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Analysis of Space Usage on Train Station Platforms Based on Trajectory Data

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Abstract: The functionality of railway platforms could be assessed by level of service concepts. They describe interactions between humans and the built environment and allow one to rate risks due to overcrowding. To improve existing concepts, a detailed analysis of how pedestrians use the space was performed, and new measurement and evaluation methods are introduced. Trajectories of passengers at platforms in Bern and Zurich Hardbrücke (Switzerland) were analysed. Boarding and alighting passengers show different behaviour, considering the travel paths, waiting times and mean speed. Density, speed and flow profiles were exploited and a new measure for the occupation of space is introduced. The analysis has shown that it is necessary to filter the data in order to reach a realistic assessment of the level of service. Three main factors should be considered: the time of day, the times when trains arrive and depart and the platform side. Therefore, density, speed and flow profiles were averaged over one minute and calculated depending on the train arrival. The methodology developed in this article is the basis for enhanced and more specific level of service concepts and offers the possibility to optimise planning of transportation infrastructures with regard to functionality and sustainability.

Keywords: trajectory data; railway platform; boarding; alighting

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1. Introduction

Pedestrian dynamics are of interest in a lot of fields of application, such as the evacuation plans of buildings; the organisation of events; and the designing of public buildings like museums, theatres and stadia. From a theoretical perspective, an interdisciplinary community studies complex phenomena such as stop and go waves, lane formation in bi-directional flows and clogging at bottlenecks. For an overview of this topic, we refer the reader to the biannual conference series [1,2], the review articles [3,4] and the glossary for research on human crowd dynamics [5]. In this article the design of platforms of public transportation facilities is considered.

To evaluate the safety and comfort of pedestrians in public spaces and the impacts of certain optimisation measures, an understanding of the behaviour and motion of pedestrians under normal conditions is essential. Pedestrian facilities are usually valued by capacity analysis and by the means of the level of service concept (LOS). Following the LOS, the degree of comfort is estimated by calculation of densities in chosen time intervals. Besides, level of service concepts allow one to rate whether the load on a system can lead to dangerous situations.

Criteria for the design of pedestrian facilities were given by [6] as pedestrians being able to move freely at their own desired speeds and to avoid crossing persons. Depending on the density, the LOS is defined for walking areas, stairways and queues. Reference [7,8] gave a definition for the LOS for pedestrians walking on a flat surface depending on density. While this estimation is a helpful tool in the evaluation of comfort in facilities where pedestrians continuously move, e.g., walkways and underpasses, the LOS reaches its limits in facilities where waiting pedestrians who are not standing in a queue are present, such as railway platforms. In order to be able to evaluate the usage and comfort of pedestrians at train station platforms, new measures are needed that can be used as the bases for new design methods. This article will generate the groundwork for those measures.

In order to analyse the movement and behaviour of pedestrians on railway platforms, an understanding of the variability of kinds of users and types of usages is essential. On the one hand different types of trains (e.g., regional or long distance trains) depart from the same platform. This very fact already influences the behaviour and distribution of the passengers. For example, due to the fact that most long distance trains offer seat reservations, passengers for those trains are distributed along the platform in a different way than commuters using local or regional trains. Other differences are the amount of luggage and the degree of familiarity with local environments and operations. On the other hand, the pedestrians use the platform in various ways. The users can perform various actions, including boarding, alighting, waiting, reading information boards, etc. The location of, e.g., entry ways or information boards, influences users to move to certain spaces of the platform. Hence, users performing different actions can be associated with different regions of the platform. Moreover the commuters will behave in a different way than persons that are not familiar with the train station. Commuters especially often have specific strategies to reduce travel time or, for example, board the train through doors that minimise the path to the destination.

The train arrivals structure these actions into distinct phases that are regularly repeated, but can also overlap. An exemplary sequence of phases is the arrival of boarders at the platform, followed by a waiting phase before the train arrives; the train arrival and the boarding and alighting process, a phase in which the alighters exit the platform; and subsequently, the arrival of the boarders for the next train.

The goal of this article is the development of a method that describes the dynamics of pedestrian movements at train platforms and the characteristics of waiting behaviour. Based on this, the comfort and functionality and the influences of certain optimisation and safety measures can be evaluated.

Concerning the processes at platforms of train stations, several different topics are discussed in literature. The following section is intended to give a brief overview of certain aspects of these processes.

Reference [9] analysed the capacities of train stations, including stairways, escalators and underpasses. The ration between density and walking speed was only determined for the underpasses and the regions directly in front of the stairs. The platform itself was not considered.

An important factor in train station performance is the time a train spends at the platform. The dwell time of a train consists of a static part—the time needed for opening and closing doors; and a dynamic part, namely, the boarding and alighting process [10–12]. In order to decrease the dwell time, the boarding and alighting times could be reduced. Several studies, both in the field and experimental, were performed. A field study of boarding clusters, an agglomeration of boarding passengers in front of the door after train arrival, was performed by [13] using trajectory data from the railway station in Bern, Switzerland. During boarding, passengers interact with the spatial layout of the platform and form different clusters. Bigger clusters do not necessarily relate to higher densities. As field studies are in most cases not suitable to analyse the effects of certain parameters independently, several experimental studies have been conducted in order to determine factors that have an influence on the boarding and alighting times. Exemplary variations performed were different ratios of boarding and alighting passengers [14] and train design factors (e.g., door widths and number of doors [11,15–19], horizontal and vertical gap sizes [17,18,20,21], vestibule setback [17,18], boarding and alighting through different doors [22]). The types of passengers influence the boarding and alighting times, as age or the presence of luggage are factors that should be considered [23,24].

Moreover the design of the train station, especially that of the platform itself, has an influence on the pedestrian movements. Reference [25,26] found that the boarding and alighting process is not uniform along the platform, as passenger distribution is not even but influenced by the locations of the entry ways. This effect is stronger if, e.g., ticket vending machines are located close to the platform entries [27].

While the boarding and alighting processes were the subjects of several studies, only a little research has been done on the choices of waiting positions and the distribution along the platform. Reference [28] investigated the distribution of passengers at two railway stations in Zurich, Switzerland. In two minute intervals prior to train arrival the waiting positions of the pedestrians were recorded. Favoured waiting spots were determined to be close to obstacles or walls, with the possibility of being leaned against. In these zones the pedestrians seem to accept higher densities than in open spaces without obstacles. Reference [29] found that passengers under normal conditions often wait close to the platform entrances. With the intervention of a guide, waiting places far from entrances are also chosen, which are usually not crowded, causing the passenger distribution to be more even. Reference [30] states that pedestrians arriving with head time to the train arrival cluster at the subsections with seats, beginning with those closest to the entry points. Closer to train departure, persons aim for specific positions or gather at the main entrances. Pedestrians tend to walk not as far along the platform as indicated by the over head signals, which state the stopping places of the trains. A questionnaire survey in [30] revealed that passengers in Sweden do not know that there is information about that (51%) or that it is too difficult to find (29%). Reference [31] analysed the choices of waiting points and distance kept from other waiting passengers. Passengers were found to avoid positions close to the platform edge and to the escalators. Distances between waiting passengers in this study were higher in the morning, but as densities were higher in the evening, this cannot be generalised. Additionally, the presence of social groups, which are likely to stay closer, should be considered. Pedestrian distribution and waiting points are not solely influenced by platform design features but also by the individual passengers strategies. Reference [32] inspected different hypotheses, including: "Alighters leave the train in a section that minimises the walking distance to the desired platform exit". This hypothesis seems to apply, but whether this is caused by the alighters using the closest exit or whether they already move inside the train during their journey and therewith use a door close to their desired exit cannot be distinguished.

Although a lot of research has been done concerning the processes at train stations, the distribution of passengers along the platform; the waiting behaviour; and the density, speed and flow distributions have not been analysed elaborately.

The article is structured as follows: In Section 2 the data sources of the used tracking data and a method to categorise pedestrians as boarding or alighting is shown. In Section 3 the differences in space usage at the platform for boarding and alighting passengers, and density, speed and flow profiles are discussed. In order to determine how often different regions are occupied, a new measure for the occupation of space is introduced in Section 4. The application of the introduced methods can be found in Section 5. The results are discussed in Section 6. The conclusion is given in Section 7.

