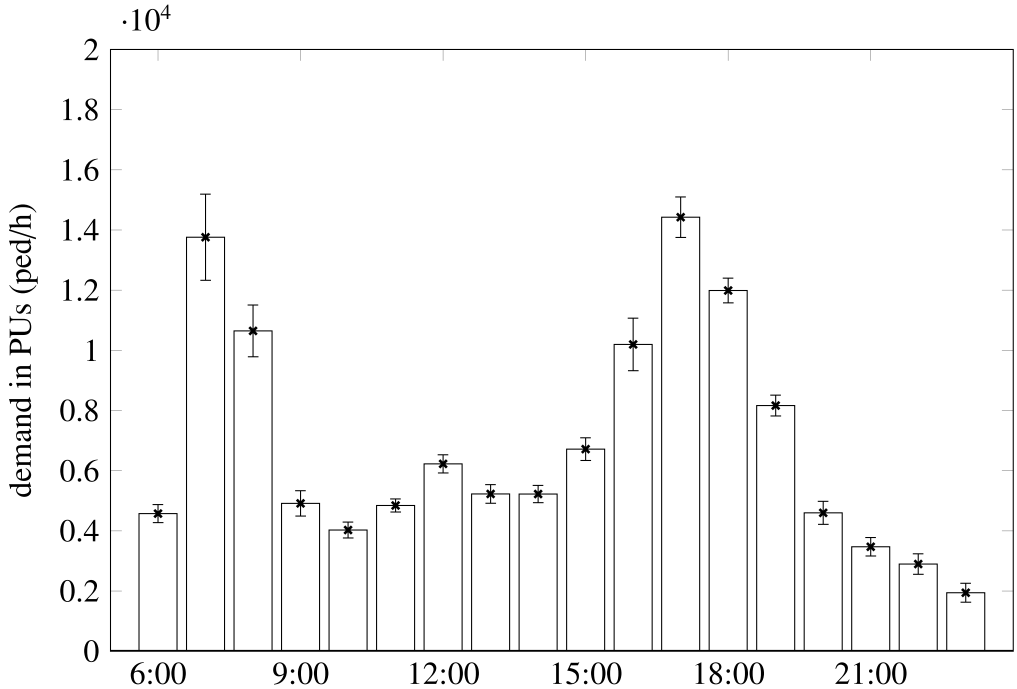


Figure 6: Mean hourly pedestrian demand over a day in the pedestrian underpasses in Lausanne railway station (PU West and PU East). Morning and evening peak hours stand out clearly. Data: 10-day reference set, 2013.

On the time scales studied so far, demand patterns are 'stable', as indicated by relatively small error bars (the standard deviation amounts typically to less than 10% of the mean values in Fig. 5 and Fig. 6). Regarding minute-by-minute demand in Lausanne's PUs, fluctuations across days are much larger. In Fig. 7, demand is aggregated by two-minute intervals. The shown 90-minute interval represents an average over the 10-day reference set. While absolute demand levels are lower outside rush hours, the underlying pattern with peaks around :10 and :40 every hour is characteristic for the whole day.

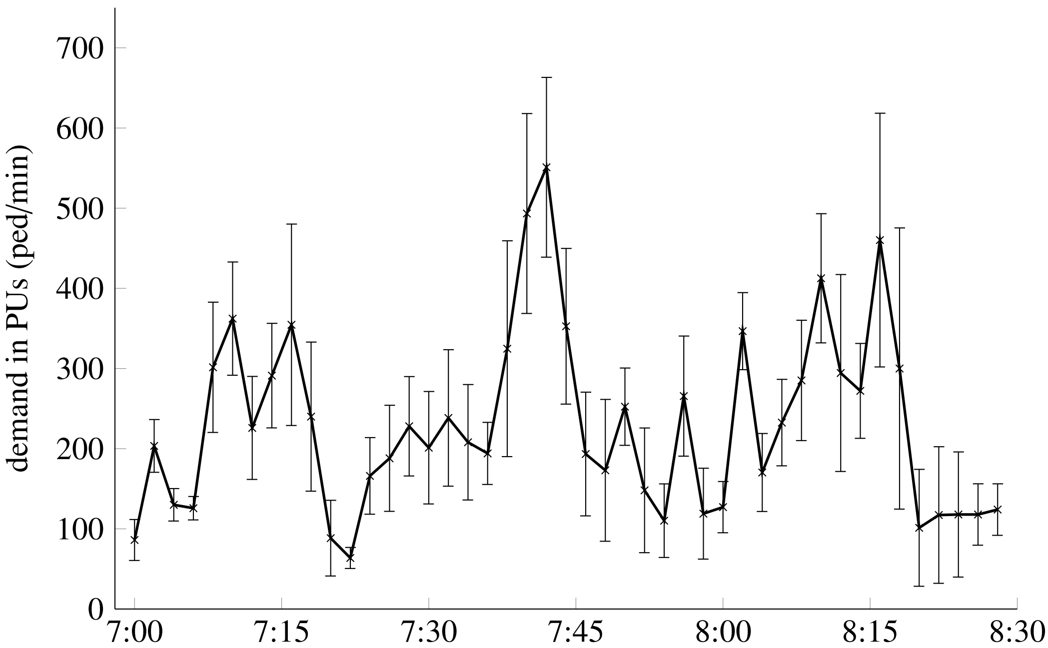


Figure 7: Pedestrian demand in the morning peak hour between 07:00 and 08:30, aggregated by two-minute intervals, in the pedestrian underpasses of Lausanne railway station (PU West and PU East). Data: 10-day reference set, 2013.

The average pedestrian demand aggregated by two-minute intervals varies roughly by one order of magnitude, i.e., between 50 and 500 pedestrians per minute. If demand is aggregated by the minute, the results are largely the same, except that standard deviations are slightly larger (results not shown). Given the observed temporal fluctuations, an appropriate level of aggregation for estimating OD demand is in the order of a few minutes. For the estimation of demand presented in Sec. 4, a dynamic model with a resolution of one minute is considered.

3.2 Train-induced flows

Pedestrian flows depend significantly on train arrivals and departures. In the following, an empirical relationship is established between the arrival of trains and flows from platforms into PUs, i.e., the flows measured at the interface between platform access ways and PUs.

Fig. 8 shows flows from platforms #3/4 and #5/6 into PUs as measured in the morning peak hour of January 22, 2013. Results are shown for a single day as train arrival times vary significantly across days, often due to 'early arrivals'. Vertical lines denote train arrivals on corresponding platforms. Clearly, there is a strong correlation between the arrivals of trains and the magnitude of the flow. In Sec. 4, a mathematical model is proposed that describes this relationship in detail.

