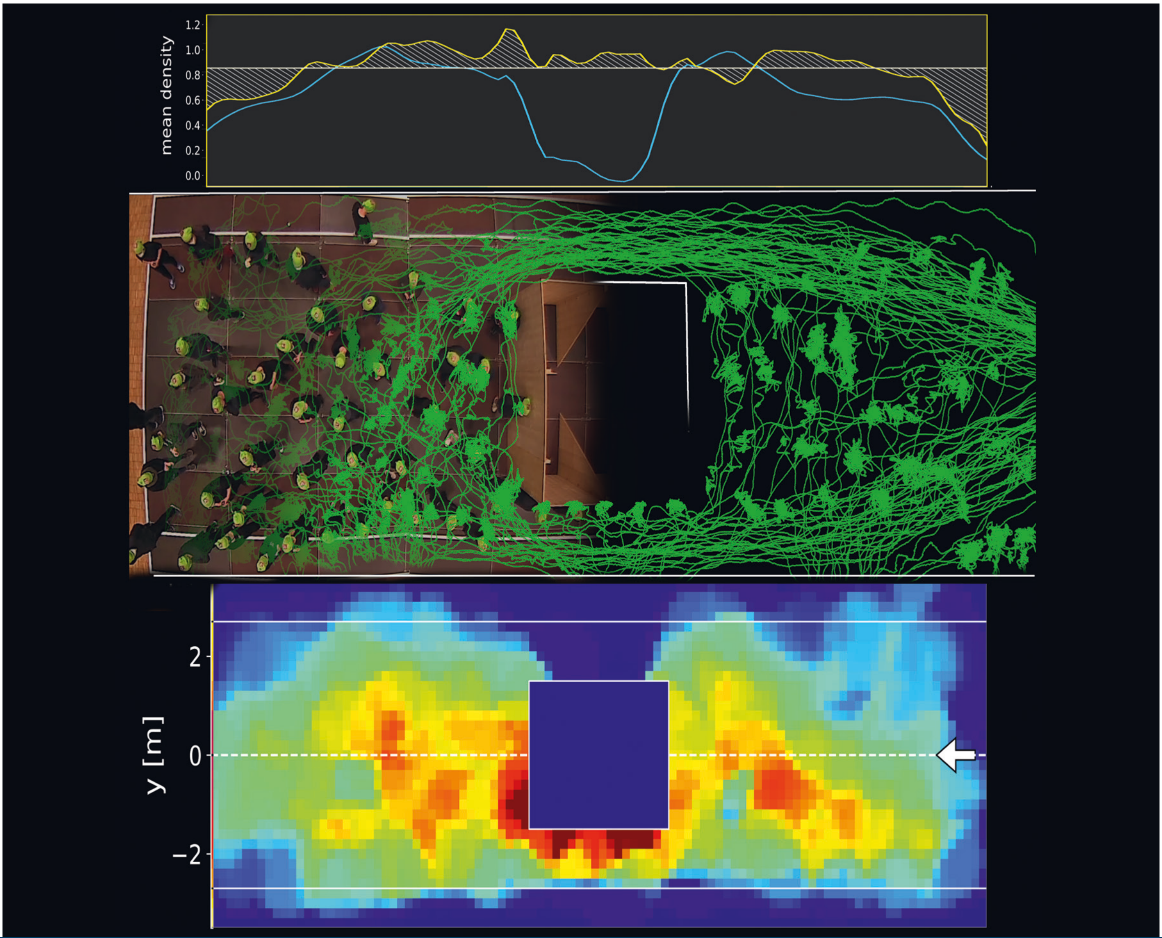

Space Usage and Waiting Pedestrians at Train Station Platforms

Mira Küpper

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Abstract

In many daily situations, like at train station platforms, the dynamics are dominated by the presence of waiting and standing pedestrians. However, pedestrians' waiting behaviour and their interaction with moving persons has rarely been studied to date.

This dissertation consists of three publications which aim at investigating the waiting processes at train station platforms. In publication I, measurement and evaluation methods that describe the use of space by passengers at train stations were developed. Therefore, the influence of train arrivals on density, speed and flow profiles were analysed and a new measure for the occupation of space was introduced. Using trajectory data a method to divide boarding and alighting passengers based on their travel paths was developed. Subsequently, differences between boarding and alighting persons were described in terms of travel times and speed.

In the next step (publication II), the boarding passengers were subdivided into members of social groups and passengers travelling individually. In order to achieve this, a method to identify social groups in trajectory data based on distances and their preservation over time was developed. Additionally, the waiting places were investigated in dependence of group membership and waiting times. Passengers travelling in social groups were found to position themselves in circles in order to ensure the groups' communication and therefore exhibit higher space requirements. This often causes groups to wait in front of the entrances. Passengers with long waiting times often wait at undisturbed places.

In order to reduce the complexity and number of influencing factors, in publication III laboratory experiments in a controlled environment were performed. Those were aiming at an investigation of the influence of obstacles on the platform, the number of passengers and waiting time. These experiments gave insight into processes which were previously masked in the field data. While the density distributions are in-homogeneous, the inter-personal distances show only small variances and are mostly independent of the presence of obstacles and the number of participants. This indicates collective optimisation phenomena within the crowd which have not been observed before. The final waiting positions of passengers can be reproduced by a superposition of floor fields which were estimated based on an optimisation of distances and comfort. This model is not only valid in the context of train stations but can be adapted for other scenarios.

Zusammenfassung

In zahlreichen Alltagssituationen, wie zum Beispiel auf Bahnsteigen, wird die Personendynamik durch die Anwesenheit von wartenden und stehenden Fußgängern dominiert. Allerdings wurde das Warteverhalten sowie die Interaktion von stehenden und sich bewegenden Personen bisher kaum wissenschaftlich untersucht.

Diese Dissertation umfasst drei Publikationen, welche die Prozesse während des Wartens untersuchen. In Publikation I wurden Mess- und Evaluierungsmethoden zur Beschreibung der Raumnutzung durch Passagiere an Bahnhöfen entwickelt. Dazu wurde der Einfluss der einfahrenden Züge auf die Dichte, Geschwindigkeit und Flussprofile analysiert und ein neues Maß zur Beschreibung des Besetzungsgrades eines Raumes eingeführt. Auf Grundlage von Trajektoriendaten wurde eine Methode entwickelt um ein- und aussteigende Personen anhand ihrer Laufwege zu differenzieren und weiterhin deren Unterschiede hinsichtlich Geschwindigkeit und Verweildauer zu beschreiben.

Im nächsten Schritt (Publikation II) wurden die einsteigenden Fahrgäste in Mitglieder von sozialen Gruppen und Einzelpersonen unterteilt. Dazu wurde eine Methodik zur Erkennung von sozialen Gruppen in Trajektoriendaten basierend auf Abständen und deren zeitlicher Erhaltung entwickelt. Desweiteren wurde die Abhängigkeit der bevorzugten Warteorte von der Zugehörigkeit zu einer sozialen Gruppe und der Wartezeit untersucht. Es wurde festgestellt, dass sich Mitglieder von sozialen Gruppen häufig kreisförmig anordnen um die Kommunikation innerhalb der Gruppe zu gewährleisten und dadurch einen größen Raumbedarf aufweisen. Dies führt dazu, dass Gruppen häufig im Bereich der Bahnsteigzugänge warten. Fahrgäste mit langen Wartezeiten hingegen bevorzugen ungestörte Warteplätze.

Um die Komplexität und die Anzahl der Einflussfaktoren zu reduzieren, wurden für Publikation III Laborexperimente unter kontrollierten Bedingungen durchgeführt. Dabei sollte der Einfluss von Aufbauten, der Anzahl der wartenden Fahrgäste und der Wartezeit untersucht werden. Diese Experimente lieferten Einblicke in Prozesse, welche in den Felddaten bisher überlagert und verdeckt wurden. Während die Dichteverteilungen während der Wartephasen inhomogen sind, weisen die Abstände zwischen benachbarten Personen nur geringe Varianzen auf und sind weitgehend unabhängig von Bahnsteigaufbauten und der Anzahl der Personen. Dies deutet auf kollektive Optimierungsphänomene innerhalb der Menschenmenge hin, die in dieser Form bisher nicht beobachtet wurden. Die endgültigen Wartepositionen der

Fahrgäste können durch eine Überlagerung von Bodenfeldern reproduziert werden, die auf Basis einer Entfernungs- und Komfortoptimierung berechnet wurden. Dieses Wartemodell ist nicht nur im Bahnkontext anwendbar, sondern kann auch für andere Szenarien adaptiert werden.

Acknowledgements

The works in this thesis would not have been possible without the endless support of my supervisors, colleagues, family and friends. When I started my PhD project at the end of 2018, I never would have guessed that it involved years of social distancing, working from home, empty train stations, cancelled experiments and pre-recorded conference talks... But despite the challenges and difficult times, my PhD phase also involved lots of laughter, discussions about useful things and complete nonsense, and making new friends. Even though research on over-crowded railway platforms was not in the cards during a pandemic, in the end my PhD-Project did somehow work out and I would like to thank everyone who joined me on the way to achieve this.

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All this would not have been possible without the support of my family. Therefore, a huge thank you goes to my parents. Even though research on pedestrians was probably easier to grasp than geophysics, you always supported me in what I was doing without sometimes even understanding what that actually was... Thanks to Speedy for being the best brother ever and for listening to my endless rants during our trips through the forests.