2. Data Sources and Preparation

Used for the analysis were tracking data acquired by stereo sensors provided by Swiss Federal Railways (SBB AG) (see Supplementary materials section) for the train stations Bern and Zurich Hardbrücke, Switzerland. The datasets were checked with respect to plausibility, but nevertheless, completeness of the trajectories cannot be guaranteed (cf. [33]). The movements of pedestrians inside a sensor area are tracked by recording their positions with a frame rate of 10 frames per second. Due to technical reasons during recording, the tracking data are mirrored horizontally.

2.1. Study Area

Mainly used for this study were data recorded at Bern central station (track 3/4); data from Zurich Hardbrücke were used for comparison. The sensor area covers a length of approximately 50–60 m and includes stairs and a ramp as entry ways (cf. Figure 1).

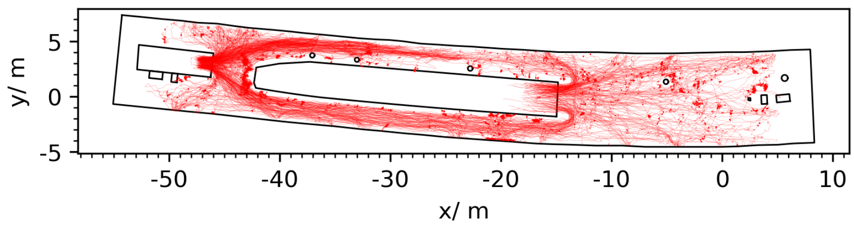
The study area in Bern consists of narrower parts adjacent to a ramp and stairway, obstacle-free parts and parts with small obstacles at the right side of the area, where, e.g., recycle bins and ash trays are present in a smoking area. In addition to the stairs, Zurich Hardbrücke exhibits two elevators in the sensor area. As an obstacle in Zurich an information board is located in the centre part of the platform.

Not all regions of the platform sections are covered by sensors with the same precision. The data quality is affected by height changes of a pedestrian ascending or descending at the stairs and ramps. These regions are excluded from analysis. Some pedestrians are not directly detected when entering the platform—for example, because they where screened by others or the camera loses them for some frames and when they are re-detected, so a new ID number is assigned. When a train is at the platform, coverage of the adjacent platform side close to the train can be subsided. The presence of several pillars at the upper track in Bern leads to some blind spots and therefore to difficulties in detection. Trajectories of pedestrians passing the blind spots behind the pillars cannot be reunited in all cases, which leads to incomplete trajectories. A method to select complete trajectories of boarding and alighting passengers for analysis is described in Section 2.2.

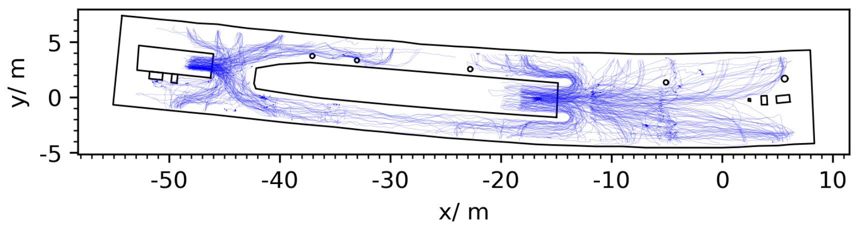
2.2. Categorising Pedestrians at the Platform

In order to divide all pedestrians at the platform according to their goals, different categories were defined.

The layout of the sensor covered area of the platform allows the sorting of the pedestrians into certain user groups. Generally there are three ways to either enter or leave the platform area: (a) the stairs, ramps or elevators; (b) the trains; and (c) the sensor edges at the left and right side of the platform, as only a part of the platform is covered by the sensors. Therefore persons at the platform can be sorted into the groups boarders, alighters and not-assignable persons. Pedestrians are assigned to their groups based on their locations first arrival and their last recorded positions. Correspondingly a boarding person's trajectory begins at the stairs or ramp and ends at the train, while trajectories of alighting passengers begin at the train and end at the stairs or ramps. This definition describes the movement of all boarding and alighting passengers that do not leave the sensor area during their time at the platform. Therefore, only passengers that board or alight the trains locally are included in this definition, which refers to the area covered by the sensors; see Figure 1. All pedestrians that enter or leave the area at the sensor edges are therefore not included as boarding or alighting passengers.



(**a**) Boarding



(**b**) Alighting

Figure 1. Trajectories of (**a**) boarding (red) and (**b**) alighting passengers (blue) at Bern in the afternoon peak hours from 3:30 p.m. to 6:00 p.m. The comparison shows that the use of space differs significantly. While the movement of the alighting passengers is directed and straight-lined, the trajectories of the boarding passengers cover a larger part of the available space and are more scattered.

All pedestrians whose trajectories do not fit the definition of either boarding or alighting are therewith categorised as "not-assignable". This category holds all incomplete trajectories and pedestrians passing through the sensor area. With this categorisation it is possible to ensure that only persons whose trajectories are complete are used for certain parts of the analysis. For the calculation of, e.g., the density at the platform, all persons are included, as pedestrians with incomplete trajectories do contribute to the overall density and filling at the platform.

3. Measures of Space Usage for Platforms

For an analysis of how the railway platforms are used, one has to differentiate between the dynamics of different types of users and the dynamic that is triggered by train arrivals.

3.1. Dynamics of User Groups

For the investigation of the different user types at the platform, only boarding and alighting passengers are taken into account. Those passengers have different goals and therefore also show differing behaviour at the platform, which will be determined in terms of travel paths, waiting time and average speed. The data in this section were taken from the afternoon peak hours from 3:30 p.m. to 6:00 p.m. of 6 February 2019 in Bern. For comparison, data from Zurich Hardbrücke were used. In total 10,267 persons (IDs) were detected during this time, and 1391 persons were categorised as boarding and 1106 as alighting.

The first differences between boarding and alighting persons become visible by comparing the times that they spend at platform (cf. Figure 2). While the majority of alighting pedestrians leave the platform directly and do not stay at the platform for longer than approximately one minute, most boarding passengers arrive in an interval of about 7 minutes prior to the train's arrival, though there are persons that arrive up to 20 minutes earlier than the train they board.

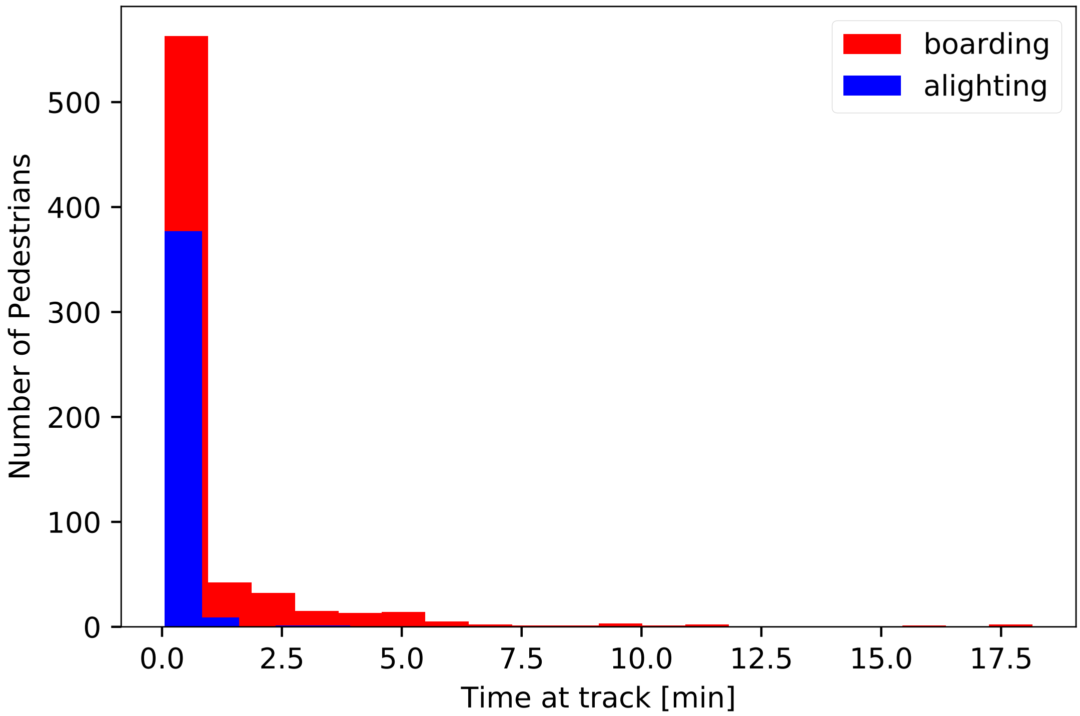
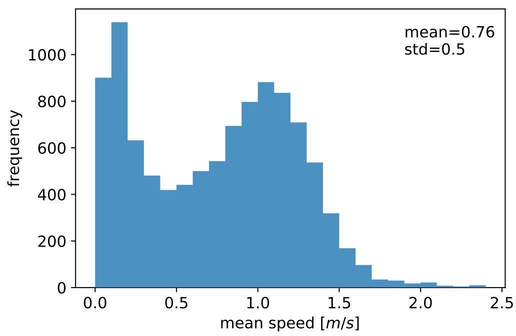