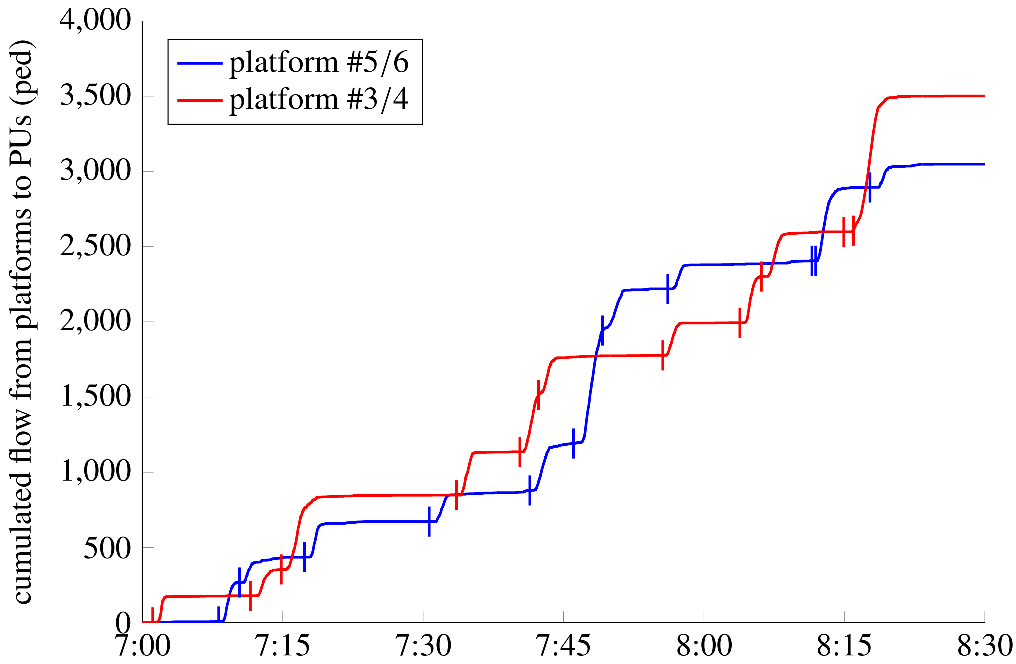


Figure 8: Train-induced flows from selected platforms into PUs on January 22, 2013, observed using VisioSafe's tracking system. Vertical lines indicate actual train arrivals.

The alighting volume of a train varies with each day. Assuming a normal distribution, the standard deviation amounts to approximately 20% of the mean. In contrast, the flow rate at which passengers reach the bottom of the access ramps from platforms varies little in time. These unloading rates remain almost constant in the couple of minutes following train arrivals.

3.3 Speed distribution

Fig. 9 shows a speed histogram as observed in both PUs during the morning peak hours of the 10-day reference set. A total population of 165,275 pedestrians is considered.

A mean velocity of 4.13 km/h is observed. The median lies at 4.04 km/h. These values are slightly lower than reported in the literature. For instance, Weidmann (1992) reports a mean speed of 1.34 m/s, or 4.8 km/h.

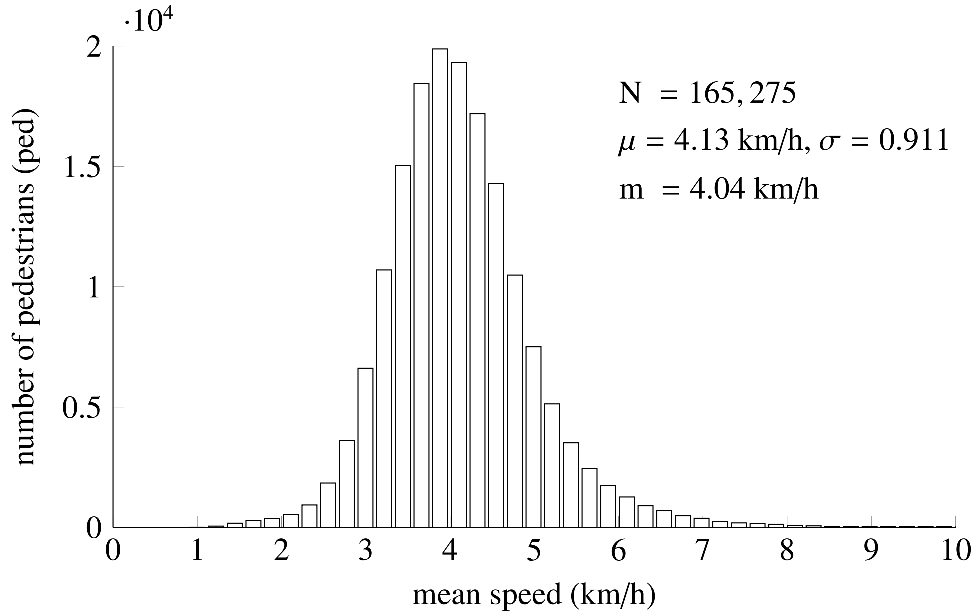


Figure 9: Histogram of speed for pedestrians during the morning peak hour in the two pedestrian underpasses of Lausanne railway station (PU West and PU East). Data: 10-day reference set, 2013. Adapted from Anken *et al.* (2013).

Using the same dataset, the occurrence of a density-speed relationship has been investigated by Nikolić *et al.* (2015). This relationship is typically referred to as 'pedestrian fundamental diagram' (see also Sec. 5). Alternatively, at a spatially more aggregated level, the relationship between the occupation, i.e., the total number of pedestrians in an area, and travel times may be investigated. Such an approach is pursued in the following.

3.4 Density-travel time relationship for PU West

Fig. 10 shows the correlation between occupation in PU West and selected travel times as observed in 2,890 pedestrian trajectories associated with the morning peak period of the 10-day reference set. The occupation is assumed to be equal to the number of people that are present when a pedestrian enters PU West. Travel times correspond to the paths from the lower end of the ramp associated with centroid #1C (see Fig. 4) to the South exit in PU West associated with centroid SW, as well as to the platform access ramp associated with centroid #3/4C.

According to this figure, the distribution of travel times is relatively wide and disperse at low values of occupation, and slightly narrower at larger densities. The mean travel times do not depend significantly on the overall level of occupation. An analysis of the evening peak hour as well as of the relationship between occupation and travel times in PU East yields the same result. Therefore, the level of interaction between demand and supply due to congestion can be

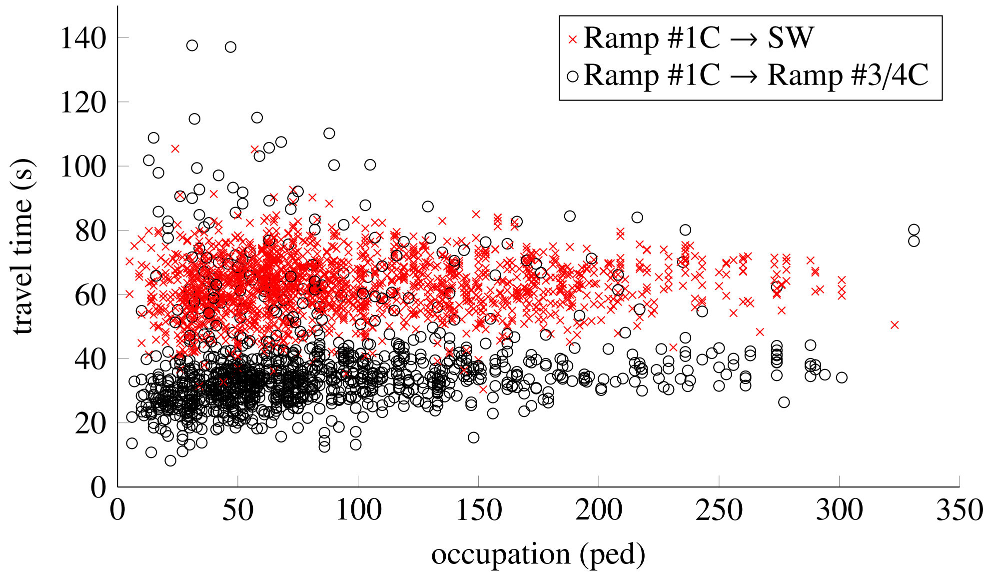


Figure 10: Correlation between pedestrian occupation and selected travel times for a population of 2,890 pedestrians crossing PU West along two selected routes. Data: 10-day reference set, 2013.

considered negligible in the case of Lausanne railway station. Average and median residence times within PUs are around 40 s, with a standard deviation of 17 s.