I could probably go on like this forever and share some more stories about my quite adventurous PhD journey at the University of Wuppertal and the IAS-7 in Jülich. So in case you are reading these lines and are not mentioned by name, you can be assured that I also have some nice memories of the time with you.

List of Publications

Publication I
Küpper, M.; Seyfried, A. "Analysis of Space Usage on Train Station Platforms Based on Trajectory Data". Sustainability 2020, 12, 8325.

Publication II
Küpper, M.; Seyfried, A. "Identification of social groups and waiting pedestrians at railway platforms using trajectory data". PLoS ONE 18(3): e0282526.

Publication III
Küpper, M.; Seyfried, A. "Waiting in crowded places: influence of number of pedestrians, waiting time and obstacles". Journal of the Royal Society Interface, 2023, 20:20230193.

Table of Contents

CHAPTER 1

Introduction

1.1 Motivation

In many daily situations, like in city centres, shopping malls, train stations or while attending events such as concerts, pedestrians are part of larger crowds. Moving inside these crowds can be perceived as uncomfortable and even lead to dangerous situations, for example if there is not enough space for all pedestrians. Despite being part of peoples' daily lives, there are still gaps in understanding the complexity of the processes happening inside crowds, which shows that more research in the field of pedestrian dynamics is needed.

In order to ensure pedestrian's safety in buildings or public spaces, many studies were focused on the movement inside crowds. Several phenomena such as lane formation [1, 2], stop-and-go waves [3–5] or crowding at bottlenecks [6–8] were observed and the influence of different factors, such as e.g., corridor width or motivation, were investigated. Typical measures used to analyse pedestrian movements are density, speed and flow. These measures are linked in the fundamental diagram, cf. [9], that is often used to estimate the capacity of pedestrian facilities. In order to rate the comfort of pedestrians in different densities, level of service concepts are used [10–12]. In these concepts the density is used as a criteria to determine if pedestrians can move freely. In low densities this relates to unhindered movement at a pedestrian's own desired speed, while in high densities the walking speed is restricted and an accumulation of unintended contacts can occur. For example, in [10] depending on the density, the levels A (absolutely free movement) to I (massive crowding) are assigned. While the fundamental diagram and the level of service can indicate how pedestrians feel in certain situations and provide information whether dangerous situations might occur due to density and congestion, these concepts were developed for environments in which pedestrians are moving in uni- or bi-directional flow. They thus reach their limits in situations in which standing pedestrians are present or in multi-dimensional pedestrian streams. Standing pedestrians are solely considered while standing in queues [12]. But obviously standing in a queue with all surrounding persons orienting in the same direction with probably the same destination to reach, is a different situation than waiting at freely chosen spaces in an environment where other people are walking towards their specific destinations. In this context, standing pedestrians and their interaction with moving persons will have a great impact on crowd dynamics and should therefore be considered.

Despite often being neglected in previous research, waiting pedestrians are present in many daily situations, like in city centres, at events, markets or public transportation facilities. In some situations the dynamics are even dominated by waiting pedestrians. Hence, despite being rarely studied in the past, standing and waiting pedestrians and their interaction with moving pedestrians should be investigated. This thesis aims to develop a better understanding of the space usage by waiting pedestrians, which is analysed in the context of train station platforms.

1.2 Train Stations

Train station platforms are places that are predominatingly used for waiting. Waiting and thus often standing pedestrians narrow the available space and can interfere with passing pedestrians. It is therefore important to consider how waiting passengers use the space in order to preserve the platform's performance. Especially assuming an increase of passenger numbers in Central Europe in the near future, an understanding of the waiting behaviour, space usage and motion of passengers is essential.

1.2.1 State of Research

In the following, the state of research concerning the main processes at train station platforms is briefly summarised. For a detailed literature review the reader is referred to the introduction sections of the publications which form this thesis and are included in subsequent chapters.

Train station platforms form a complex environment due to various kinds of users and types of usages that are present simultaneously. Passengers can perform different actions such as boarding, alighting, waiting or passing through. The train arrivals structure those actions into regularly repeating phases, which can overlap in case of two-sided platforms.

An important factor for the performance of train stations is the time that trains spend at the platform. This so called dwell time consists of a static part, which describes the time needed for opening and closing of the doors, and a dynamic part, which consists of the boarding and alighting time [13–16]. In order to reduce the dwell time the boarding and alighting times can be optimised. Several field and experimental studies were focused on determining factors that influence the boarding times, e.g. the indoor setup of the trains, the number of boarders and alighters or the vertical and horizontal gaps [17–31]. Other studies investigated the influences of passengers' characteristics like age, mobility or pedestrians carrying luggage [32–37]. Varying types of passengers, like for example commuters, passengers travelling alone or members of social groups (families or friends), often show different behaviours, movement and waiting strategies [38–49]. A uniform distribution of passengers along the platform was found to lead to a more uniform use of the doors in the boarding process and can thus reduce the boarding times [50, 51]. How passengers choose their waiting places and therewith distribute along the platform was to date subject to fewer studies. Passengers' waiting places were found to be influenced by the platform's infrastructure and setup, e.g. the location of entrances, seats, obstacles, ticket machines or hazard zones [50–61] and by individual strategies [38, 62].

1.2.2 Regulations and Guidelines

Guidelines for the building and structure of train stations are usually regulated at national levels. This thesis does not claim to provide an overview of the regulations in Europe. Only the German regulations will be described here and be briefly compared to the regulations in Switzerland. Therefore, this section gives a summary of the existing regulations for waiting areas at German train stations with the focus on pedestrian density.

Regulations for the planning and design of German train stations are stated within the modules of the regulations sheets of Deutsche Bahn AG "813 - Personenbahnhöfe planen" [63]. Therein the platforms are divided into two areas a) the traffic area, which includes the zones between the safety line and the platform's edge, the entrances and the regions directly in front of the entrances; and b) the service and waiting area. All infrastructure elements like seating arrangements and information boards are to be placed within the latter area, taking into account specified distances to the platform's edges or entrances. As the works in this thesis are focused on waiting passengers, in the following solely the regulations of the service and waiting area are shortly introduced. For this area pedestrian densities are given for both regional and long distance trains for i) normal situations, ii) peak hours and iii) events. The densities for long distance traffic, which are given inside the brackets, are lower in order to consider the space needed for luggage. The following densities are stated in the regulations for the corresponding situations: i) 1.5 (1.0) m^{-2} ii) 2.5 (2.0) m^{-2} and iii) 2.5 m^{-2}. However, it is unclear and not specified how these density values were estimated. Especially considering that waiting passengers are often observed to accumulate at certain places, local densities will be higher than densities estimated for the whole platform area. Additionally, it is not distinguished between waiting and boarding phases.

Regulations in Switzerland [64] for example give different densities depending on the presence of trains. During the waiting phases and thus before the arrival of trains, densities up to 1.0 m^{-2} are allowed at the platform. During the boarding and alighting phases it is distinguished whether one or both sides of the platform are occupied by trains. For the first case a density of 1.0 m^{-2} is stated as accepted maximal density for boarding passengers, in the latter case the density can increase to 2.0 m^{-2}. Thus densities on the platforms are allowed to be higher during simultaneous boarding situations at a two-sided platform.

While regulations for the placement of infrastructural elements relating to the safety of passengers (e.g. the minimum distance to the hazard zones or obstacle free areas in front of the entrances) are given in both the German and Swiss guidelines, the influence these elements have on the distribution of waiting passengers is not mentioned. In order to ensure passenger safety and the functionality of the train stations under increased passenger loads, an understanding of pedestrian waiting behaviour and distribution under normal conditions is essential. Based on this knowledge, strategies aiming to optimise the space usage at platforms can be developed.

The works of this thesis are created within the framework of the research project "CroMa - Crowd Management in Verkehrsinfrastrukturen". One of the project's aims is to develop recommendations for the structural design of train station platforms that can be of use to optimise the passenger distributions and increase the robustness during peak loads. The resulting recommendations, also including measures of crowd management and inter-organisational communications, can be found in [65]. Several aspects leading to these recommendations are results of the works forming this thesis.

1.3 Objectives and Approach

The main goal of this dissertation is to contribute to a methodology that allows to describe waiting pedestrians in crowds.

In order to achieve this, trajectory field data was analysed. Due to recent technical achievements in data collection, large trajectory data sets became available, cf. [66, 67], which offer the opportunity to study variables such as walking speed or social groups [41–45, 67–72] in real-life environments. This promoted the development of methods to analyse the movement of passengers and their distribution based on trajectories, which is also an objective of this thesis. For the works of publication I and II trajectory field data collected at train stations in Switzerland was used. Platforms at the stations Bern and Zürich Hardbrücke are equipped with stereo sensors tracking the movement of passengers with usually 10 frames per second within certain measurement areas. The data thus consists of an unique ID number for each pedestrian, a timestamp and the corresponding x- and y- coordinates of the pedestrian's position at the given timestamp. As only the trajectories but no personal data or videos are recorded, this data is fully privacy conserving and does not allow the identification of individuals. All data sets used in this thesis were checked with respect to plausibility but the completeness of the trajectories can not be guaranteed, cf. [73]. Even though the field studies in this thesis were performed with data from the railway platforms in Switzerland, it can be assumed that the observations and findings are transferable to Germany.