Figure 2. Times that boarding and alighting passengers spend at the platform. While alighting passengers leave the platform directly, boarders spend significantly more time at the platform.

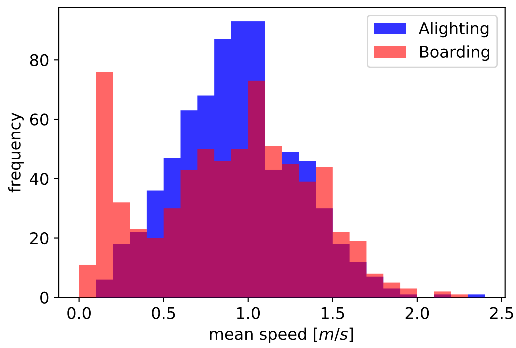
Considering the fact that boarding passengers spend longer times at the platforms, their stay at the platform contains an amount of waiting time. To investigate how this waiting time is used, the trajectories of boarding passengers which were found based on the definition given in Section 2.2 were compared with trajectories of alighting passengers (Figure 1).

When comparing the trajectories of boarding and alighting passengers, different characteristics are apparent. Alighting passengers (blue) mainly walk directly from the train doors to the exits. Trajectories of alighting persons with significant detours are mostly induced by cluster of boarding passengers. The trajectories from boarding passengers (red) show different properties. In contrast to the straight walking behaviour of alighting passengers, the boarding pedestrians tend to walk longer ways and stand at certain places, which can be identified by "knots" in the trajectories. The trajectories of boarding persons cover larger areas on the platform.

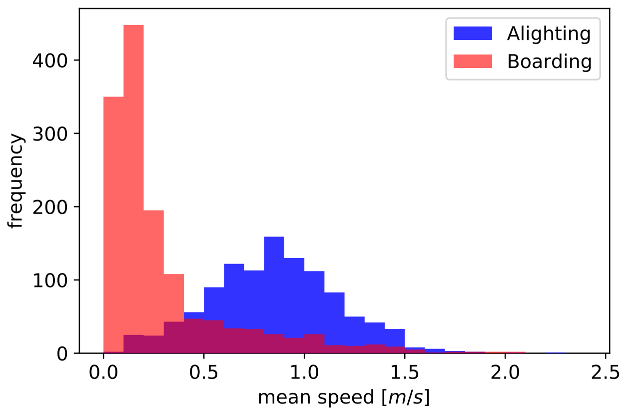
To determine whether the boarders spend their waiting time walking slowly on the platform or whether they pick a waiting spot and stand there for a distinct time, the mean speed of pedestrians at the platform was calculated. While Figure 3a takes all pedestrians into account, Figure 3b only considers pedestrians that alight or board a train in the area of interest.



(**a**) All pedestrians, Bern



(**b**) Only boarding and alighting pedestrians, Bern



(**c**) Only boarding and alighting pedestrians, Zurich Hardbrücke

Figure 3. (**a**) Mean speed of all pedestrians during afternoon peak hours in Bern; (**b**) mean speeds of boarding persons (red) and alighting persons (blue); (**c**) mean speed at Zurich Hardbrücke. Mean speed distribution exhibits a double peak structure, with the lower peak corresponding to boarding passengers and the higher speeds mostly corresponding to alighters. Differences in mean speed distribution of boarding passengers in Bern and Zurich Hardbrücke indicate different waiting behaviour. Many boarders in Bern enter the platform shortly before train arrival.

For all pedestrians a mean speed of 0.76 m/s with a standard deviation of 0.5 was observed.

The histogram of the mean speed distribution of all pedestrians at the platform (c.f. Figure 3a) displays a double peak structure, with one peak at mean speeds of about 0.2 m/s and the other at

1.2 m/s. In Figure 3b the mean speed distribution is divided into boarding and alighting passengers. Boarders in Bern show a mean speed of 0.9 m/s with a standard deviation of 0.5, and alighters a mean speed of 0.95 m/s with a standard deviation of 0.4. Figure 3a,b shows that the mean speeds of alighters in Bern are almost evenly distributed around 1 m/s, while the mean speeds of boarders feature a double peak structure as well. The second peak in the histogram of boarders in Bern is caused by boarding passengers that enter the platform shortly before train arrival.

In order to show how the distribution of mean speed depends on the train station, the mean speed of boarders and alighters in Zurich Hardbrücke is shown in Figure 3c. The distribution of mean speed for all pedestrians in Zurich does not exhibit significant differences to Bern; see Figure 3a. Additionally the numbers of boarders and alighters are comparable. However, the histogram of mean speeds for boarders and alighters features a different structure. Boarding persons in Zurich Hardbrücke show a mean speed of 0.3 m/s with a standard deviation of 0.34, and alighting persons a mean speed of 0.85 m/s with standard deviation of 0.33. In contrast to Bern, most boarding passengers in Zurich Hardbrücke arrive some minutes before their trains and therewith wait at the platform, causing the mean speed to show a one-peak structure.

The differences between boarding passengers also become apparent in the average waiting times of boarders at Bern (1 min) and Zurich Hardbrücke (3 min). It is assumed that the difference in waiting behaviour between Bern and Zurich Hardbrücke is due to the fact that the underpass in Bern offers an attractive waiting area, which is not offered in Zurich. In addition, trains in Bern frequently have long dwell times, enabling passengers to board directly.

Comparing this with the histograms in Figure 3c, it is visible that the peak for lower speeds corresponds to boarding persons, while mainly alighting pedestrians speeds contribute to the second peak.

The observed mean velocity of pedestrians at the platforms is therewith lower than the values for the free velocity given in literature. For example, [7] gives a mean velocity of 1.34 m/s for commuters. The double peak structure of the histogram of mean speed is not seen in other studies concerning pedestrian speeds (cf. [8,34]). Reasons for this are passengers spending a noteworthy amount of time standing while waiting for the train or being part of congestion.

3.2. Density, Speed and Flow Profiles

For density calculations the Voronoi method was used, as introduced in [35]. For each person i in each frame, the area A_i is calculated that includes all points in space that are closer to this person than to all other persons.

The density for a measurement area A is obtained as

$$\langle \rho \rangle_v = \frac{\iint \rho_{xy} dx dy}{A_i} \quad with \quad \rho_{xy} = \begin{cases} \frac{1}{A_i}, & \text{if } (x, y) \in A_i \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

In order to conduct a spatial analysis, as introduced by [36], of the density, speed and flow distributions, the measurement area was parcelled into tiles with sizes of 0.2 by 0.2 m. Densities and speeds were integrated over a time interval of different lengths for the corresponding tiles.

To evaluate the influence of time intervals used for averaging and the differentiation of arrival and departure of trains, various density profiles are illustrated and discussed.