3.5 Boarding, alighting and transferring passengers

As an alternative to pedestrian tracking data, the travel survey HOP ('Hochrechnung Personenverkehr', see Olesen, 2006, for a description. Data from 2010.) can be used to estimate the number of incoming and outgoing passengers in Lausanne railway station. Fig. 11 shows the number of boarding, alighting and transfer passengers over a day as extracted from this data.

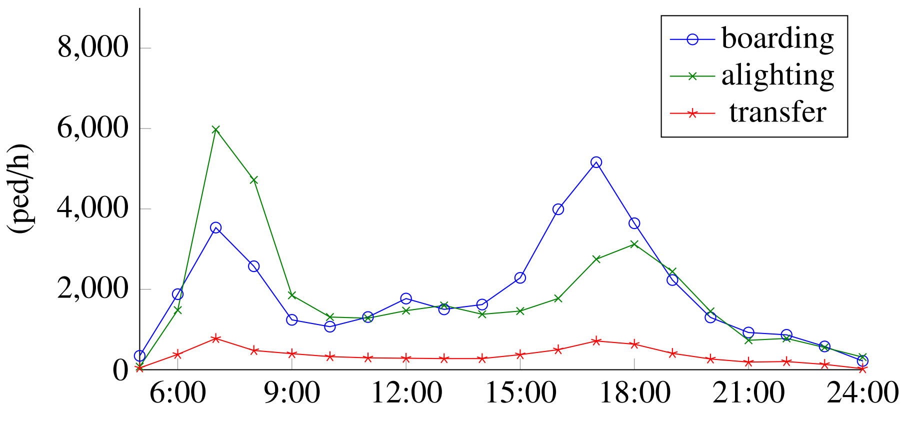


Figure 11: Estimated number of boarding, alighting and transferring passengers over one day extracted from HOP 2010 data. Adapted from Anken *et al.* (2012).

Between 7:00 and 8:00, the alighting volume (5,975 ped) is higher than the boarding volume (3,536 ped), whereas in the evening rush hour between 17:00 and 18:00 the number of boardings is higher (2,749 vs. 5,163 ped). Between 7:00 and 8:00, there are on average 10,287 passenger movements; between 17h and 18h, the average amounts to 8,626 movements. According to these results, people mostly come to Lausanne for work and leave the city again in the evening. The percentage of transfer passengers is just below 10% and nearly constant during the day.

3.6 Comparison of pedestrian trajectories and flow counts

VisioSafe's sensor system records pedestrian trajectories across space and time. From this data, flows across arbitrary cordons can be computed and compared to flow counts from other sources. This represents one way of assessing the reliability of the data.

Fig. 12 shows a comparison of measured outflows from PU East towards North (including both the corridor leading to the metro and the stairways up to the Place de la Gare) as recorded by ASE and VisioSafe in the morning peak hour of January 15, 2013.

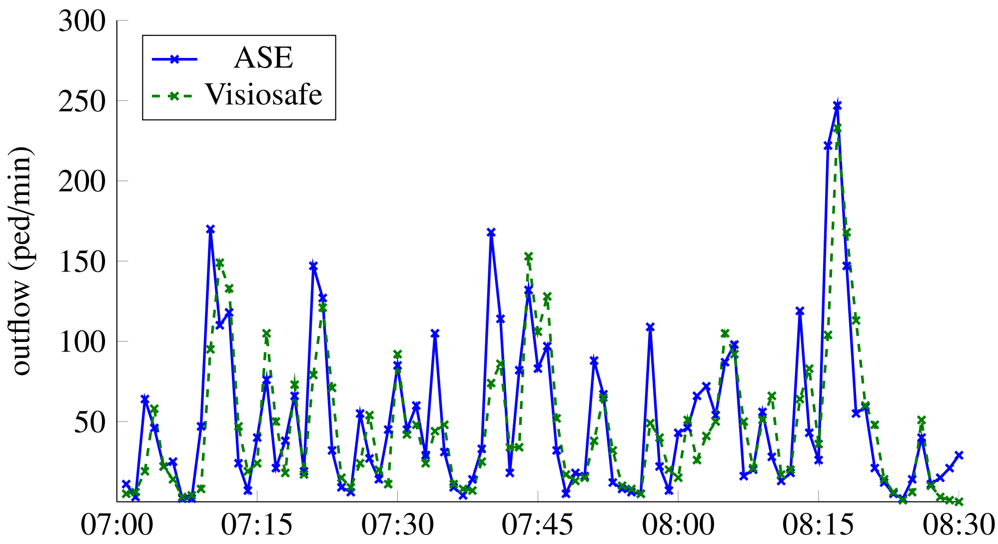


Figure 12: Comparison of measured flow leaving PU East towards North, as recorded by VisioSafe's pedestrian tracking system and ASE's flow sensors on January 15, 2013. Adapted from Zimmermann *et al.* (2013).

Both curves show a similar pattern. The VisioSafe data slightly underestimates flows as compared to the data provided by ASE. This discrepancy is presumably due to the fact that whenever the system looses track of a pedestrian, the whole trajectory is removed (Alahi *et al.*, 2013). Given the different techniques and scope, the agreement between the two data sources seems satisfactory.

Based on the foregoing explorative data analysis, two model frameworks for demand estimation and network loading are developed as described in the following.

4 Demand estimation

In this section, a brief description of a framework for dynamically estimating pedestrian demand in railway stations is provided, and results from a case study analysis of Lausanne railway station are discussed. For a mathematical description of the framework, the reader is referred to Hänseler *et al.* (2015).

The problem of estimating OD demand consists in finding an estimate which, if applied to the pedestrian network of the train station, is 'most consistent' with the corresponding train timetable, historical surveys, and all other data sources that are available for the estimation (Cascetta and Improta, 2002). In the case of Lausanne railway station, all the aforementioned data sources are used with the exception of pedestrian trajectory data, which is considered for validation purposes instead.

The train timetable is considered in the estimation process by means of the pedestrian flows that it induces. Fig. 13 provides a schematic representation of a potential classification of such flows, which are divided in boarding/alighting flows at train doors, as well as exit and access flows on platform access ways.

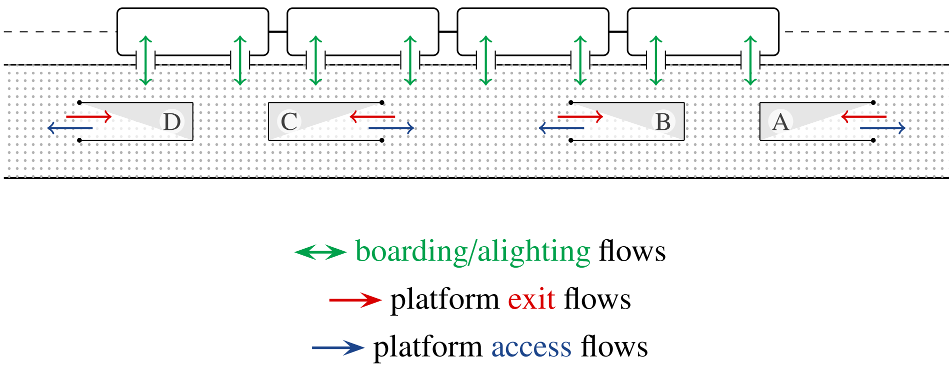


Figure 13: Illustration of train-induced flows on platforms and platform access ways.