Based on this data, evaluation methods that consider both moving and waiting pedestrians and are therewith applicable to analyse the space usage of passengers at train station platforms are developed. This is done in three steps: first the variability of users and the complexity of the system is analysed (publication I). The influence of train arrivals on the processes at the platform is investigated and a method to divide the users into boarding and alighting passengers is introduced.

Secondly, the boarding passengers are subdivided further into social groups and pedestrians travelling individually (Publication II). This is implemented through a consideration of distances and their preservation over time. A velocity threshold is introduced to identify waiting pedestrians.

In a third step laboratory experiments are performed in a controlled environment which can reduce the number of influencing factors and consequently the complexity (publication III). These are aiming at investigating the influence of obstacles on the platform, the number of passengers and waiting time and give insights into dynamics which were previously masked in the field data. The experiments introduced in publication III were filmed using over-head cameras. The participants wore green caps in order to automatically extract their trajectories using the software PeTrack [74, 75]. Hence, for the analysis and interpretation of the experiments video recordings, trajectories and personal information about the participants can be taken into account.

CHAPTER 2

Results

This thesis consists of three publications, which can be found in subsequent chapters at the end of this thesis. In this chapter only the main research questions and results of the publications are summarised.

2.1 Publication I: Analysis of Space Usage

Publication I generates the groundwork for the design of new measurement methods, which can be used to describe the space usage at railway platforms. In a first step, passengers at train platforms are divided into boarders and alighters depending on their trajectory's origin and destination. This allows for a comparison of travel paths, average speed and waiting times of those two user groups and highlights the differences in behaviour. While alighting passengers mainly cross directly from the train doors to the platform exists, boarding passenger's trajectories cover a larger area of the platform and exhibit certain positions at which the passengers stand and wait which is identifiable through "knots" in the trajectories. The presence of waiting pedestrians causes the distribution of mean speed to display a double peak structure: one peak at lower speeds representing the boarding and waiting passengers and a second peak corresponding to the alighting and moving passengers. This double peak structure of mean speed is not described in other studies on pedestrians speed distribution (cf. [11, 76]).

In a following step, the influence of the arrival of trains on density, speed and flow profiles is investigated. The density on the platform was calculated based on the Voronoi method introduced by [77] and, as well as speed and flow, analysed spatially using an integration over certain time intervals for the parcelled measurement area, cf. [8, 78]. In publication I several different time intervals and their corresponding density profiles are analysed. The train arrivals structure the processes at the platform in waiting and boarding phases. For two-sided platforms these phases can alternate but also overlap in time. As these factors were found to significantly influence the profiles, it is essential to consider the time of train arrival and examine the platform sides separately in order to obtain realistic density values.

The results show that high density clusters either occur at preferable waiting spots or at train doors and stairs due to temporary congestion. Densities are higher in the vicinity of obstacles, which offer the possibility to be leaned against, than in obstacle-free regions. Even when the density on the opposite side of the platform is much lower, passengers mainly wait at the side of the expected train arrival. During waiting phases, speed profiles only show minimal movement. Hence, also notable flows are only observable during boarding and alighting processes.

While density profiles can highlight regions of congestion or crowded waiting places, these regions are not necessarily the mostly used spaces at the platform. Passengers waiting at individual places and therewith in low densities can occupy these places over a larger time interval without being shown in the density profiles. In order to investigate which places are mostly used, the occupation of space is introduced as a new measure. It gives the percentage of time that different regions of the platform are occupied by pedestrians in a certain time interval and therefore identifies places that are preferred waiting spots. For the stations Bern and Zürich Hardbrücke the occupation of space showed that the regions next to the sides of obstacles like stairs are preferred waiting positions. In obstacle-free areas pedestrians orientate towards the middle of the platform and keep a distance to the hazard zones at the track's edges.

Both the calculation of density profiles and the occupation of space can be useful to determine how certain infrastructure variations (e.g. relocation of benches or the removal of obstacles) influence the way passengers use the platform. While modifying the design of railway platforms, it is necessary to consider that the goals of optimising safety, comfort and performance do not necessarily coincide and can also contradict each other.

2.2 Publication II: Social Groups and Waiting Passengers

As it became clear in publication I that the variability of types of users has a strong influence on the processes at train station platforms, in publication II the impact of social groups on the waiting behaviour and distribution was the main objective. The effect of social groups on pedestrian dynamics has become a growing research area. Previous studies revealed differences in the walking behaviour of social groups and individuals, cf. [41–45, 68, 70, 71] and introduced methods to automatically detect social groups in public environments using trajectory data.

These methods, however, identify social groups on the basis of movement patterns and are therefore not applicable to waiting pedestrians. Hence, publication II seeks to fill the gap between studies on social groups and passengers' waiting behaviour. Members of social groups are identified by thresholds of inter-personal distances that are present over certain time intervals. Two pedestrians are considered as members of a social group if they have a distance of less than 1.5 m for 85% of the time they are inside the measurement area simultaneously and a distance of less than 1 m for at least 40% of that time. These time intervals were determined in a parameter study and checked against a ground truth for validation. In order to establish this ground truth two persons (without knowledge of the developed method) manually noted all IDs of passengers, who they perceived to be members of social groups, in an exemplary data set. The set of ID numbers identified by both testers was considered as ground truth and thus an ID number not included in this set but found by the proposed detection method was assumed to be a false positive. The best suited parameter set for the time intervals was defined as the combination of parameters that is able to detect the highest number of members of social groups, but at the same time does not produce any false positives. In this context a false positive is referring to an individual that is erroneously labelled as member of a social group. Due to the necessary observation times, alighting passengers are not included.

As example of application the method was used on a set of trajectories from a platform in Zürich Hardbrücke. The passenger amount and the percentage of passengers travelling in groups was determined for one month, revealing a lower passenger count on weekends but a higher percentage of members of social groups than on workdays. Independent of workdays or weekends, the most frequent group size are pairs. In accordance to [46] each group size occurs less frequently than the next smaller group size. With increasing group size, the group members' mean speed is decreasing. In order to analyse waiting places of individuals and members of social groups, the occupancy by waiting passengers, which are determined by speeds of less than 0.4 m/s, is mapped. This threshold was determined through the mean speed distribution of boarders and alighters from publication I. While individual travellers often wait at the sides of the stairs or obstacles, members of social groups were found to be more likely to wait in front of the entrances. Social groups position themselves in circles, which ensures the groups' communication, but results in higher space requirements. Additionally and regardless of group membership, waiting places are influenced by the total waiting time of the passengers. Passengers with small waiting times wait close to the entrances, while for the longer waiting times the undisturbed rearward sides of stairs are used.

The results suggest that passengers choose their waiting places in accordance to the following criteria, which were adapted based on the work of [79]: a) short walking distances, b) possibility to turn towards the side of train arrival, c) being undisturbed by other pedestrians or avoiding to disturb others, d) ensuring communication. For different kinds of passengers these comfort criteria are ranked differently. Passengers with short waiting times prefer places close to the entrances. With increasing waiting times the comfort of undisturbed waiting places becomes more important. In contrast to individuals, communication is the predominant criterion for social groups, even if this leads to waiting places in the vicinity of highly frequented areas.

The results regarding the different comfort criteria and space requirements of waiting passengers can be used to enhance the level of service concepts of different kinds of users, to avoid temporary bottlenecks which can improve the boarding and alighting process and to increase the robustness of the performance of the station by optimising the passenger distribution.

2.3 Publication III: Waiting Experiments

As the first two publications have shown that many different factors are influencing the passengers at platforms, laboratory experiments were conducted in a controlled environment. While in field observations several (and often unknown) parameters and effects are present simultaneously and therewith superpose, laboratory experiments allow to focus on certain factors and study those in detail.

The aim of publication III is to investigate how platform obstacles, the number of participants and the waiting time influence the distribution of waiting passengers. Therefore, a mock-up platform with the size of 7 x 20 metres was used, which was either equipped with no obstacle, a narrow or a wide obstacle. The number of participants was either 40 or 100 and in the first case also the waiting time was varied to be either two or four minutes. After each experiment the participants were asked to express their perception of comfort during the experiment by pressing a button on a mood button terminal. Questionnaires, among other questions asking for the perception of available space and density, were only used in selected runs. As the side of the expected train arrival was not varied and known to the participants due to the instructions, their attention is focused towards the corresponding side causing an alignment of viewing directions.

Obstacles were found to have a two-sided effect: the side facing towards the side of train arrival is a preferred waiting spot while the opposite side has a repulsive effect. Possible reasons for the attractiveness of waiting places close to obstacles are the comfort those provide by offering the possibility to be leaned against and the reduction of the number of neighbouring persons, especially those standing behind. However, the side of the obstacle facing towards the opposite track is not used as a waiting spot as the line of sight towards the train arrival is blocked, which makes these regions unattractive. Narrow obstacles cause the passengers to mainly choose waiting positions at the side where the train is expected, while wide obstacles, despite blocking the passenger's view, were found to lead to distributions that were more even along the platform.

With an increase of the waiting time (from two to four minutes in runs with 40 participants) some participants were observed to slowly walk around instead of waiting at a fixed position, which did not occur in runs with the shorter waiting time. This might indicate that during longer waiting times the desire for waiting place optimisation is increased. Due to the limited number of variations, the influence of waiting time on higher passenger numbers was not investigated. Considering the participants' rating of the experiments, an increase of waiting time has almost the same effect as increase by a factor of more than two of the number of passengers as both decrease the rating significantly.