Considering the whole afternoon peak hours at Bern (Figure 4), the highest density values occur at the side of the ramp at the upper track and close to obstacles such as pillars. In those regions the average density reaches up to 0.23 m^{-2}. The area with the highest average density in the upper right corner should be treated with caution, as this region is close to both a pillar and the edge of the sensor area and therewith a correct detection of pedestrians cannot be guaranteed. Density values of about 0.15 to 2.0 m^{-2} occur around the sides of the entry ways and in the obstacle-free area near the ramp. At railway platforms, phases of waiting (where mainly boarding passengers are present) and the boarding and alighting phases alternate. In case of a two-sided platform, those phases can overlap. As boarding passengers arrive at the platform several minutes before their train (cf. Figure 2), time intervals associated with waiting will outweigh the boarding and alighting phases.

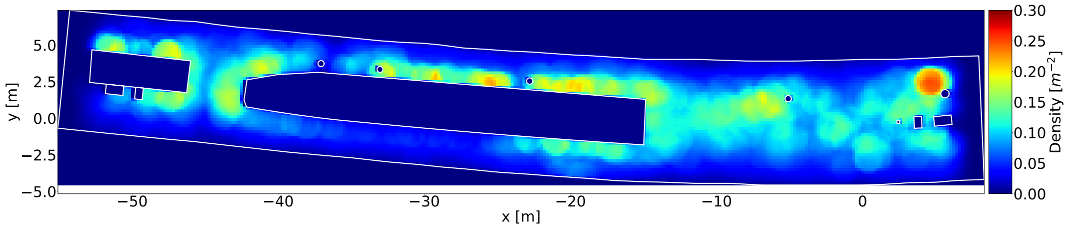


Figure 4. Density profiles in the afternoon peak hours from 3:30 p.m. to 6:00 p.m. in Bern. Densities are integrated over a time interval of 150 min.

In order to investigate how the density distribution at the platform is influenced by the arrival of trains, time intervals of one minute were selected for three, two, one and zero minutes before train arrival. To compare the density distribution for distinct time intervals in relation to train arrival, only phases wherein trains stopped within the sensor area and boarding passengers could be observed are included in Figure 5. In total, 10 trains fulfilled those criteria in the afternoon peak hours in Bern; six trains arrived at the upper track, and four at the lower track. Density profiles averaged over those ten trains are illustrated in Figure 5.

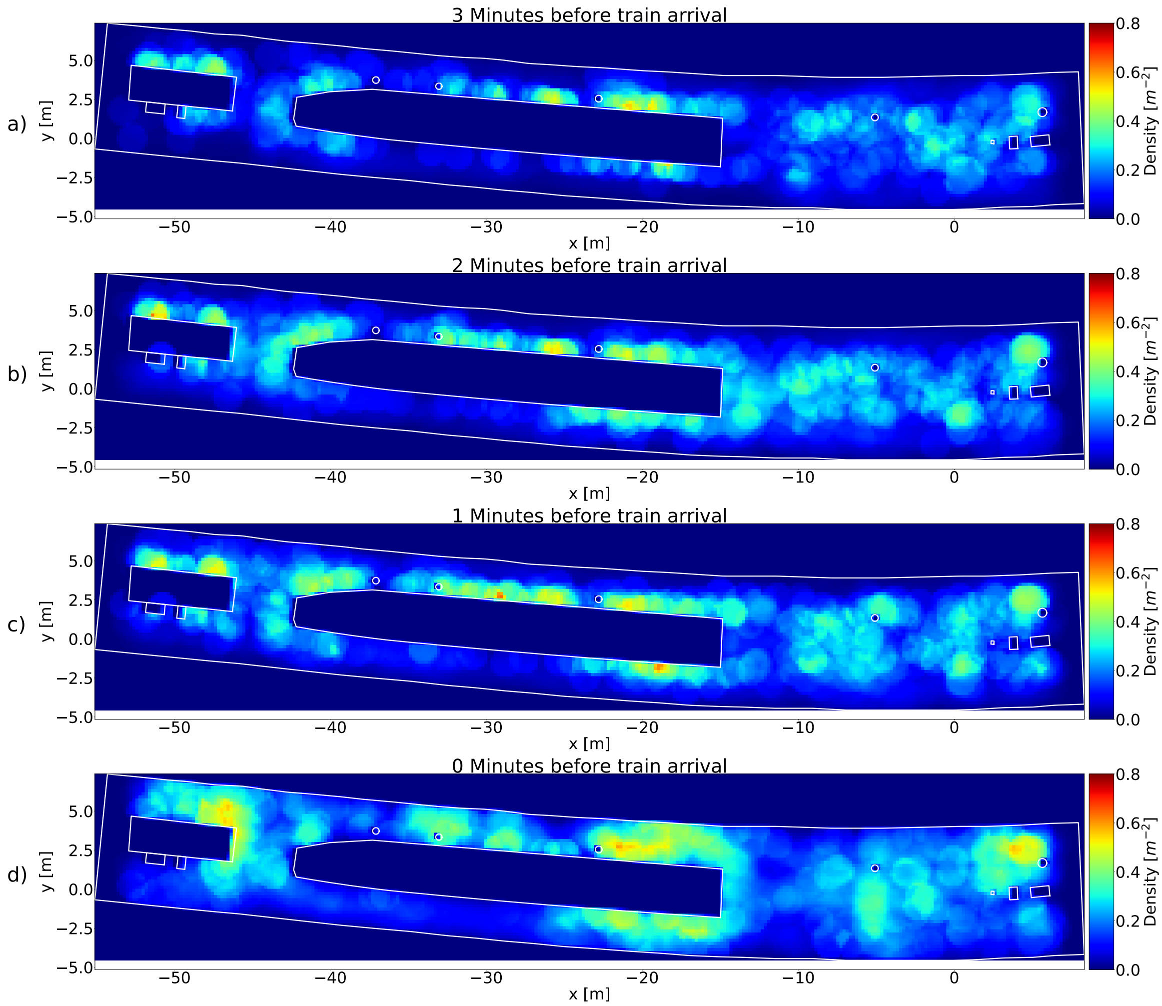


Figure 5. Density profiles for trains in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival.

The data selected in this way gives a more detailed image of the distribution of passengers along the platform. Three minutes before train arrival, mainly the sides of the entry ways are used for waiting (cf. Figure 5a); closer to arrival time, more passengers accumulate at the sides of stairway and ramp, increasing the areas of higher density, and the open areas free of obstacles $x = [-12, 2]$ m are occupied also (cf. Figure 5b,c). The values for the averaged density in the waiting phases (cf. Figure 5a,c) and in the boarding and alighting phases (Figure 5d) do not exceed 0.5–0.6 m^{-2}.

The reason for those low density values is the fact that boarding passengers tend to wait at the side of the track that their train is supposed to arrive. On a two sided platform, where the trains on the opposite tracks do not arrive simultaneously, there will therefore be higher densities on the side where the next train will arrive, while the opposite platform side will likely be empty. Therefore, the subsequent phases of waiting and train arrival on a two sided platform have to be taken into account when providing average values. Taking this into account, only the six trains departing from the upper track are considered in Figure 6.