In the estimation framework considered here, platform exit flows succeeding the arrival of a train are considered specifically (see Sec. 3). For that purpose, a piece-wise linear model is developed as illustrated in Fig. 14. After the arrival of a train, a certain time elapses until the first pedestrians reach the platform exit ways. This 'dead time' may be due to a delay in the opening of doors after the train has stopped, or due to the walking time required to reach the exit ways. Subsequently, a constant flow is established, whose magnitude is mostly limited by the capacity of the exit ways. This assumption is based on empirical observations, showing that the exit ways typically represent the bottleneck in that particular flow situation (Benmoussa *et al.*, 2011). Once all alighting passengers have left the access ways, the flow reaches again zero.

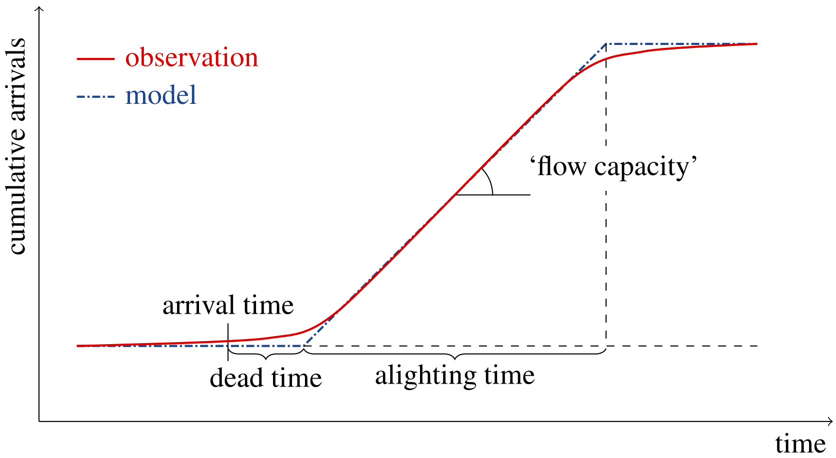


Figure 14: Illustration of a piece-wise linear model for describing flows of alighting passengers on platform exit flows following the arrival of a train.

By assuming that the parameters such as flow capacity and alighting volume are distributed, a stochastic model formulation results. Such a formulation is used in Fig. 15 to predict train-induced platform exit flows on platform #5/6 in Lausanne railway station. The good agreement between the prediction and the observation underlines the quality of the developed model in estimating the flows induced by train arrivals.

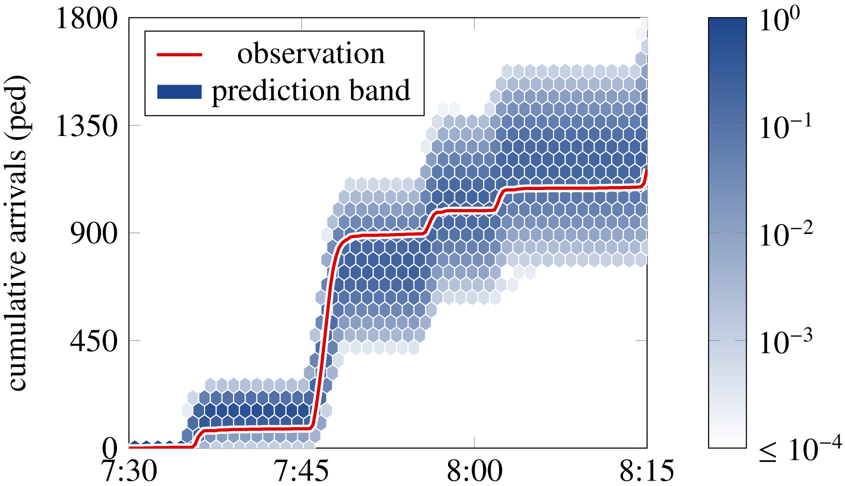


Figure 15: Observed and simulated platform exit flows on April 10, 2013 at platform #5/6 in Lausanne railway station.

The same model can be applied to predict flows on exit ways of all platforms, if the corresponding model parameters are known. Some guidelines on how they can be estimated are provided by Molyneaux *et al.* (2014).

The OD demand is estimated from count data, trajectories or flows, where the latter may be directly observed or computed by the previously described model for train-induced flows. In the process of estimating OD demand, some assumptions regarding the prevailing traffic conditions are necessary. They are typically estimated by the network loading model, as illustrated in Fig. 2. Since flows in walking facilities in Lausanne railway station are largely uncongested even during peak periods (see Sec. 3), the walking speed is assumed to be independent from demand. Specifically, for the estimation of demand discussed in this section, the walking speed is assumed to be normally distributed with a mean of 1.34 m/s and a standard deviation of 0.34 m/s (Weidmann, 1992).

In the following, the developed estimation framework is applied to study the demand during the busiest 30-min period during the morning peak hour in Lausanne railway station. In the considered interval between 07:30 and 08:00 in the year 2013, 25 trains arrive and depart, as can be seen from Table 1. As discussed in Section 3, the demand is known to fluctuate significantly across days even if they are 'similar', such as e.g. a series of consecutive Tuesdays. For that reason, the demand is jointly estimated for the 10-day reference set defined in the same section.

For this set of days, Fig. 16 provides the evolution of the total demand during the morning peak period, showing both the mean, and the standard deviation band. As indicated by the standard deviation band, the day-to-day variation is highly significant.

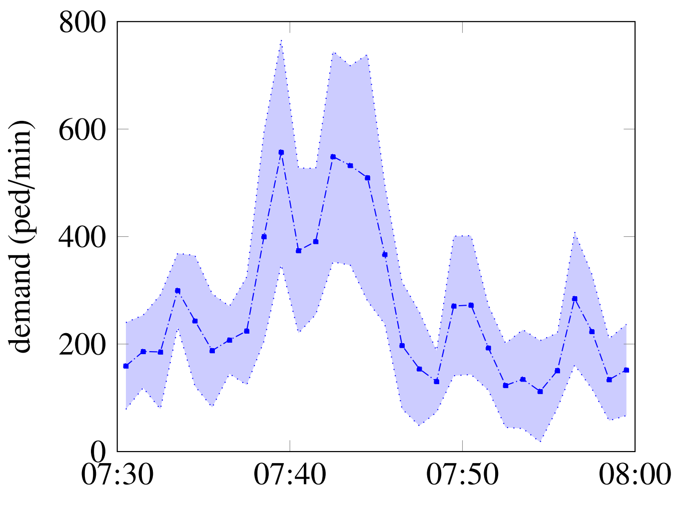


Figure 16: Total demand in Lausanne railway station during the morning peak period. The pair of dotted lines represent the limits of the standard deviation band (±1 std). Data: 10-day reference set, 2013.

The average cumulative demand over the studied 30-min period amounts to 7,906.5 ped, representing about 8% of the daily station throughput (Amacker, 2012). The highest average demand is found between 7:39 and 7:40, where the overall demand rate amounts to 557.3 ped/min. A

Table 1: Official train timetable of Lausanne railway station between 07:30 – 08:00 (with a margin of 7 min before and after) for the period of December 11, 2011 to December 14, 2013. Regional trains account for the largest number of connections, subdivided into suburban (S), Regio (R) and RegioExpress (RE) trains. Additionally, there are seven express trains, classified as InterRegio (IR), InterCity (IC) and InterCity tilting (ICN) trains. These interregional trains arrive and depart in a relatively short period between 7:39 and 7:46, and 7:42 and 7:50, respectively. Columns represent the train number (train no.), associated track (#), scheduled arrival time (t_a), origin of train, scheduled departure time (t_d) and destination of train.