Even though the available space per person is larger for runs with less participants, the inter-personal distances are distributed around 1.0 - 1.2 m in all runs. According to the work of [80] these distances are extending into the "personal zone" and hence smaller than expected in a public environment. As the distance-zones of [80] were derived in face-to-face situations, while waiting passengers at train stations stand aligned behind each other facing towards train arrival, an adaption of the personal space concept might be necessary depending on the context. The phenomenon of maintaining equal inter-personal distances was already described by [81]: maximising the distance to other pedestrians leads to equal distances and eventually the available space is covered completely. The latter is however not observable in the experiments, as some regions of the platform remain unused. This might be caused by the chosen waiting times; the limited variations do not allow a statement whether a further increased waiting time would lead to a uniform coverage of the whole space.

The criteria for the choice of waiting places determined in the context of social groups in publication II were abstracted and reformulated based on the work of [79], taking into account the new findings. In order to reproduce the final distribution of waiting places, qualitative floor fields are estimated based on optimisation of distances and comfort. The factors influencing the choice of waiting places are now defined as: a) distance to entrance, b) distance to exit, c) repulsion of hazard zones, d) flow avoidance and e) stationary obstacles. A superposition of the floor fields of these factors resulted in patterns comparable to the results of the experiments and can benefit in the modelling of waiting passengers. Despite being developed for the context of a train station platform, the suggested floor fields can be adapted for other usages.

CHAPTER 3

Discussion and Outlook

The works of this thesis were aiming at investigating the processes at train station platforms by narrowing the research questions and corresponding difficulties in each step. This approach resulted in the detection of processes which were previously screened and superposed. However, this did not necessarily make the findings easier to interpret. Especially the data from the laboratory experiments leaves room for future investigations, as some questions remain unanswered or only arose during the interpretation of the data. In the first part of this chapter, research questions and findings will be discussed that were not elaborated in the three publications but could give useful practical insights into the processes at train stations and therefore be of interest for guidelines on the design of train stations. In the second part, the methodological findings are abstracted and discussed outside the context of train station platforms, and an outlook of possible future research is given.

Since the experiments were performed on a two-sided platform where only one train was expected to arrive, the interaction effect between passengers waiting for trains at opposing sides could not be considered. Especially in situations with higher numbers of participants and therewith increased densities, these effects will become important. In almost all runs with 100 participants the opposed track side is used for walking to the side further away from the entrance; this would be hindered in case of waiting passengers at that side. These interaction processes were also not studied elaborately in the field data as these are mainly of interest in case of a high passenger amount. For publications I and II situations during normal traffic were analysed and the stations Bern and Zürich Hardbrücke did not exhibit high passenger densities. In case of a high passenger load, e.g., caused by a local event, the interaction between waiting passengers at opposite platform sides can be useful to analyse.

As concepts such as the level of service assign the comfort of pedestrians to certain density values, it is necessary to study how people perceive the density. For example, does the comfort of waiting pedestrians simply decrease with increasing density or are there adaption effects like observed in [82]? Does one occurrence of high density, for example in a temporary congestion, lead to an overall negative rating of the whole waiting time or is the density perception more complex? An attempt to study these questions was made by a questionnaire survey during the experiments of publication III. However, the questionnaires, which were only used in selected runs in the experiments, did not posses suitable variances as the rating of density and available space was always very positive, despite the varying numbers of participants and therewith varying densities. As this might indicate that the densities reached in the experiments were not high enough to be the cause of discomfort, experiments and questionnaire studies with an increased number of participants could be used to investigate if and how the density perception is correlated to the overall density. Laboratory experiments on this matter would even allow to study whether densities are perceived differently at certain waiting places, like e.g. in the vicinity of obstacles or entrances, as the questionnaires can be linked to the waiting places and local densities of the individual participants. It should however be kept in mind that the results achieved under experimental conditions might differ from real-life scenarios as in those situations the perception is also influenced by factors such as stress, shortage of time or moods caused by factors unrelated to the waiting environment.

Closely linked to the perception of densities are the distances between the pedestrians. In the experiments the inter-personal distances were found to be around 1.0-1.2 m, mostly independent of the total number of participants. In field studies this was not subjected as the distances between the passengers were only used in identifying members of social groups. If these equal distances are observable in field data as well, this threshold can be used in the planning of waiting areas at train station platforms. Passengers standing in 1.0 - 1.2 m distance correspond to densities of 1 - 0.7 m^{-2}, which can be used in the guidelines and regulations (cf. section 1.2.2) and update the current values. As participants chose these distances without any need even in situations with a low passenger number, these densities seem to correspond to a density that still ensures the passengers' comfort and can therewith be used to determine the maximum number of passengers in the waiting areas.

The three publications mainly focused on the waiting phases, hence the filling processes were not studied in detail. Pedestrians entering the platform have to decide on a waiting place under consideration of the setup of the waiting areas, some personal preferences and the positions of pedestrians already present. If the passengers already located at the platform act as orientation for the subsequently following pedestrians or rather as repulsive was not investigated.

While the works of this thesis were conducted in the context of railway platforms, the results can be transferred to other situations in which waiting or standing pedestrians are predominant. For example, filling and position finding processes are (like waiting) present in many daily situations, like in elevators or entrance halls of public buildings.

While the final distribution of waiting places will probably be describable with an adaption of the floor fields introduced in publication III and by [79], it is currently unclear if also the equal inter-personal distances can be observed in other situations. In this context several research question could follow. The equal distances are in accordance to the work of [81], but in the experiments not the whole available space is covered. However, the inter-personal distances were studied during the waiting time which started after the last participant had entered the platform. Hence, the filling process and therewith a probable adaption of the inter-personal distances caused by the entering of the next participant was not investigated. It is unknown if the equal distances are ubiquitous or the final result of these adaption processes. Additionally, it was not studied whether an increase of waiting time would eventually lead to a complete coverage of the whole available space as pedestrians adapt the inter-personal distances to maximise the distance to others.

In abstract terms, it can be stated that the processes leading to the observations of Goffman [81] and their limitations would be of interest for future studies. How do the equal inter-personal distances propagate through the crowd, even if the pedestrians are lacking a total overview of the situation due to local densities or even obstacles that block the view? What are the spatial limits of these processes?

Even though filling processes have to date only rarely been studied, many experiments or observations already include them, for example during the positioning process at the beginning of queuing experiments. Therefore, data to study the processes of position finding to a certain extent already exists, but was never analysed with respect to inter-personal distances, even though care should be taken to rule out misinterpretations due to influences caused by the experiment's instructions.

As it became clear while interpreting the results of this thesis, studies on the inflow and position finding of pedestrians would benefit from a combination of methods from natural sciences and social-psychology. This would for example allow to link data such as distances, density and the perception of comfort experienced by the pedestrians, as well as give a much more differentiated view on the interpretation of data. On the one hand, the subjective experience of pedestrians influences positioning and distancing, therefore social-psychology can help to explain the results more in-depth. On the other hand, the results of a trajectory evaluation (human-environment interaction) help to better map aspects of the subjective experience psychologically. Hence, processes present in crowds can not solely be explained and described by physical measures but need a combination of different disciplines and research fields.

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PUBLICATION I

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

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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

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) 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

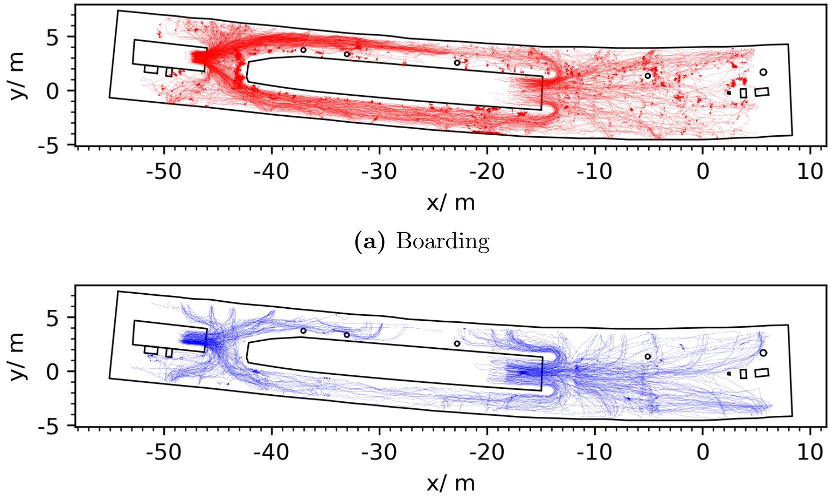
In order to divide all pedestrians at the platform according to their goals, different categories were defined.

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.

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.



(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.

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.

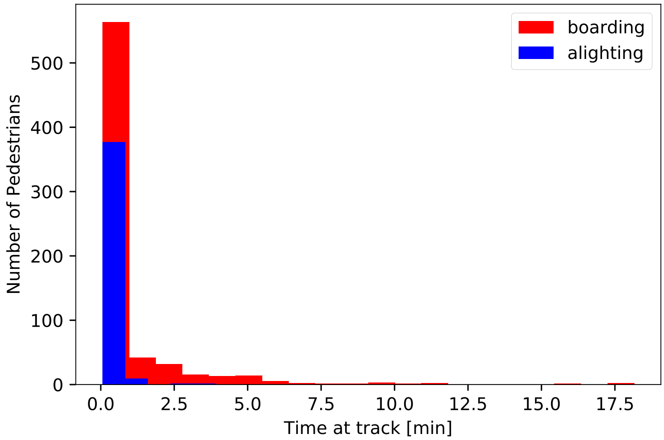


Figure 2: Times that boarding and alighting passengers spend at the platform. While alighting passengers leave the platform directly, boarders spend significantly more time at the platform.