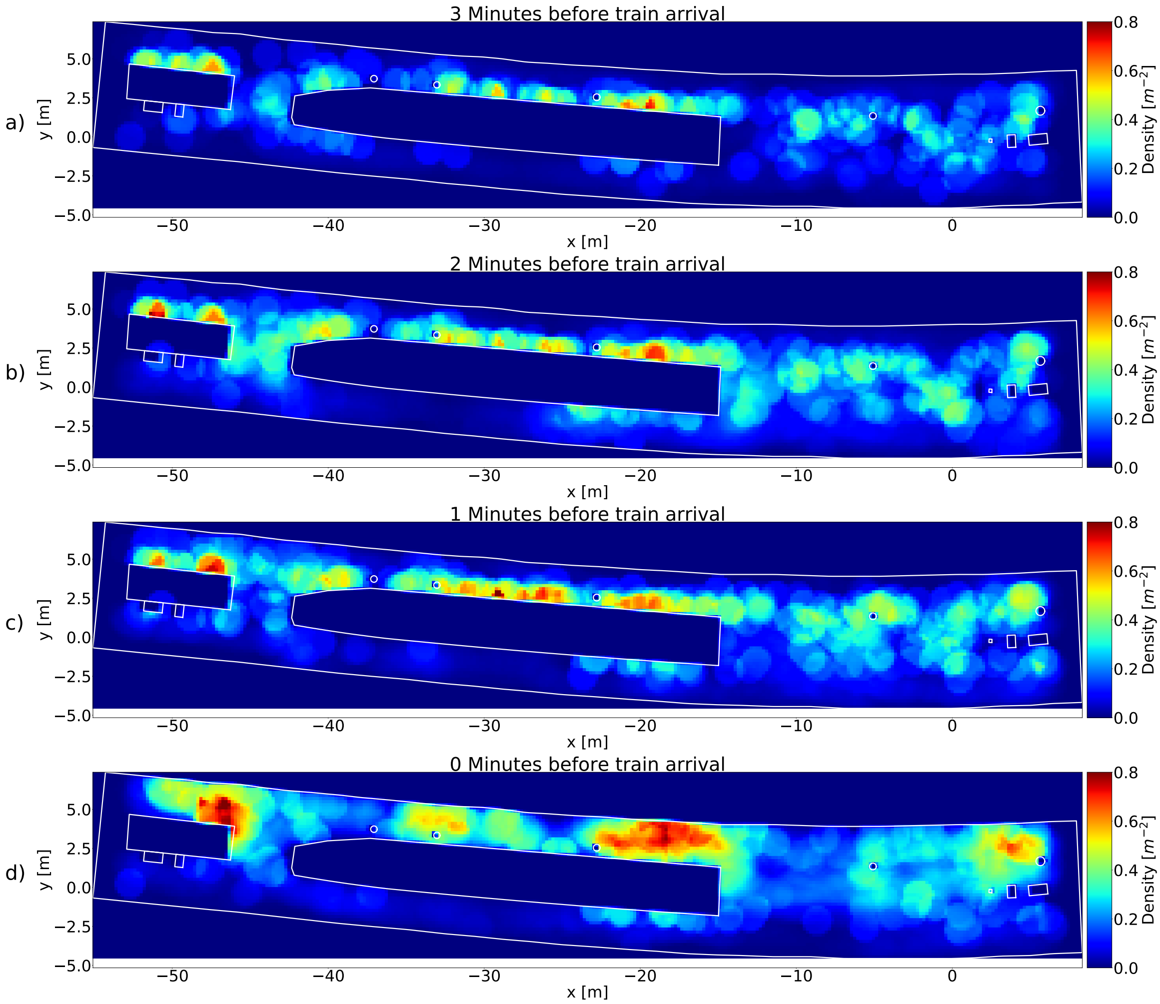


Figure 6. Density profiles for trains at the upper track in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival. Passengers mainly wait on the sides where their trains are scheduled. In areas close to obstacles, higher densities occur during waiting phases than in obstacle-free regions.

Compared to the density profiles in Figure 5 the profiles in Figure 6 reach higher density values (0.5 to 0.7 m^{-2}) at the upper side of the ramp and stairs, while the density in the open area remains similar. This indicates that the open areas are used by passengers waiting for trains at both sides, whereas the ramps are only occupied by boarders of trains at the corresponding track. During the boarding and alighting phase (Figure 6d) the density in the boarding clusters increases to up to 0.8 m^{-2}.

Analysing the tracks of a two sided platform independently gives a more detailed image of the density distributions during both waiting and boarding phases than observing trains stopping on both sides of the platform. While a more generalised statement can be given by including all trains that arrive on the upper track, density values for a single train can still exceed the average densities.

For an evaluation of the speed and flow profiles, the same time intervals and trains were used as for the density profiles in Figure 6. Hence only trains arriving at the upper track were considered.

The speed profiles of the waiting phase (cf. Figure 7a–c) indicate that there is almost no movement on the upper side of the platform, while the lower side of the platform is still used for walking. Higher speed values at the side of the lower track can have different reasons. Higher speeds at the lower track can indicate that due to the higher densities at the upper side of the platform, the lower side is chosen for walking. Pedestrians standing near the stairs and ramps decrease the available walking space, making it difficult for other passengers to pass through. As the time intervals used for averaging the profiles are solely based on the times at which trains arrive at the upper track, it could not be excluded that the data include alighting passengers from a train that arrived at the lower track just before.

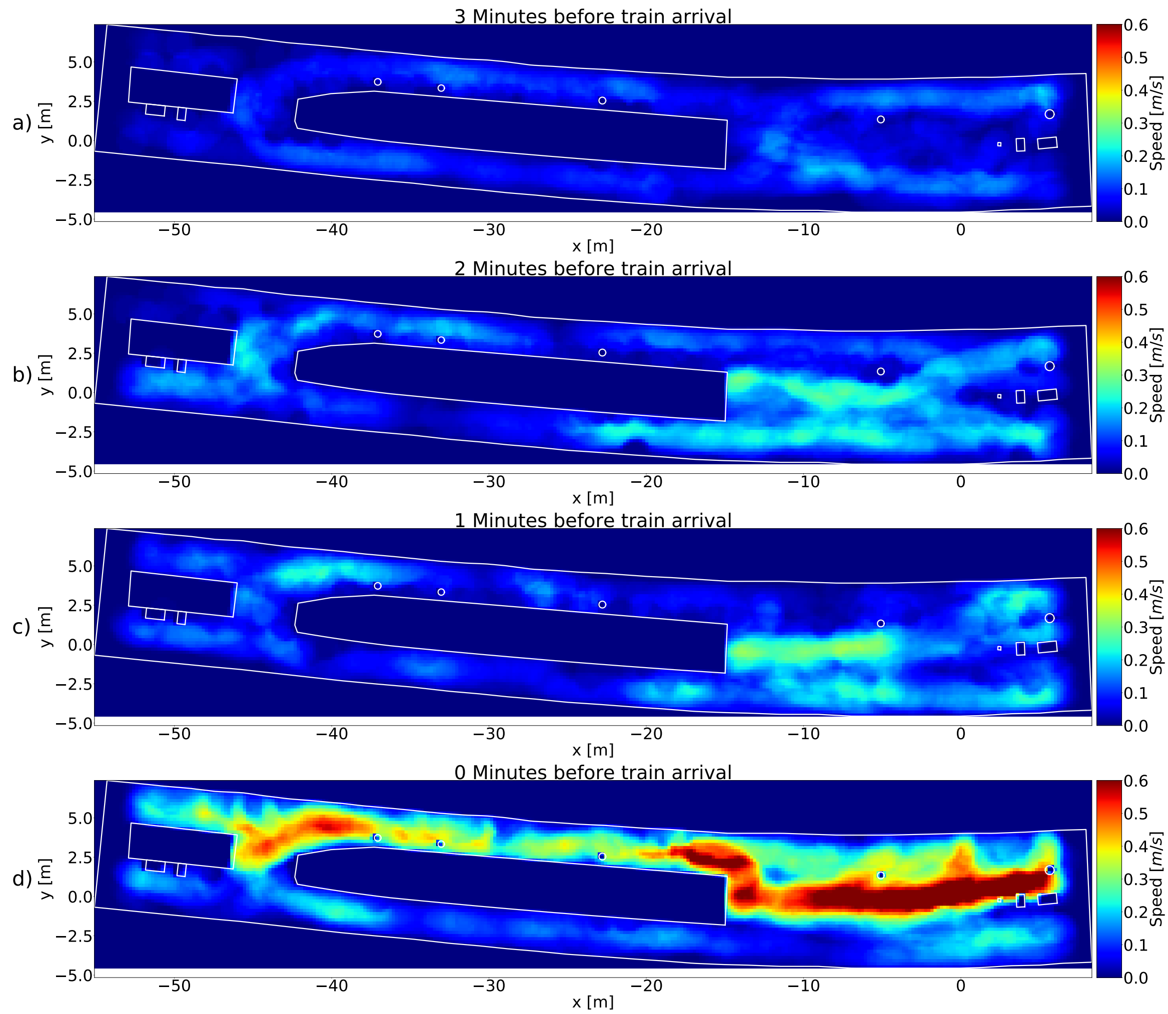


Figure 7. Speed profiles for trains at the upper track in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival. High speeds mainly occur during the boarding and alighting process.