Train no.	#	t_a	Origin	t_d	Destination
S21 12917	70			7:24	Payerne
S3 12318	8	7:24	Villeneuve	7:26	Allaman
S2 12217	1	7:26	Vallorbe	7:30	Palézieux
RE 4060	7	7:28	St-Maurice		
S2 12218	5	7:30	Palézieux	7:32	Vallorbe
S3 12317	3	7:33	Allaman	7:35	Villeneuve
S21 12918	70	7:36	Payerne		
IR 1712	6	7:39	Sion	7:48	Genève-Aéroport
RE 2607	1	7:39	Genève	7:42	Romont
IC 706	5	7:40	Zürich HB	7:42	Genève-Aéroport
ICN 1517	8			7:45	St. Gallen
IR 1407	3	7:42	Genève-Aéroport	7:46	Brig
IR 1710	7	7:42	Brig	7:45	Genève-Aéroport
IR 1606	4	7:43	Neuchâtel		
IR 2517	1	7:46	Genève-Aéroport	7:50	Luzern
RE 2710	9	7:49	Vevey	7:51	Genève
S 12017	5	7:49	Vallorbe		
S11 12820	8			7:55	Yverdon-les-Bains
S1 12119	3	7:56	Yverdon-les-Bains	8:00	Villeneuve
S4 12420	6	7:56	Palézieux	7:58	Allaman
RE 4024	70	8:00	Payerne/Romont		
S1 12120	7	8:02	Villeneuve	8:04	Yverdon-les-Bains
S4 12419	4	8:02	Allaman	8:04	Palézieux
S11 12819	3	8:05	Yverdon-les-Bains		
R 12014	8	8:06	St-Maurice	8:08	Renens

quarter of an hour later, between 7:54 and 7:55, the mean demand reaches a low of 112.0 ped/min. Within only a couple of minutes, the average demand thus varies by almost a factor of 5. Compared to the average hourly demand reported for the morning peak hour between 07:00 and 08:00 in Fig. 6, amounting to 13,759.4 ped/h (or 229.3 ped/min), the overall peak is almost 2.5 times as large, underlining the importance of a fine-grained, dynamic estimation.

To consider the spatial distribution of demand, the latter may be aggregated over time. Fig. 17 shows a 'Circos' diagram of the average pedestrian OD demand (Krzywinski *et al.,* 2009). Centroids are grouped into a set of ten aggregated centroids, representing the railway platforms #1, #3/4, #5/6, #7/8, #9 and #70, the entrances North and South, the passageway to the metro, and a collection of shops. Blue strips represent pedestrian flows emanating from railway platforms, green those originating at the entrance ways North and South as well as at the interface to the metro station, and red strips pedestrian demand emanating from one of the sales points. According to this classification, around 44.12% of all station visitors represent inbound passengers, 31.18% represent outbound passengers, 16.42% are transfer passengers, and the remaining pedestrians represent local users.

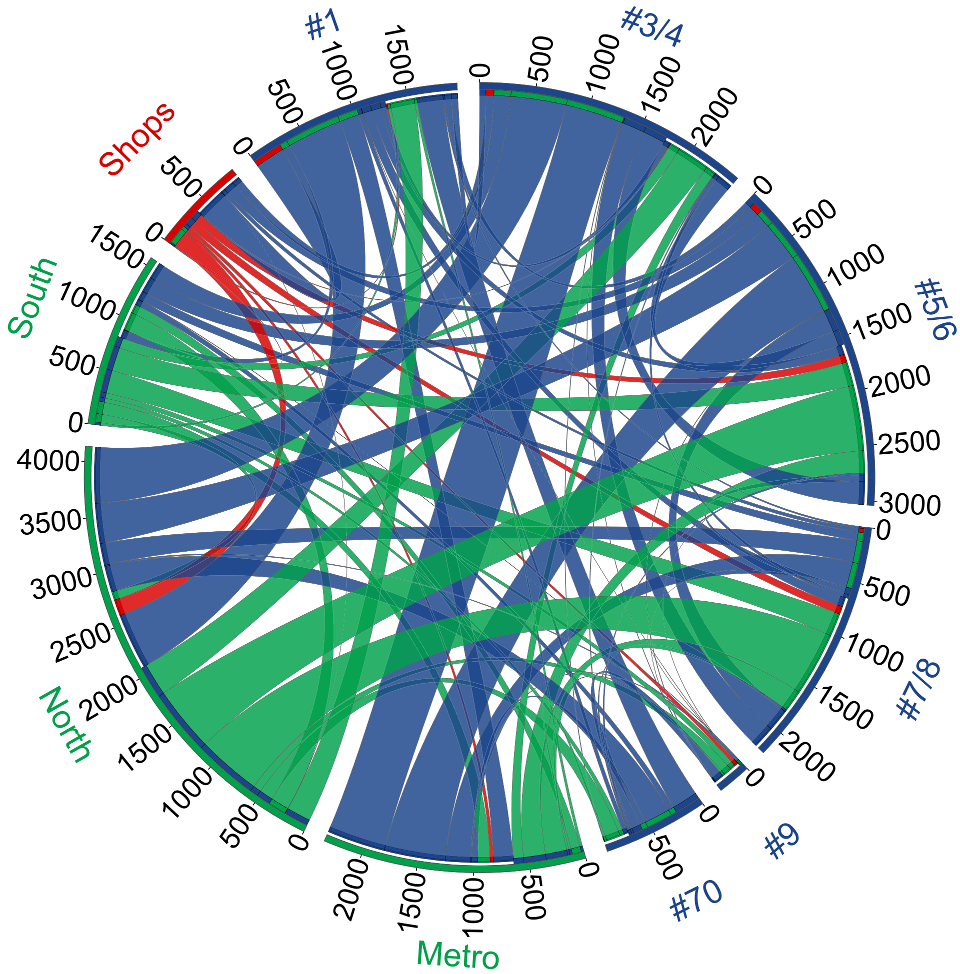


Figure 17: A Circos diagram representing the average pedestrian OD demand in Lausanne railway station in the morning peak period between 07:30 and 08:00. Blue strips represent inbound and transfer passengers that alight from a train, green strips outbound passengers or local users, and red strips customers leaving any of the three sales points, i.e., the origin of streams represent depending on their color either train platforms, city/metro/bus or shops. Data: 10-day reference set, 2013 (see Hänseler *et al.,* 2015, for more details).

A further way of visualizing demand is by means of network flows. Fig. 18 shows a map of the estimated minute-by-minute link flows for the time period between 7:40 and 7:48 on April 30, 2013. Here, the demand estimate of a specific day is chosen as it allows to visualize the demand peaks caused by individual train arrivals and departures.