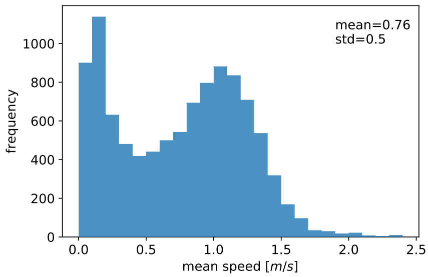
Considering the fact that boarding passengers spend longer times at the platforms, their stay at the platform contains an amount of waiting time. To investigate how this waiting time is used, the trajectories of boarding passengers which were found based on the definition given in Section 2.2 were compared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

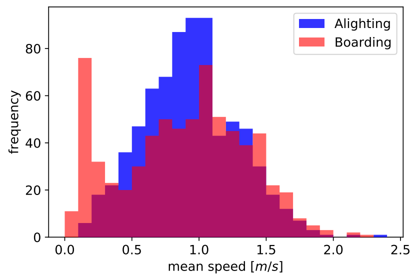
To determine whether the boarders spend their waiting time walking slowly on the platform or whether they pick a waiting spot and stand there for a distinct time, the mean speed of pedestrians at the platform was calculated. While Figure 3a takes all pedestrians into account, Figure 3b only considers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

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

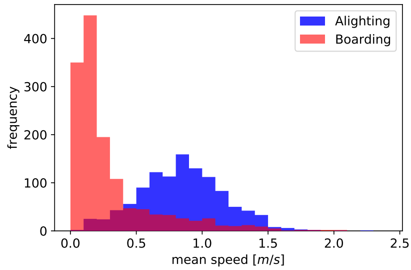
The histogram of the mean speed distribution of all pedestrians at the platform (c.f. Figure 3a) displays a double peak structure, with one peak at mean speeds of about 0.2 m/s and the other at 1.2 m/s. In Figure 3b the mean speed distribution is divided into boarding and alighting passengers. Boarders in Bern show a mean speed of 0.9 m/s with a standard deviation of 0.5, and alighters a mean speed of



(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.

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

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

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.

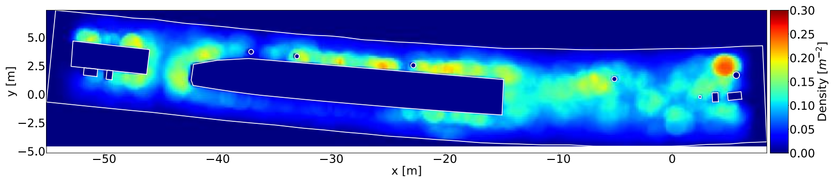


Figure 4: Density profiles in the afternoon peak hours from 3:30 p.m. to 6:00 p.m. in Bern. Densities are integrated over a time interval of 150 min.

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.

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. The data selected

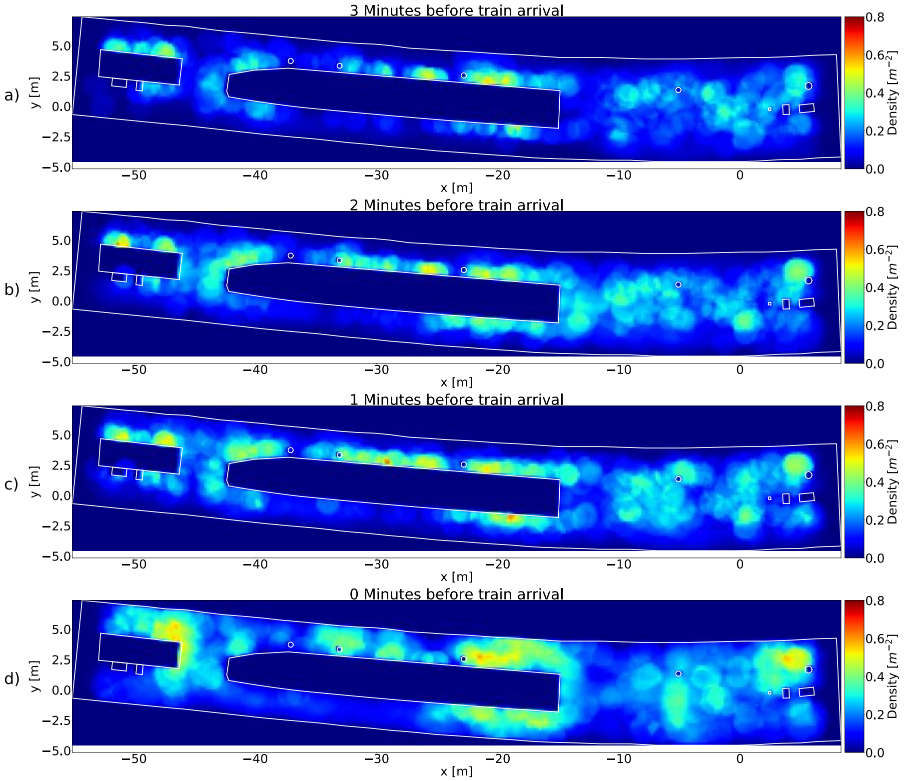


Figure 5: Density profiles for trains in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival.

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. Compared to the density profiles in Figure 5 the profiles in

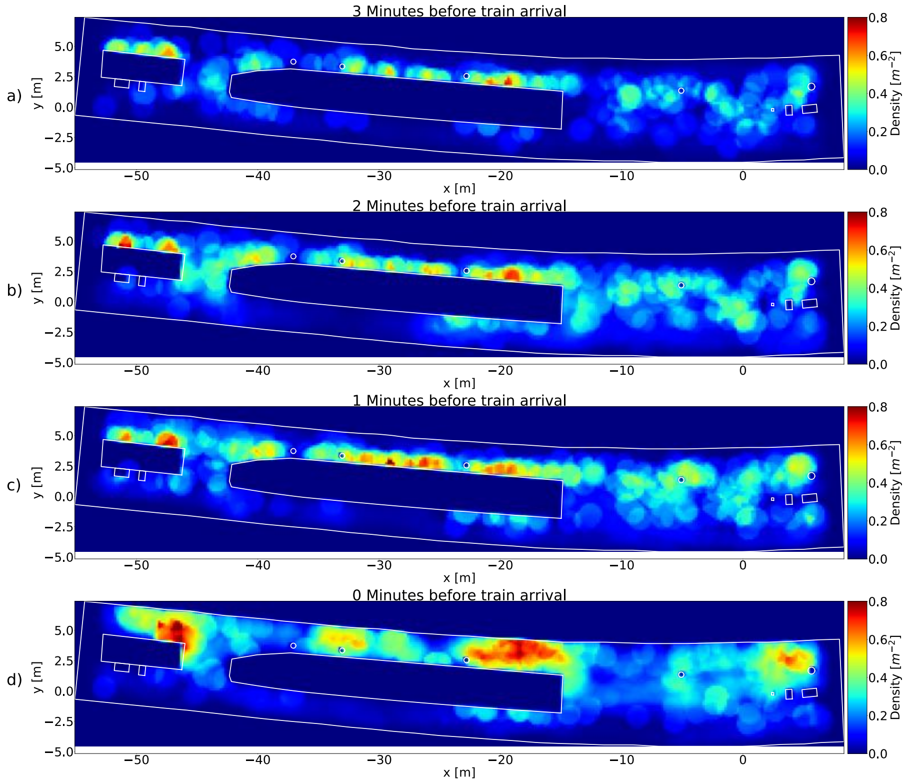


Figure 6: Density profiles for trains at the upper track in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival. Passengers mainly wait on the sides where their trains are scheduled. In areas close to obstacles, higher densities occur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

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.

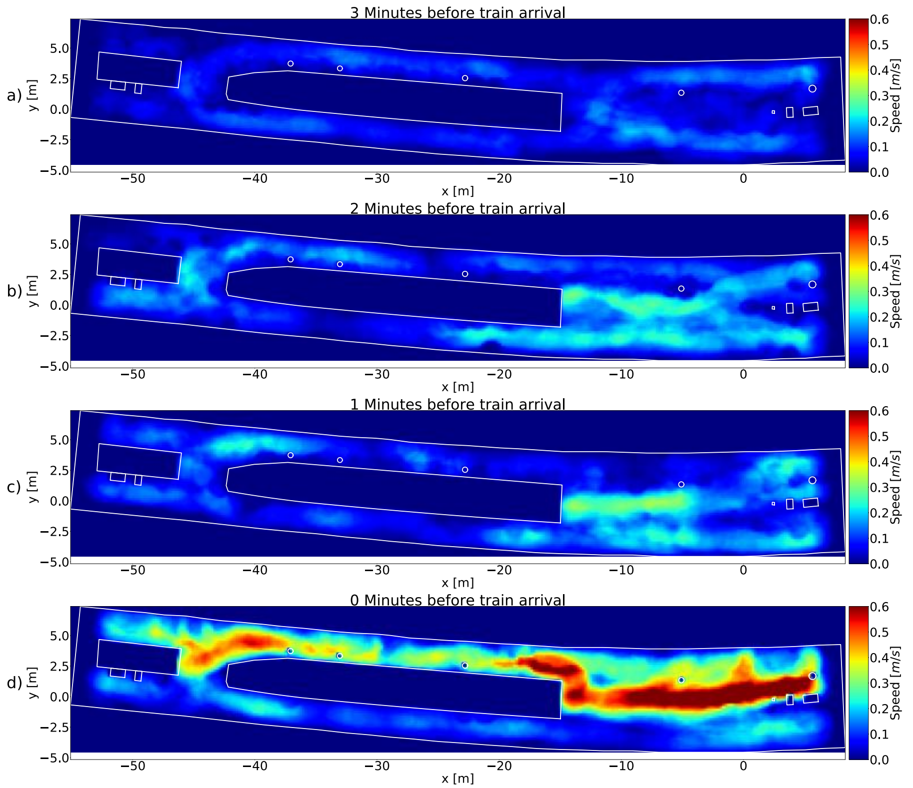


Figure 7: Speed profiles for trains at the upper track in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival. High speeds mainly occur during the boarding and alighting process.