One minute before train arrival (Figure 7c, speeds of 0.25 to 0.35 m/s were observed in the vicinity of the ramp. Those are associated with boarding persons arriving shortly before the train. During the boarding and alighting phase the greatest diversion of speeds along the platform occurs; cf. Figure 7d. While boarders and alighters move towards the train or the platform exits, passengers waiting for another train to arrive generally remain standing. Those standing passengers serve as obstacles for walking pedestrians and therefore have a strong impact on the dynamics at the platform by forming temporary bottlenecks or causing elongations of paths.

The specific flow f is calculated as $f = \rho \cdot v$. Regarding the flow profiles (Figure 8), almost no flow is present during the phases where boarding passengers wait for a train's arrival (Figure 8a–c), as regions where significant density values are observed (cf. Figure 6a–c) do not feature high speeds (cf. Figure 7) and vice versa.

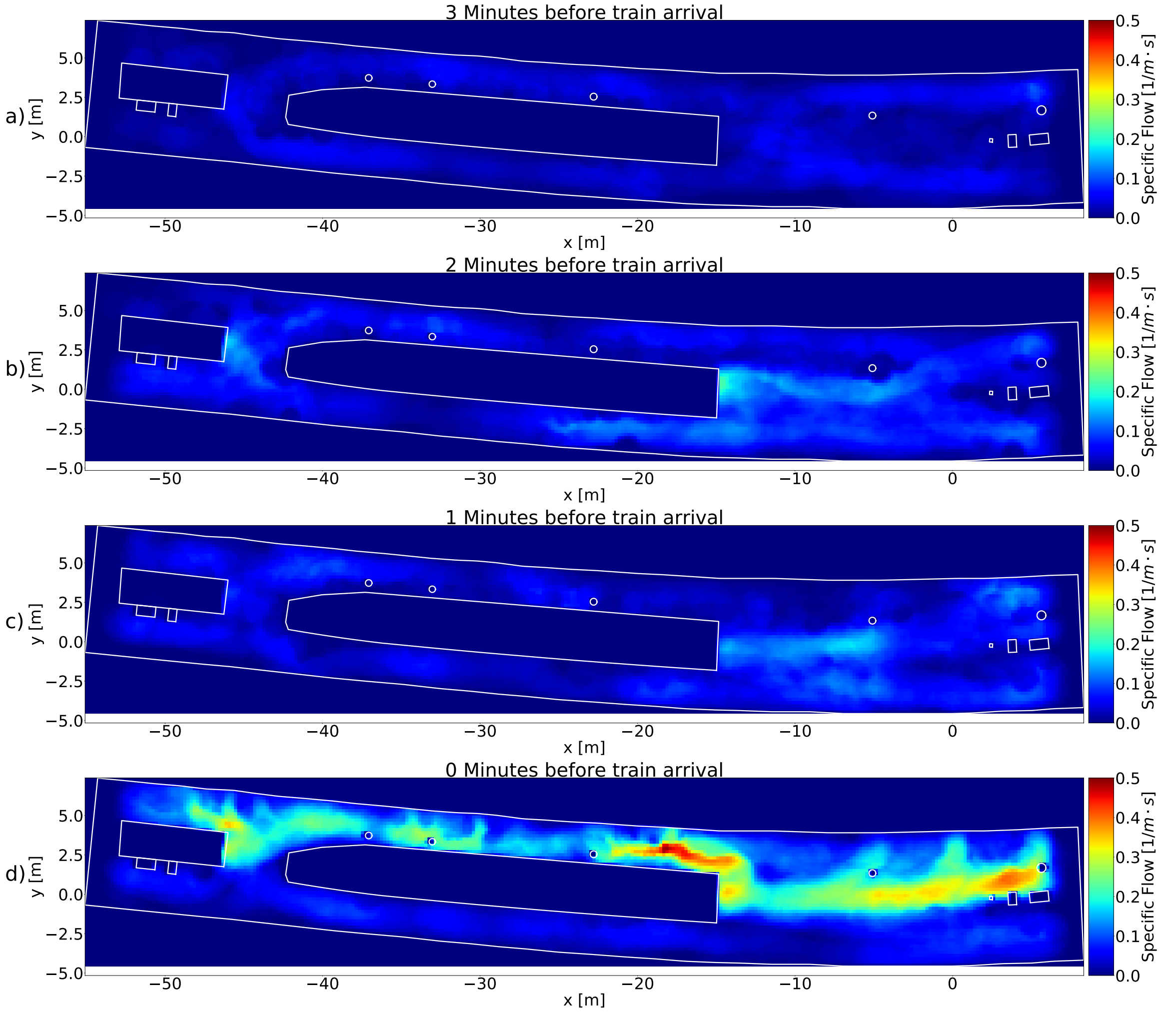


Figure 8. Flow profiles for trains at the upper track in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival. During waiting phases the flows at the platform do not vary regionally; during boarding and alighting, flow profiles show higher flows at the side where the train arrived.

During the boarding and alighting phase the flow profiles (Figure 8d show specific flows from 0.2 to 0.5 1/m·s on the side of the upper track along the paths from train doors to the platform exits. High flux values indicate a dynamic that is associated with high density and at the same time with high speeds. These characteristics indicate situations of maximum capacity and overload. High flow values indicate a dynamic that is associated with high density and at the same time with high speeds. These characteristics indicate situations of maximum capacity and overload.

4. Occupation of Space

Density distributions along the platform during different phases indicate regions of local congestions or crowded waiting places. However, those places are not necessarily the most often occupied or preferred waiting places. Pedestrians standing at individual places, and therewith in low densities, can occupy those places for a longer time span without being represented in density profiles. Nevertheless, those pedestrians narrow the available walking space at the platform and interfere with passing pedestrians. It can be helpful to identify these places and reasons for their use in order to optimise the use of space.

4.1. Calculation

In order to describe the occupation of space at the platform a new measure was developed. First the platform is divided into tiles with a size of 0.5 m by 0.5 m. Those values were selected in order to fit to the average human body's ellipse [8]. In a next step the occupation of every tile is checked for each time frame. If a persons is positioned on a tile, the value assigned to this tile is increased by one. If the tile is not occupied during that frame, the value added is zero. This calculation is performed for all frames in the considered time interval. Afterwards the resulting value of each tile is divided by the number of analysed frames. Hence a measure is created that gives the percentage of time each platform tile is occupied by pedestrians in a distinct time interval.

4.2. Occupation of Space at Different Platforms

To analyse which parts of railway platforms are preferably occupied and how the spatial structure (e.g., width of platform, location of obstacles) or frequency of train arrivals and departures effects the occupation of space, the platforms of two different railway stations (Bern and Zurich Hardbrücke) are considered. The data (afternoon peak hours from 3:30 p.m. to 6:00 p.m.) for Zurich Hardbrücke were taken from 16 May 2019; data from Bern were taken from 6 February 2019.

The occupation of space at the platform in Bern in the afternoon peak hours (Figure 9) shows different regions with higher occupation. Areas in the vicinity of the sides of ramps and stairs are occupied for longer times, as is the smoking area (area with obstacles at the right hand side in Figure 9). As in the analysed time span more trains stopped at the upper track, the space of the lower track appears to be less used. During afternoon peak hours about 20 trains arrive at the platform in Bern (both tracks), but only 10 were featured with boarding passengers.

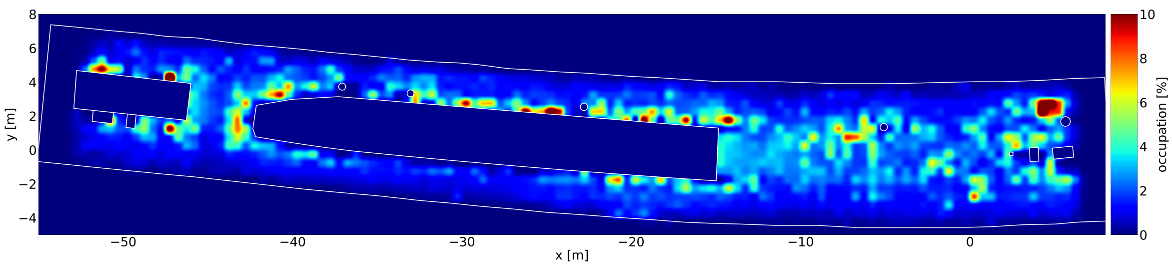


Figure 9. Occupation of space at the platform in Bern in the afternoon peak hours from 3:30 p.m. to 6:00 p.m. Areas close to obstacles and the sides of the entry way are preferably occupied.