Between 7:40 and 7:41, the arrival of IR 1712 from Sion at 7:38:57 is still discernible by the origin flow it creates on platform #5/6. In the time period considered, this train is among those with the highest alighting volumes. During 7:41 and 7:42, the arrival of IR 1606 from Neuchâtel on track #4 can be seen by the trace it leaves in the pedestrian flow map. Within less than a minute, IR 1710, IC 706 and IR 1407 arrive on platform #7 at 7:42:24, platform #5 at 7:42:59, and on platform #3 at 7:43:18, respectively. Especially the former two represent major lines (from Brig and Zürich), causing large pedestrian movements. Their impact is visible in Fig. 18d and 18e. After the last arrival of a train, IR 2517 from Geneva arriving on platform #1 at 7:44:37, pedestrian flows decay, as can be seen from Fig. 18g and 18h.

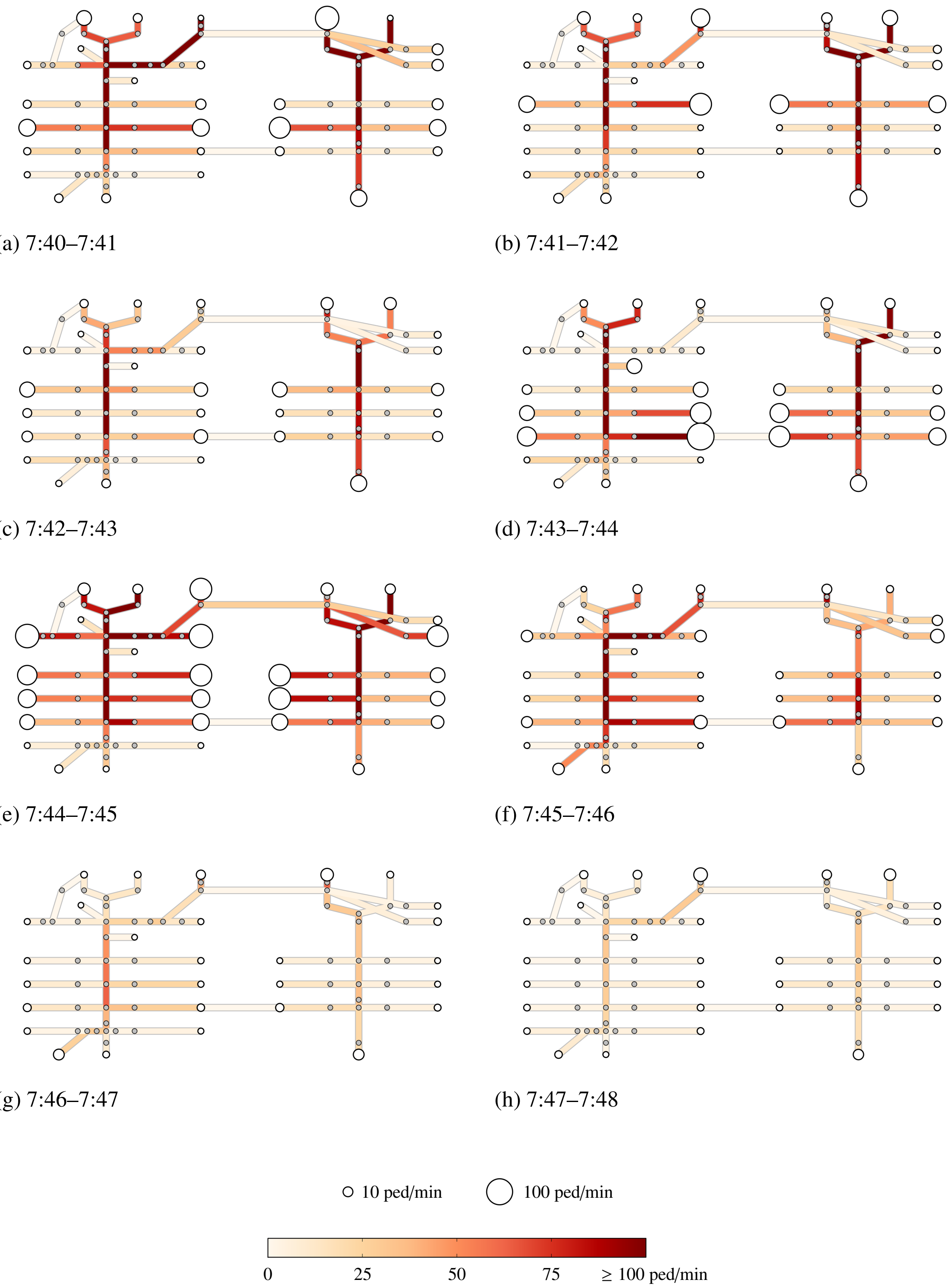


Figure 18: Pedestrian flow map for Lausanne railway station as estimated for the time period between 07:40 and 07:48 on April 30, 2013. The shading of links represents the cumulative link flow over a minute in both directions. The diameter of centroids represents the minute-by-minute origin flow.

5 Network loading model

Origin-destination demand alone reveals little about expected traffic conditions. To assess the latter, the interaction between infrastructural supply and demand needs to be taken into account. Similarly, if the demand for a congested railway station is to be found, the consideration of that interaction is key in the estimation process as well. For both problems, a pedestrian network loading model is necessary. In the following, such a model is described and applied to investigate density levels in PU West of Lausanne railway station. The focus is again on the presentation of the main ideas. The reader interested in mathematical details is referred to Hänseler *et al.* (2014).

In the development of the pedestrian network loading model, it is assumed that the network topology and demand are known a priori. Specifically, for all pedestrians, the origin and destination, as well as their route is assumed to be given at the aggregate level. The framework for OD estimation described in Sec. 4 may be used to obtain this information.

Instead of predicting the behavior of individual pedestrians, an accurate prediction of travel time distributions and density levels is aimed for. For that purpose, an empirically observed density-speed relationship is used to describe traffic conditions. Fig. 19 shows the corresponding relationship (Weidmann, 1992). In the same figure, additionally the 'hydrodynamic flow' is shown, representing the flow per unit of length that results for a given density in case of a uni-directional motion.

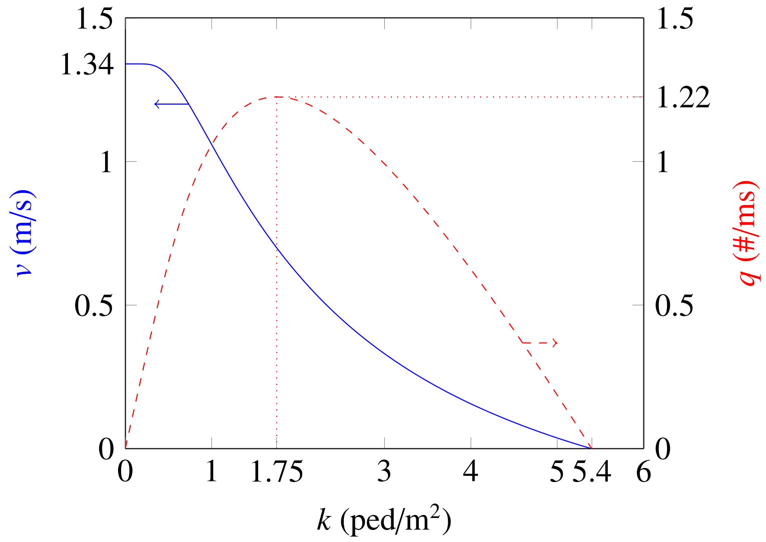


Figure 19: Average pedestrian speed (solid blue) and specific flow (dashed red) as a function of density according to Weidmann (1992).