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.

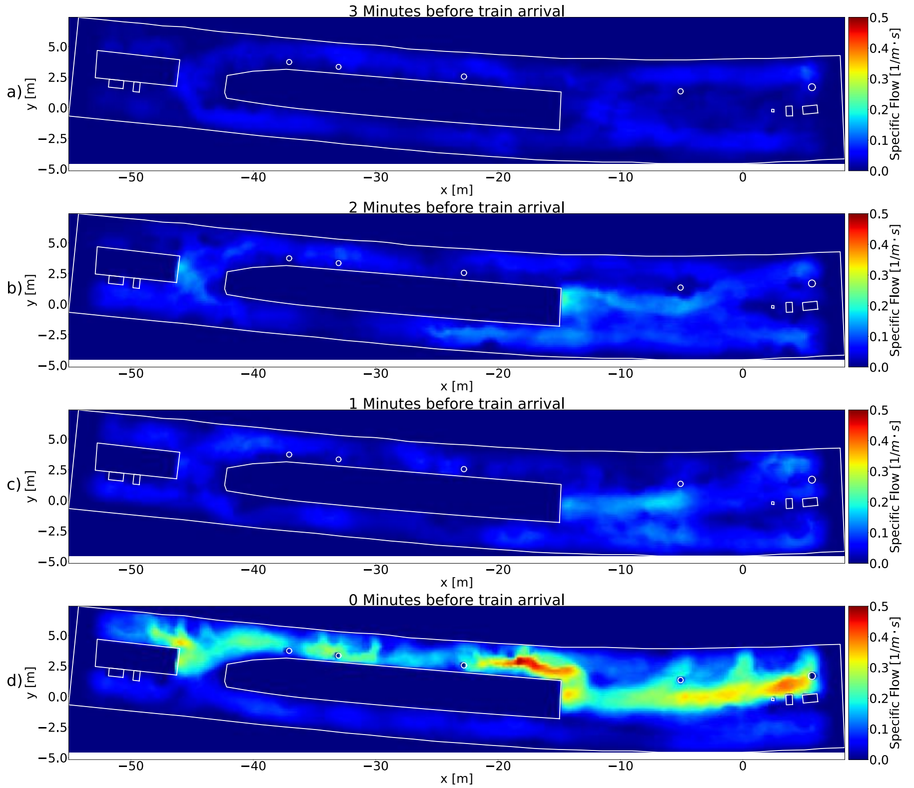


Figure 8: Flow profiles for trains at the upper track in Bern during afternoon peak hours for (**a**) 3 min, (**b**) 2 min, (**c**) 1 min and (**d**) 0 min prior to train arrival. During waiting phases the flows at the platform do not vary regionally; during boarding and alighting, flow profiles show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

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 8 a–c), as regions where significant density values are observed (cf. Figure 6a–c) do not feature high speeds (cf. Figure 7) and vice versa. 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.

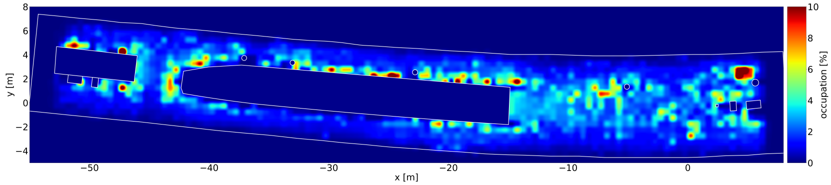


Figure 9: Occupation of space at the platform in Bern in the afternoon peak hours from 3:30 p.m. to 6:00 p.m. Areas close to obstacles and the sides of the entry way are preferably occupied.

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.

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.

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.

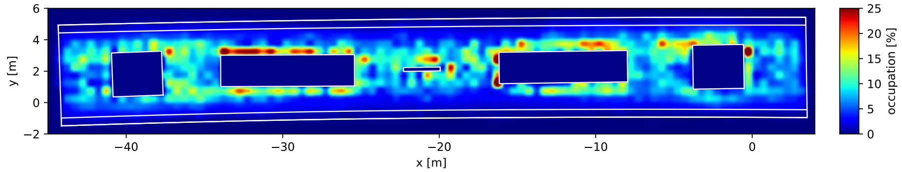


Figure 10: Occupation of space at the platform in Zurich Hardbrücke in the afternoon peak hours from 3:30 p.m. to 6:00 p.m.

The 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 Conclusion

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

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PUBLICATION II

Identification of social groups and waiting pedestrians at railway platforms using trajectory data

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Identification of social groups and waiting pedestrians at railway platforms using trajectory data

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Abstract

To investigate the impact of social groups on waiting behaviour of passengers at railway platforms a method to identify social groups through the monitoring of distances between pedestrians and the stability of those distances over time is introduced. The method allows the recognition of groups using trajectories only and thus opens up the possibility of studying crowds in public places without constrains caused by privacy protection issues. Trajectories from a railway platform in Switzerland were used to analyse the waiting behaviour of passengers in dependence of waiting time as well as the size of social groups. The analysis of the trajectories shows that the portion of passengers travelling in groups reaches up to 10% during the week and increases to 20 % on the weekends. 60% of the groups were pairs, larger groups were less frequent. With increasing group size, the mean speed of the members decreases. Individuals and pairs often choose waiting spots at the sides of the stairs and in vicinity of obstacles, while larger groups wait close to the platform entries. The results indicate that passengers choose waiting places according to the following criteria and ranking: shortest ways, direction of the next intended action, undisturbed places and ensured communication. While individual passengers often wait in places where they are undisturbed and do not hinder others, the dominating comfort criterion for groups is to ensure communication. The results regarding space requirements of waiting passengers could be used for different applications. E.g. to enhance the level of service concept assessing the comfort of different types of users, to avoid temporary bottlenecks to improve the boarding and alighting process or to increase the robustness of the performance of railway platforms during peak loads by optimising the pedestrian distribution.

Keywords: waiting pedestrian; social group; railway platform; trajectory data

1 Introduction

The movement of pedestrians is studied in different situations, e.g. evacuations of buildings or large-scale events, and was analysed in both field and laboratory experiments; for an overview see [1–3] and the conference series [4, 5]. Most previous studies focused on characteristics of pedestrian flows and the parameters that influence their movement. The key concepts for evaluating a facility regarding pedestrian traffic include the fundamental diagram and the Level of Service (LOS) concept [6, 7]. The fundamental diagram is used to estimate the capacity of pedestrian facilities and whether heavy congestion occur. The Level of Service concept allows to rate the comfort at a certain density. While those concepts provide information on the comfort pedestrians feel and whether the pedestrian load can lead to dangerous situations, they were designed for environments in which movements occur. Waiting pedestrians were solely considered while standing in queues, as for example in the LOS presented in [8]; but obviously the interaction between moving and waiting and therewith standing pedestrians could have a great influence on the dynamic and must be considered in dependence of the context. Larger social groups in particular can be an impactful obstacle in pedestrian flows. This is for example the case at train station platforms, where both moving and waiting passengers are present simultaneously. The first part of this introduction focuses on research on waiting behaviour at train platforms, and the second part addresses aspects of the research on social groups.

Only limited research has been published to date about pedestrian waiting behaviour and the factors that influence how and where pedestrians wait at railway platforms and how these waiting positions influence the pedestrians moving on the platform. Previous studies on this topic revealed that pedestrians tend to cluster in the vicinity of the platform entries [9–12] and around obstacles [13]. Seating arrangements are frequently used as waiting place, beginning with the ones closest to the platform entries [9]. The ticket machines were found to lead to crowding and congestion [14, 15], especially if placed close to stairs. Even if the stopping positions of trains are indicated on the overhead signals, passengers tend not walk to the farther ends of the platform as they do not trust the information or are unaware of its existence [9]. Reference [16] state that a confusing station layout leads to longer passenger waiting times, as pedestrians tend to arrive to such stations earlier in order to ensure they find their way. Moreover, the type of passengers using the train station platforms has an impact on the distribution and waiting behaviour. Depending on the purpose of the journey, passengers carry different amounts of luggage and possess varying degrees of familiarity with the environment. Passengers carrying luggage e.g., become important when the vertical or horizontal gaps between platform and train are larger [17], as those will increase the boarding time. Commuters often develop individual strategies [18] to minimise travel times and therefore for example wait in places where the train car that provides the shortest way at the desired destination is expected to arrive. This literature review highlights the previous studies on waiting pedestrians in the context of railway platforms. Those studies made no differentiation whether the pedestrians were individual persons travelling alone or members of social groups. Such a distinction however is necessary in order to interpret the findings and to respect the characteristics of individuals and social groups. This differentiation can help to sharpen the findings obtained on passenger's waiting behaviour.