With 67 arriving trains in the afternoon peak hours, the frequency of trains is much higher in Zurich Hardbrücke. Therefore the occupation of space is also different; cf. Figure 10.

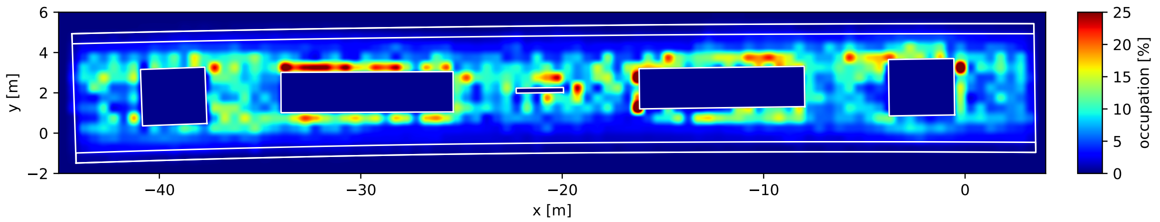


Figure 10. Occupation of space at the platform in Zurich Hardbrücke in the afternoon peak hours from 3:30 p.m. to 6:00 p.m.

The highest values of occupation of space were calculated for regions close to the stairs or elevators and the information board, where the space is occupied for up to 25 % of the peak hours. As only a few people wait at the platforms for times longer than a few minutes, those spots do not represent places occupied by the same people over a long interval of time, but waiting spots that are chosen by several successive passengers.

The occupation of space at both platforms shows that there are almost no pedestrians waiting in the danger zone close to the track for a long time span. Passengers that are not waiting close to obstacles such as stairs, pillars and information boards, tend to prefer places at the centre of the platform.

The calculation of the occupation of space at platforms therewith gives information about places that are preferably used as waiting spots. It can hence be a useful tool to determine how certain modifications of the infrastructure (e.g., removal of obstacles, re-positioning of benches or ticket vending machines) influence the waiting areas and how these modification can be used to optimise the space usage, e.g., by a more uniform distribution of the passengers or preferred waiting places away from entrances to stairs or ramps.

5. Application in Practice

The results presented above can give guidance on possible optimisation strategies for applications. Density profiles provide information on regions where passengers crowd, either at waiting places or in local congestion which can cause safety issues. Flow profiles highlight areas that are highly frequented and therewith important for the performance of the platform. With knowledge of the density and flow profiles and the occupation of space, safety and efficiency of the platform can be improved.

For example, in order to optimise the performance by increasing the flow, areas on the platform that are highly frequented, such as the regions in front of the entries (cf. Figure 8d), should be kept clear of obstacles and as well should not offer any stimuli to stop or wait. In order to allow undisturbed flows to and from the platform, no installations that encourage passengers to stand still should be placed in those regions (e.g., benches or information boards). However, the comfort of passengers improves if informational material and seating arrangements are available at short distances rather than far away from the entrances to the platform (e.g., for passengers carrying luggage). A further example is preferred places for waiting. Often passengers chose places located in the vicinity of the side rails of the entries (cf. Figure 9 and 10). However, passing pedestrians would be forced to walk closer to the platform edges, which is a safety risk and would also interfere with the flow during boarding and alighting. One possible solution would be to increase the attractiveness of alternative waiting areas by installing benches and walls for leaning against or using information boards. Care must be taken to ensure that locations of alternative waiting areas do not reduce the performance of the platform.

This discussion makes it apparent that the goals of optimising safety, comfort and performance do not necessarily coincide and do could lead to different solutions. Furthermore, the impacts of certain optimisation measures will depend on the types of trains that arrive at the platform. In case of regional trains, waiting times of boarding passengers are usually smaller, and therewith different waiting spots are chosen than by boarders of long-distance trains. Hence, the comfort of the passengers will be perceived differently. As a consequence, the assessment of whether optimisation should be performed with respect to performance, safety or comfort has to be decided under consideration of multiple criteria and by considering the types of trains arriving at and departing from the platform in order to find practical solutions.

6. Discussion

The article introduced measurements and evaluation methods that describe the use of space by waiting persons. An example of application trajectories of rail passengers on platforms was analysed. The variability of users and types of usages has been considered.

Boarding and alighting passengers display different behaviour at the platform. While alighters leave the platform in a mostly straight way and do not spend a long time at the platform, boarders usually arrive with head time to their desired train and therefore have to spend some time waiting at the platform. The average waiting time for boarders in Bern is with about 1 minutes lower than in Zurich Hardbrücke (3 min). The reason for this is the fact that many boarders in Bern arrive shortly before the train. Alighters at both stations leave the platform on average in under half a minute. Due to the amount of waiting time, the mean speed of boarders is significantly lower that the mean speed of alighters, causing the histogram of mean speeds of all persons at the platform to form a double peak structure. It is assumed that the underpass in Bern offers an attractive waiting area and reduces the waiting time on the platform.

The analysis has shown that it is necessary to filter the data in order to achieve a realistic assessment of the level of service. Besides the time of the day (morning and afternoon rush hours) train arrivals and departures structure the processes at platforms in time. In case of a two sided platform, phases of waiting and boarding and alighting can overlap. Therefore the choice of time intervals, in length and position, is significant in analysing density, speed and flow profiles at train stations. The position of the chosen time interval in the different phases (waiting or boarding/alighting phase) is substantial in determining the resulting density measurements. Platform sides should be examined separately as well. These effects significantly influence the level of service derived from the density.

In order to distinguish both the waiting and boarding and alighting phases, profiles in this study were averaged over the interval length of one minute and calculated for the times three, two, one and zero minutes prior to train arrival. The resulting density and speed profiles indicate the characteristics of train induced dynamics at the platform. High density clusters either occur in regions where passengers wait preferably, or in front of train doors or stairs due to congestion. In the vicinity of stairs or obstacles, which exhibit the possibility of being leaned against, observed densities are higher than in open spaces free of obstacles. Generally pedestrians wait on the side of the platform, where the train they intend to board will arrive, even if the density on the other side of the platform is much lower. Speed profiles show only minimal movement during the waiting phases, while the highest speeds occur during boarding and alighting phases. Notable flows were only observed during the boarding and alighting phases.

As pedestrians waiting scattered at individual places do not contribute to high density values, but narrow the available platform space, a new measure for the occupation of space was developed. This is a useful tool to determine waiting places as regions that are often occupied in time. A comparison of the occupation of space during the afternoon peak hours at the railway platforms of Bern and Zurich Hardtbrücke showed that for both stations the side rails of the entries (stairs, elevators) are preferred waiting spots. At open spaces pedestrians gravitate towards the middle of the platform and avoid the danger zone close to the tracks. Both the calculation of density profiles and the occupation of space can be used to determine the effects of certain variations in infrastructure (e.g., removal of obstacles, relocation of benches or vending machines) on the way the passengers use the spaces at the platform.

In Section 5 it was argued that for optimising the design of a platform, multi-criterion approaches considering performance, comfort and safety are necessary.

7. Conclusions

The methodology developed here enables a detailed analysis of the level of service and the impacts of certain risk-reduction or optimisation measures. We are planning field experiments and observations in the near future to test constructional changes and their effects on the level of service. At railway stations in Switzerland and Germany the effects of different measures will be analysed. These include information boards, seating, video screens for entertainment, type of lighting, etc. The aim is to optimise the spatial use of platforms and avoid crowded areas.

Supplementary Materials: The data used for this study are available on request addressed to Swiss Federal Railways (SBB AG). Contact: entwicklung.bahnhof@sbb.ch.