To apply the aforementioned density-speed relation, walkable space is partitioned into a set of cells as illustrated in Fig. 20. For each cell at each point in time, the density is calculated, and based on the relationship shown in Fig. 19, the corresponding flow is computed. It is thereby assumed that the walking speed within a cell is the same in all directions, i.e., isotropy of walking speed is assumed. This is a fair assumption for mildly congested flows or those that are inherently uni-directional.

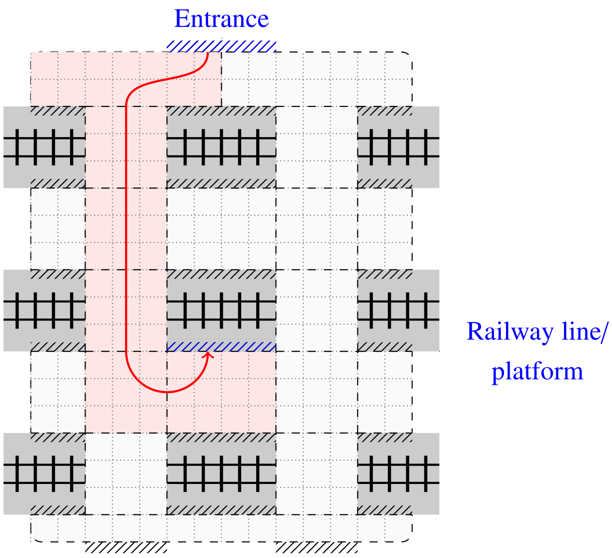
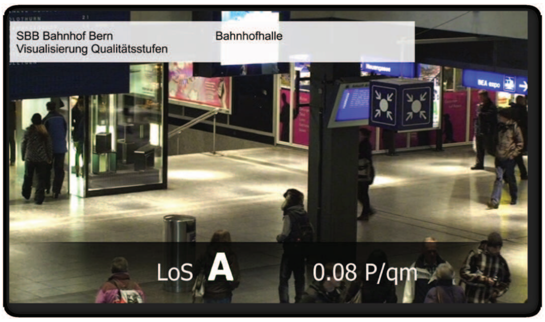


Figure 20: Space is discretized into cells (delimited by dotted lines). Contiguous sets of cells represent areas (delimited by dashed lines). Each pedestrian is assigned to a sequence of these areas, which is referred to as a route (illustrated by an arrow).

The density in cells can be used to assess the perceived comfort and performance of a facility, or more generally its 'level of service' (LOS). Fig. 21 illustrates different levels of pedestrian density by means of pictures taken with a CCTV camera in Bern railway station. Also, the LOS scale recommended by the US-American National Cooperative Highway Research Program (NCHRP) is shown, representing one of the most common classification schemes for pedestrian density levels (Fruin, 1971). LOS level A represents the most favorable condition, and LOS level E the least favorable one.

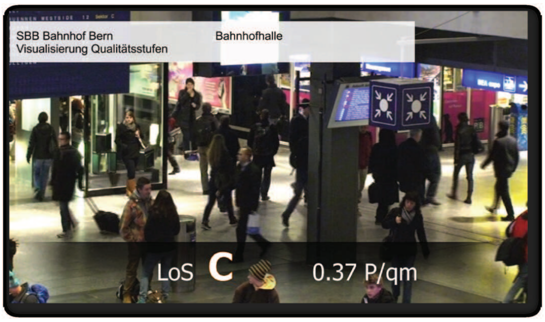
In the following, the developed pedestrian network loading model is applied to a case study involving Lausanne railway station. Fig. 22 shows the density maps of PU West as derived from pedestrian tracking data, and as computed by the network loading model. In the figure captions, train arrivals relevant for each time interval are indicated. As can be seen, train arrivals induce pedestrian waves that propagate through walking facilities and potentially cause local congestion.

The proposed network loading model is able to reproduce the evolution of local pedestrian density relatively well. The highest pedestrian densities are observed between 7:41 and 7:43 due



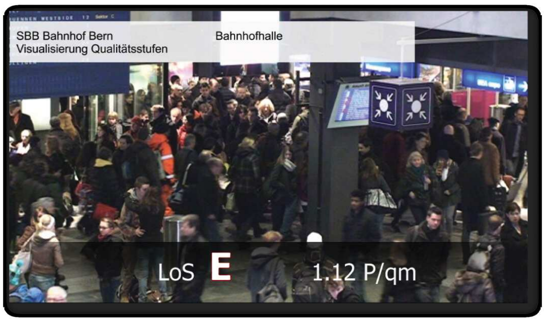
(a) LOS A

(b) LOS B



(c) LOS C

(d) LOS D



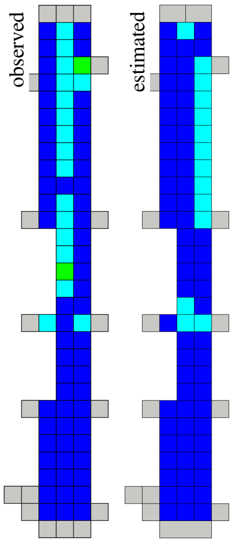
(e) LOS E

	LOS	Pedestrian density
	A	$k < 0.179$ [m^{-2}]
	B	$0.179 \leq k < 0.270$
	C	$0.270 \leq k < 0.455$
	D	$0.455 \leq k < 0.714$
	E	$0.714 \leq k < 1.333$
	F	$1.333 \leq k$

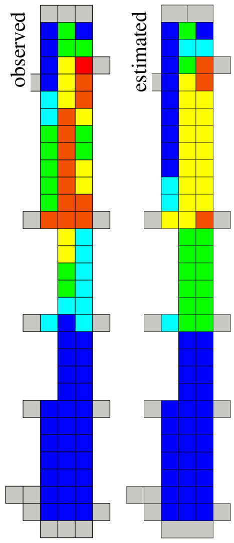
(f) Level-of-service scale provided by NCHRP for pedestrian walkways (HCM, Exhibit 18-3).

Figure 21: Visualization of level of service in terms of pedestrian density in the train station hall of Bern (Source: SBB-I-AT-BZU-PFL) as well as a level of service scale recommended by the US-american transportation authorities.

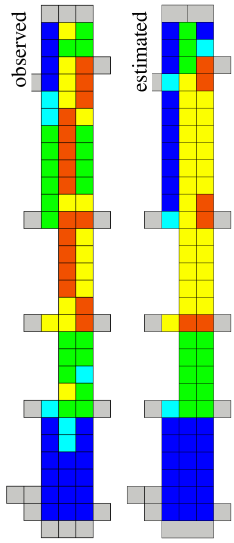
to various incoming trains. The level of service lies in the range between A and E, i.e., densities are generally below 1.333 m^{-2}. The model slightly underestimates the level of congestion during the peak minutes 07:41–07:44. According to the observed data, a region of high density forms along the center line of the corridor. In the model prediction, space is occupied more evenly, i.e., densities are overestimated laterally, and underestimated along the center line. The non-uniform use of space may be due to a lower perceived comfort along walls. Small 'visual'



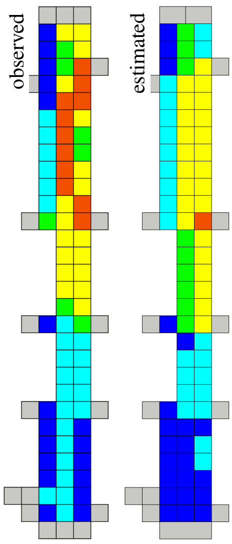
(a) 7:40–7:41: Relatively low occupation.