Instead of considering a pedestrian crowd as consisting solely of a certain number of separate individuals who have no social relation, a crowd is rather to be understood as a gathering of individuals and small groups that are at the same place at the same time [19–21]. The dynamics of inter-group behaviour are proposed as social identity theory and self-categorisation theory by [22] and [23]. The effect of group behaviour on pedestrian movements has become a growing research area. The following will present the main findings of previous studies, which reveal differences between (moving) groups and individual persons in public environments. Depending on the group size and the density conditions social groups are expected to walk in specific manners: small groups of two to three members tend to walk side by side in low density environments [24] and form lines perpendicular to the groups walking direction, causing such groups to occupy a large area. With increasing density and therewith limited available space, groups adapt their walking behaviour and move in "V" or "U"-like formations [24–26]. Usually the central pedestrian in those configurations walks in the rear, ensuring the groups communication. Large groups split up into smaller subgroups, since communication with all group members becomes impossible [24]. Groups are slower than individuals and with increasing group size the velocity of the group members reduces; this was observed regardless of the density [26–28]. However, in high density conditions the velocity differences between members of social groups and individual persons become smaller, as groups give up their social interaction in favour of collision avoidance and start walking in single file [28]. [29] and [30] analysed group sizes of free-forming small groups and found that each group size is less frequent than the next smaller group size.

In field observations social groups can be identified by the relation of their members. This relation is indicated by communication that is composed of oral and non-verbal elements such as gestures, body language and eye contact. Recent technical achievements in data collection (c.f. [31, 32]) enabled the collection of large trajectory data sets, which prompted the development of methods to analyse the movement of social groups. For example [24, 26–28, 33–35] use video recordings and trajectory data from public spaces to analyse and develop dynamical models for the movement of pedestrians in groups. The combination of video recordings and trajectory data offers the possibility to generate an annotated data set, in which information extracted from the videos, e.g., the visual identification of socially related pedestrians, can be transferred to the trajectories. Such an approach enables the analysis of the data of known social group members with respect to interpersonal distances, motion direction or angles between the group members velocity vectors. However, all these studies focus on pedestrians that are walking. A method using trajectory data applicable for waiting pedestrians was proposed by [36]. Social groups at train station platforms were identified based on their space and time relation. Pedestrians who showed a pairwise distance of below 1.5 m for 90% and a distance below 1 m for 40 % of the time they spend at the platform were considered to be a social group (see also section). The study was performed with data collected in the first phase of the COVID-19 pandemic in 2020 and analysed with respect to contact tracing and distancing rules.
Up to 70 % of pedestrians moving in urban environments can be assigned to social groups [24, 37], during events (such as sport events or public celebrations) the portion can be even higher [25]. It than follows that the presence of social groups

impacts the dynamics of pedestrian flows. Simulations indicate that large groups behave as moving obstacles [38]. [39] found that social groups walk slower, further and maintained closer proximity than non-group members. The presence of social groups influenced other pedestrians to walk faster and at a greater distance (even in counter-flow) in order to avoid moving inside the group. The characteristics of movement and walking configurations of social groups were also found to impact the evacuation processes. [40] reports on a positive effect on the evacuation time when groups are present, as self-ordering processes were observed in the crowd at the exits. However, [41] performed egress experiments in which the presence of groups resulted in longer egress times, as members of social groups took longer to respond and move in the direction of the exits.

The findings of the studies presented above highlight the influence of social groups on the dynamic of crowds. It is expected that this also applies in the context of railway stations where both moving and waiting passengers are present. It is therefore of great interest to examine the influence of social groups on the capacity of pedestrian facilities such as railway platforms as well as in bottleneck situations like in the boarding and alighting process. Moreover, pedestrians that are members of social groups are expected to use the available space differently. A current application of the results of such an analysis is the detection of offenders against the social distancing rules during the COVID-19 pandemic. While members of social groups, e.g., families, are allowed to have close contact, strangers are obliged to keep a distance from one another in order to reduce the risk of infection. To identify situations or regions in which the mandatory distance is not kept, the identification of social groups and individuals is essential.

This paper seeks to fill the gap between existing studies on pedestrian waiting behaviour and research on social groups. Since only limited research has been published concerning the detection and analysis of characteristics of non-walking social groups, this article presents a method to identify social groups at train station platforms, where both moving and waiting / standing behaviour is present. Based on the proposed method of group detection, the waiting behaviour of pedestrians at train station platforms is analysed. The use of trajectory data, in contrast to video recordings, ensures a privacy conserving methodology. The method is applied to data from a railway platform in Switzerland. The portions of pedestrians travelling in groups and the distribution of group sizes are analysed and the differences between members of social groups and individuals are discussed with respect to mean speed and choice of waiting places.

2 Data Sources

The tracking data used in this study was provided by the Swiss Federal Railways (SBB AG) and was collected at platform 2/3 of the station Zürich Hardbrücke, Switzerland. This train station platform is equipped with stereo sensors tracking the movement of pedestrians inside the area of observation with 10 frames per second. The data consists of an unique ID number for each pedestrian, a timestamp and the x and y coordinates of the pedestrian's position at the given timestamp. As only the trajectories are recorded the data is fully privacy conserving and no information can be accessed that would allow to identify any individual pedestrian. The data was collected between 1^{st} and 28^{th} of February 2020 during the afternoon peak hours from 4 p.m. to 7 p.m. The data set thus consists of 8 weekend days and 20 workdays. The chosen time interval does not intersect with any measures introduced during the Covid-19 pandemic. The afternoon peak hours were selected with respect to comparability due to the fact that in these hours the passenger amount is usually high during both workdays and weekends and the most passengers travelling in social groups were expected. While the morning peak hours are often assigned to individual travel to e.g. work places, in the afternoon peak hours social activities are more likely. The observed area covers about 50 metres, see Fig 1. The platform is constructed symmetrically with an information board in the central area and stairways and elevators to both sides. The direction of movement of passengers entering the platform is indicated with arrows at the stairs and elevators in Fig 1.

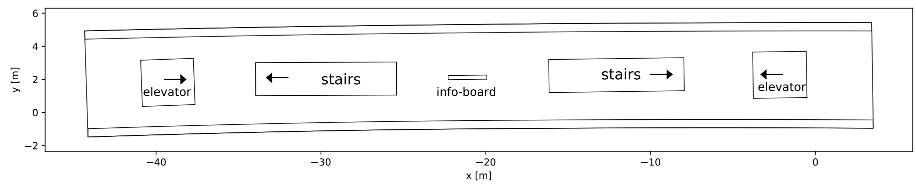

Figure 1: Spatial structure of the measurement area at the railway platform of Zürich Hardbrücke. Arrows indicate the movement direction for pedestrians entering the platform. The measurement area covers approximately 50 m of the platform.

2.1 Data Quality

In order to assess the quality of the data, the starting and ending points of trajectories were checked for plausibility. Due to the setup of the measurement area, trajectories are expected to begin and end either at the platform entrances, the platform-train interfaces or at the sides of the measurement areas. Approximately 90 % of all starting points of trajectories fulfil these requirements; the same applies to the ending points. However, in order to have a "complete" trajectory, both beginning and ending are required to be at the expected positions. This is the case for about 75-80 % of the trajectories. Incomplete trajectories were caused by pedestrians being lost by the tracking system for one or more frames, as a new ID number is assigned upon re-detection (cf. [42]). Nevertheless, those data are included in the analysis but the probability that the corresponding pedestrians are assigned as members of social groups is decreased. Due to technical reasons, the tracking data is mirrored horizontally.

3 Methodology

In manual field observations or by watching video recordings social groups can be identified by their social interaction, observable through e.g. verbal communication, eye contact and gestures (cf. [26]). This is not possible when working with trajectory data only. Nonetheless there are many research questions where a differentiation between social groups and individuals is crucial.

A method on group detection in railway environments was previously introduced by [36] and used to perform contact tracing and analyse the distancing rules during the first phase of the Covid-19 pandemic. Their method uses a sparse graph in which the trajectories of the pedestrians as well as all events in which two pedestrians had a distance smaller than a predefined threshold of 2.5 m are memorized. Hence, the distances between each pair of pedestrians that is present simultaneously at the platform have to be calculated. The calculation of distances between N pedestrians scales with N^2 and is therefore very time-consuming for large N [43]. While the distance calculation between all pedestrians is necessary for the analysis of Covid-19 distancing rules, it is not in the context of social group assessment. As members of social groups are expected to keep closer contact to each other than to non-group members, it is not necessary to calculate the distances between all pedestrians that are present at a given time. It is sufficient to determine the persons standing nearest to one another in every frame by applying Delaunay Triangulation which has a complexity $\mathcal{O}(N \cdot log(N))$ (cf. [44, 45]) and is therewith far more time efficient. Therefore, this paper proposes an adapted method to recognise social groups in trajectory data by analysing the distances and the stability of the distances between neighbouring persons which avoids the calculation of N^2 distances.