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Abbreviations

The following abbreviations are used in this manuscript:

LOS	Level of Service

References

1. Dederichs, A.; Köster, G.; Schadschneider, A. Proceedings of Pedestrian and Evacuation Dynamics 2018. *Collect. Dyn.* **2020**, *5*, 1–543. [CrossRef]
2. Hamdar, S.H. *Traffic and Granular Flow'17*; Springer: New York, NY, USA, 2019.
3. Boltes, M.; Zhang, J.; Tordeux, A.; Schadschneider, A.; Seyfried, A. Empirical results of pedestrian and evacuation dynamics. *Encycl. Complex. Syst. Sci.* **2018**, 1–29. [CrossRef]
4. Chraibi, M.; Tordeux, A.; Schadschneider, A.; Seyfried, A. Modelling of pedestrian and evacuation dynamics. *Encycl. Complex. Syst. Sci.* **2018**, 1–22. [CrossRef]
5. Adrian, J.; Amos, M.; Baratchi, M.; Beermann, M.; Bode, N.; Boltes, M.; Corbetta, A.; Dezecache, G.; Drury, J.; Fu, Z.; et al. A glossary for research on human crowd dynamics. *Collect. Dyn.* **2019**, *4*, 1–13. [CrossRef]
6. Fruin, J.J. *Pedestrian Planning and Design*; Technical Report; Elevator World, Inc.: Mobile, AL, USA, 1971.
7. Weidmann, U. Transporttechnik der Fußgänger: Transporttechnische Eigenschaften des Fußgängerverkehrs, Literaturauswertung. *IVT Schriftenreihe* **1993**, *90*. [CrossRef]
8. Buchmueller, S.; Weidmann, U. Parameters of pedestrians, pedestrian traffic and walking facilities. *IVT Schriftenreihe* **2006**, *132*. [CrossRef]
9. Westphal, J. *Untersuchungen Von Fußgängerbewegungen Auf Bahnhöfen Mit Starkem Nahverkehr*; Lehrstuhl und Institut für Verkehrswesen, Eisenbahnbau u.-betrieb; Technische Universität Hannover: Hannover, Germany, 1971.
10. Manual, H.C. *Highway Capacity Manual*; Transportation Research Board: Washington, DC, USA, 2000; Volume 2.
11. Harris, N.G. Train boarding and alighting rates at high passenger loads. *J. Adv. Transp.* **2006**, *40*, 249–263. [CrossRef]
12. Heinz, W. *Passenger Service Times on Trains. Theory, Measurements and Models*; Trita-INFRA, 03-062; KTH Royal Institute of Technology: Stockholm, Sweden, 2003.

13. Dell'Asin, G.; Hool, J. Pedestrian patterns at railway platforms during boarding: Evidence from a case study in Switzerland. *J. Adv. Transp.* **2018**, *2018*. [CrossRef]
14. Seriani, S.; Fernandez, R.; Luangboriboon, N.; Fujiyama, T. Exploring the Effect of Boarding and Alighting Ratio on Passengers' Behaviour at Metro Stations by Laboratory Experiments. *J. Adv. Transp.* **2019**. [CrossRef]
15. Fernández, R.; Valencia, A.; Seriani, S. On passenger saturation flow in public transport doors. *Transp. Res. Part A Policy Pract.* **2015**, *78*, 102–112. [CrossRef]
16. Fernández, R.; Zegers, P.; Weber, G.; Tyler, N. Influence of platform height, door width, and fare collection on bus dwell time: Laboratory evidence for Santiago de Chile. *Transp. Res. Rec.* **2010**, *2143*, 59–66. [CrossRef]
17. Seriani, S.; Fujiyama, T. Exploring the Effect of Train Design Features on the Boarding and Alighting Time by Laboratory Experiments. *Collect. Dyn.* **2019**, *4*, 1–21. [CrossRef]
18. Fujiyama, T.; Thoreau, R.; Tyler, N. The effects of the design factors of the train-platform interface on pedestrian flow rates. In *Pedestrian and Evacuation Dynamics 2012*; Springer: Cham, Switzerland, 2014; pp. 1163–1173. [CrossRef]
19. Thoreau, R.; Holloway, C.; Bansal, G.; Gharatya, K.; Roan, T.R.; Tyler, N. Train design features affecting boarding and alighting of passengers. *J. Adv. Transp.* **2016**, *50*, 2077–2088. [CrossRef]
20. Holloway, C.; Thoreau, R.; Roan, T.R.; Boampong, D.; Clarke, T.; Watts, D.; Tyler, N. Effect of vertical step height on boarding and alighting time of train passengers. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit.* **2016**, *230*, 1234–1241. [CrossRef]
21. Daamen, W.; Lee, Y.C.; Wiggenraad, P. Boarding and alighting experiments: Overview of setup and performance and some preliminary results. *Transp. Res. Rec.* **2008**, *2042*, 71–81. [CrossRef]
22. Yu, J.; Ji, Y.; Gao, L.; Gao, Q. Optimization of metro passenger organizing of alighting and boarding processes: Simulated evidence from the metro station in Nanjing, China. *Sustainability* **2019**, *11*, 3682. [CrossRef]
23. Yuan, Y.; Yang, M.; Wu, J.; Rasouli, S.; Lei, D. Assessing bus transit service from the perspective of elderly passengers in Harbin, China. *Int. J. Sustain. Transp.* **2019**, *13*, 761–776. [CrossRef]
24. Tirachini, A. Bus dwell time: The effect of different fare collection systems, bus floor level and age of passengers. *Transp. A Transp. Sci.* **2013**, *9*, 28–49. [CrossRef]
25. Wirasinghe, S.; Szplett, D. An investigation of passenger interchange and train standing time at LRT stations: (ii) estimation of standing time. *J. Adv. Transp.* **1984**, *18*, 13–24. [CrossRef]
26. Krstanoski, N. Modelling Passenger Distribution on Metro Station Platform. *Int. J. Traffic Transp. Eng.* **2014**, *4*. [CrossRef]
27. Lam, W.H.; Cheung, C.Y.; Lam, C. A study of crowding effects at the Hong Kong light rail transit stations. *Transp. Res. Part A Policy Pract.* **1999**, *33*, 401–415. [CrossRef]
28. Bosina, E.; Britschgi, S.; Meeder, M.; Weidmann, U. Distribution of passengers on railway platforms. In Proceedings of the 15th Swiss Transport Research Conference, Ascona, Switzerland, 15–17 April 2015.
29. Zhou, M.; Ge, S.; Liu, J.; Dong, H.; Wang, F.Y. Field observation and analysis of waiting passengers at subway platform—A case study of Beijing subway stations. *Phys. A Stat. Mech. Appl.* **2020**, 124779. [CrossRef]
30. Pettersson, P. Passenger Waiting Strategies on Railway Platforms-Effects of Information and Platform Facilities: Case Study Sweden and Japan. 2011. Available online: https://www.diva-portal.org/smash/get/diva2:416058/FULLTEXT01.pdf (accessed on 6 January 2020).
31. Seitz, M.J.; Seer, S.; Klettner, S.; Handel, O.; Köster, G. How Do We Wait? Fundamentals, Characteristics, and Modelling Implications. In *Traffic and Granular Flow'15*; Springer: Cham, Switzerland, 2016; pp. 217–224. [CrossRef]
32. Bosina, E.; Meeder, M.; Weidmann, U. Pedestrian flows on railway platforms. In Proceedings of the Swiss Transport Research Conference, Ascona, Switzerland, 1 July 2017; Volume 17.
33. van den Heuvel, J.; Thurau, J.; Mendelin, M.; Schakenbos, R.; van Ofwegen, M.; Hoogendoorn, S.P. An application of new pedestrian tracking sensors for evaluating platform safety risks at Swiss and Dutch train stations. In *International Conference on Traffic and Granular Flow*; Springer: Cham, Switzerland, 2017; pp. 277–286.

34. Bosina, E.; Weidmann, U. Estimating pedestrian speed using aggregated literature data. *Phys. A Stat. Mech. Appl.* **2017**, *468*, 1–29. [CrossRef]
35. Steffen, B.; Seyfried, A. Methods for measuring pedestrian density, flow, speed and direction with minimal scatter. *Phys. A Stat. Mech. Appl.* **2010**, *389*, 1902–1910. [CrossRef]
36. Liddle, J.; Seyfried, A.; Steffen, B.; Klingsch, W.; Rupprecht, T.; Winkens, A.; Boltes, M. Microscopic insights into pedestrian motion through a bottleneck, resolving spatial and temporal variations. *arXiv* **2011**, arXiv:1105.1532.