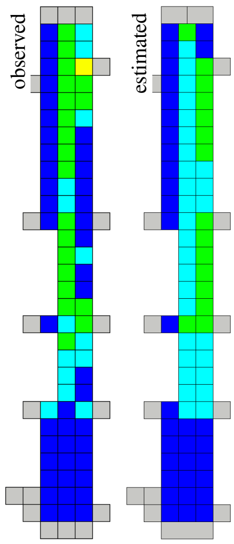
(b) 7:41–7:42: Arrival of train IR 1606 at 7:40:20 on platform 3/4.



(c) 7:42–7:43: Arrival of train IR 706 at 7:41:24 on platform 5/6.



(d) 7:43–7:44: Arrival of train IR 1407 at 7:42:20 on platform 3/4.



(e) 7:44–7:45: Gradual decrease in pedestrian occupation.

Figure 22: Pedestrian density map of PU West in Lausanne railway station for the time period between 7:40 and 7:45 on January 22, 2013. For each time period of one minute, the resulting maps obtained from pedestrian tracking data (observed) and model estimates (estimated) are shown. Color scale see Fig. 21.

obstacles that are present such as trash bins or ticket vending machines may be at the cause. For the overall assessment of the level of service, this phenomenon seems rather of limited importance, and the accuracy of the model is comparable or superior to others, such as the social force model (see Hänseler *et al.,* 2014, for details).

6 Conclusions

The main findings of a three-year research collaboration between EPFL's Transportation Center and SBB's railway access division (I-AT-BZU) have been presented. At the example of Lausanne Railway station, various aspects of pedestrian demand and flow in railway stations have been analyzed, and a dedicated modeling framework has been outlined.

The developed framework consists of a demand estimator and a network loading model. It represents a powerful tool to assess and optimize the design and operation of railway access facilities. Four concrete examples may be mentioned that illustrate its wide range of applicability:

- When dimensioning walking facilities such as a pedestrian underpass, the developed framework provides a precise instrument to optimize infrastructural investments. This applies to both the construction of new facilities and the renovation of existing ones.
- The framework allows to intelligently place sales and service points such as shops or restaurants. For instance, these may be placed such that the 'induced flow', i.e., the additional pedestrian flow caused by these attractors, is minimal, or the framework may be used to assess the attractiveness of certain locations to adjust rental prices.
- The impact of the train timetable on the expected level of service in pedestrian facilities can be predicted. Arrival and departure times of trains, or the train-track assignment may be optimized to minimize the expected congestion on platforms or in walking facilities.
- The developed framework provides a basis for real-time pedestrian monitoring and crowd control in railway stations. To minimize congestion and maximize safety, pedestrian flow could be controlled during peak periods (see Xu *et al.,* 2014, for an example from China), or during mass gatherings such as football games (see Seer *et al.,* 2008, for an example from Austria).

A Acknowledgment

The research presented in this report has been conducted in the framework of 'PedFlux', a three-year research collaboration between EPFL's Transportation Center and SBB's railway access division (I-AT-BZU). Financial support by SBB-CFF-FFS and the Swiss National Science Foundation (SNSF grant #200021-141099 'Pedestrian dynamics: flows and behavior') is thankfully acknowledged.

The following people have contributed to this work: Alexandre Alahi, Nicolas Anken, Aurelius Bernet, Michel Bierlaire, Guy Cooper, Antonin Danalet, Beat Hürzeler, Bilal Farooq, Flurin Hänseler, Herbert Kessler, Sonia Lavadinho, Gael Lederrey, Quentin Mazars-Simon, Nicholas Molyneaux, Thomas Mühlematter, Marija Nikolić, Bonnie Qian, Jérémy Rabasco, Eduard Rojas, Riccardo Scarinci, Michael Schürch, Zina Singer, Oliver Specker, Amanda Stathopoulos, Michaël Thémans, Maëlle Zimmermann.

B References

Alahi, A., L. Bagnato, D. Chanel and A. Alahi (2013) Technical report for SBB network of sensors, *Technical Report*, VisioSafe SA, Switzerland.

Amacker, K. (2012) SBB Facts and Figures, *Annual report*, Swiss Federal Railways (SBB-CFF-FFS), Bern, Switzerland.

Anken, N., F. S. Hänseler and M. Bierlaire (2012) Flux piétonniers dans la gare de Lausanne: Vers l'estimation d'une matrice OD à l'aide des extrapolations voyageurs des CFF, *Internal report (unpublished)*, Ecole Polytechnique Fédérale de Lausanne.

Anken, N., F. S. Hänseler and M. Bierlaire (2013) Analyse des données de VisioSafe: tracking piéton en gare de Lausanne, *Technical Report*, Ecole Polytechnique Fédérale de Lausanne.

Benmoussa, M., F. Ducommun, A. Khalfi, M. Kharouf, A. Koymans, M. Nguyen, A. Raies, M. Vidaud and C. Birchler (2011) Analyse des flux piétonniers en gare de Lausanne, *Technical Report*, Ecole Polytechnique Fédérale de Lausanne.

Cascetta, E. and A. A. Improta (2002) Estimation of travel demand using traffic counts and other data sources, *Applied Optimization*, **63**, 71–91.

Cascetta, E. and M. N. Postorino (2001) Fixed point approaches to the estimation of O/D matrices using traffic counts on congested networks, *Transportation Science*, **35** (2) 134–147.

Fruin, J. J. (1971) Pedestrian planning and design, *Technical Report*.

Hänseler, F. S., M. Bierlaire, B. Farooq and T. Mühlematter (2014) A macroscopic loading model for time-varying pedestrian flows in public walking areas, *Transportation Research Part B: Methodological*, **69**, 60 – 80.

Hänseler, F. S., N. A. Molyneaux and M. Bierlaire (2015) Schedule-based estimation of pedestrian origin-destination demand in railway stations, *TRANSP-OR Report Nr. 150108*, Ecole Polytechnique Fédérale de Lausanne.

Krzywinski, M., J. Schein, İ. Birol, J. Connors, R. Gascoyne, D. Horsman, S. J. Jones and M. A. Marra (2009) Circos: an information aesthetic for comparative genomics, *Genome research*, **19** (9) 1639–1645.

Molyneaux, N. A., F. S. Hänseler and M. Bierlaire (2014) Modeling of train-induced pedestrian flows in railway stations, *Proceedings of the 14th Swiss Transport Research Conference*.

Nikolić, M., M. Bierlaire and B. Farooq (2015) Probabilistic speed-density relationship for pedestrian traffic: a data-driven approach, *Technical Report*, Ecole Polytechnique Fédérale de Lausanne.

Olesen, A. (2006) HOP(P) Schwiiz, *Info Retica*, **2**, 34–35.

Seer, S., D. Bauer, N. Brandle and M. Ray (2008) Estimating pedestrian movement characteristics for crowd control at public transport facilities, paper presented at the *Intelligent Transportation Systems*, 742–747.

Weidmann, U. (1992) *Transporttechnik der Fussgänger*, Schriftenreihe des IVT Nr. 90, Institute for Transport Planning and Systems, ETH Zürich, Switzerland.

Xu, X. Y., J. Liu, H. Y. Li and J. Q. Hu (2014) Analysis of subway station capacity with the use of queueing theory, *Transportation Research Part C: Emerging Technologies*, **38**, 28–43.

Zimmermann, M., F. S. Hänseler and M. Bierlaire (2013) Analysis, comparison and visualization of pedestrian flow patterns in Lausanne CFF train station, Semester thesis, EPFL.