Train station platforms are places where boarding and alighting passengers are present. Alighting passengers usually leave the train platforms in a straight path, which makes it almost impossible to determine socially related pedestrians, even if video recordings were available. However, boarding passengers wait for a certain amount of time and can therefore be observed over longer time intervals. Hence, the identification of social groups is restricted to boarding passengers. The categorisation was performed by determining the start and end points of the trajectories: a boarding passengers trajectory starts at a platform entry and ends at a train door. A detailed discussion and analysis of that matter can be found in the authors' previous work, see [46]. All trajectories that are shorter than 20 seconds were not included in the analysis, as this time interval was identified as minimal observation time needed for visual analysis (see section).

Since the group detection method identifies group members based on their distances from one another, the applicability is limited to low density environments.

In consideration of the goal of determining members of social groups, which will be characterised by reasonably small distances, two different thresholds are defined for the distance between two pedestrians. A value of 1.5 metres was chosen as the maximum distance between persons for a contact ($d_{contact} \leq 1.5$m) which was also established as social distancing threshold in numerous European countries during the Covid-19 pandemic and is the maximum of the probability density of the pairwise distances in the data set. In order to regard the personal distance a value of 1 m is used ($d_{personal} \leq 1$m) as pedestrians that are comfortable to be inside each others personal space over a longer period are most likely related in a social way.

Hence, $t_{contact}$ is determined as the number of frames t for which holds

$$\|\vec{X}_i(t) - \vec{X}_j(t)\| \leq 1.5m = d_{contact} \tag{1}$$

and $t_{personal}$ as the number of frames for which is

$$\|\vec{X}_i(t) - \vec{X}_j(t)\| \leq 1m = d_{personal} \tag{2}$$

with $\vec{X}_i(t)$ being the position of pedestrian i at time t, for pedestrian j respectively. In words, $t_{contact}$ translates to the number of frames in which the given pedestrians i and j are at a distance of 1.5 m or less from one another, and $t_{personal}$ as the number frames for which the distance is smaller than 1 metre. Since the two pedestrians i and j do not necessarily have to arrive and depart at the same time, the time in which both pedestrians i and j are inside the measurement area simultaneously, is calculated as

$$t_{sim} = min\{t_{i,N}, t_{j,N}\} - max\{t_{i,0}, t_{j,0}\} \tag{3}$$

with $t_{i,0}$ representing the first frame and $t_{i,N}$ the last frame in which pedestrian i is inside the measurement area; for pedestrian j respectively.

Following [36] and [34] the pedestrian pairs identified based on the small distances between them, will be checked for the following relations:

$$t_{contact} \geq \alpha \cdot t_{sim} \tag{4}$$

$$t_{personal} \geq \beta \cdot t_{sim} \tag{5}$$

The values for α and β are determined in a parameter study in the following section. If both Eq (4) and Eq (5) are fulfilled, the corresponding pedestrians i and j are considered to belong to the same social group. Groups with more than two members are detected by combination of pairs.

3.1 Parameter Study and Validation

To determine a suitable parameter set for α and β and to validate the social groups found by the proposed method a ground truth of IDs that are members of social groups was established. To do so, the trajectory data of one example time interval of three hours was visualised as a video with JPSvis, which is the visualisation tool of the software JuPedSim [47].

Two persons, who had no knowledge of the group detection, were asked to individually note all ID numbers of pedestrians, who they believe to be members of social groups. No specific instructions to the determination of groups were given, but both persons were asked for their strategy afterwards. The test persons identified group members based on simultaneous movements, similar waiting locations and close proximity over longer periods of time. It was monitored whether a certain person entered or left the area of observation along with others, or if the person stayed close to others during the time at the platform. A collective change of waiting positions was also used as indication of group affiliation. However, the visual recognition of groups based solely on trajectories is not a trivial procedure. In order to guarantee reliability, the results of the two test persons were compared. The first test person noted 154 IDs as members of social groups, the second 153 IDs. In total 146 IDs were listed by both testers, which means they agreed in 90.7% of the cases. The IDs identified by both persons were used as ground truth for the parameter study. Therefore, all ID numbers that are not part of the 146 IDs found by both testers were considered to be individuals and in case one of those was found by the group detection method, it was assumed to be a false positive.

A parameter study was then performed to determine suitable values for α and β. Hence, suitable parameters are determined based on two constrains. The aim was to find a set of values for which a large number of members of social groups can be detected, however, the number of false positive detections should be zero, as those would correspond to pedestrians that are likely individuals but erroneously marked as group members.

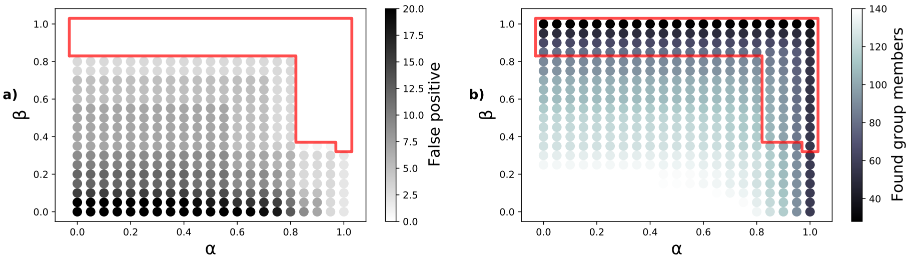

Figure 2: Parameter study. (**a**) Number of false positive in the detection of group members by different values of α and β. White colours indicate that no false positives were found. (**b**) Number of detected members of social groups. Light colours show high numbers of found members. The red area highlights the sets of parameters where the number of false positives in a) is zero.

The values of α and β were varied between 0 and 1 in steps of 0.05. For each set of values, the group detection was performed based on Eq (4) and Eq (5). All IDs that were identified for a certain parameter set were than checked against the ground truth in order to determine any false positive. The numbers of false positives increased with decreasing values for α and β (cf. darker colours in Fig 2a)). As the aim was to avoid false positives but to find a large number of group members, the numbers of identified group members for the corresponding parameters are illustrated in Fig 2b, with the red area marking the sets of parameters for which the number of false positives is zero. Therefore, the best parameter set will be identified as $\{\alpha, \beta\} = argmax(N(members), where\, N(false\, positive) = 0)$, which corresponds to the set that produces the maximum number of found groups members within the red area. From this it can be seen that the best results are achieved with $\alpha = 0.85$ and $\beta = 0.4$. In words, pedestrians are assumed to belong to a social group, if they have a distance smaller than 1.5 m to at least one member of the group for 85% of the time that they are simultaneously inside the measurement area and a distance smaller than 1 m for 40% of that time. The work of [36] proposed values of 90% and 40%, which can therewith be confirmed within 5% by the performed parameter study.

This parameter combination allows for a maximum of 107 IDs to be correctly identified as group members without any false positives. This corresponds to about 73% of the group members determined by the testers. Considering the overall data quality, which exhibits about 75-80 % of complete trajectories (cf. section), these

results are satisfactory, as incomplete trajectories will interfere with the group detection method and prevent the correct assignment of group membership.
The method reaches its limits in crowded situations where higher densities are present over longer time intervals. In those cases, the close distance between pedestrians is not necessarily caused by social interaction but rather by limited available space. Due to the distance thresholds of 1 m and 1.5 m, the method can result in incorrect group assignment if the local density exceeds $0.5 - 1.0\ 1/m^2$. If those densities remain over longer time intervals, crowding can be mistaken for social relation. The afternoon peak hours analysed in this study do not exhibit densities that exceed these threshold for longer time intervals. This will likely only occur in highly crowded situations, as e.g. in the context of public events. As the introduced method was developed for low density situations, no prediction can currently be made to what extent members of social groups preserve their close proximity in high density environments. It is expected that at least the distance thresholds and the parameters α and β need to be adjusted in order to correctly determine social groups. It may be necessary to include additional criteria, like for example the simultaneous movement of nearby pedestrians. However, the correlation of movement will not allow to expand the group detection to alighting passengers, since their walking paths inside the area of observation are generally similar and too short to allow assessment of group membership. In environments where pedestrians continuously move the correlation of group members can be expected to be higher than to unrelated pedestrians, even in increasing densities. In the context of train station platforms passengers spend most of their time waiting and therefore do not move, which will increase the correlation between (socially) unrelated neighbours in situations of limited available space (e.g. at a fully crowded platform).

3.2 Speed Calculation and Waiting

The identification of waiting passengers on train platforms using trajectory data can be achieved by analysing their speed of movement or lack thereof.

The speed of a pedestrian at a given time is calculated as the movement of a pedestrian in a time interval Δt. With $\vec{x}_i(t)$ the location of the pedestrian at time t, the speed can be calculated as:

$$v_i(t) = \frac{|\vec{x}_i(t + \Delta t'/2) - \vec{x}_i(t - \Delta t'/2)|}{\Delta t'} \tag{6}$$

In this study $\Delta t = 50$ frames, corresponding to 5 seconds, was used. To determine if a given pedestrian can be considered as waiting, a threshold of $v_i(t) < 0.4$ m/s was applied. This threshold was picked as the local minimum of the velocity distribution of the data set, which shows two peaks: One peak at mean speeds of approximately 0.2 m/s; the other at 1.2 m/s. The first peak mainly relates to boarding, the second to alighting passengers. The velocity distribution can be found in the author's previous work [46].

4 Results and Discussion

The group detection introduced in the previous section was used to analyse the differences in terms of numbers, mean speed and waiting positions between social groups and individuals at the train station platform in Zürich Hardbrücke (Switzerland). Due to recording errors, e.g., loss and re-detection of pedestrians, as well as to

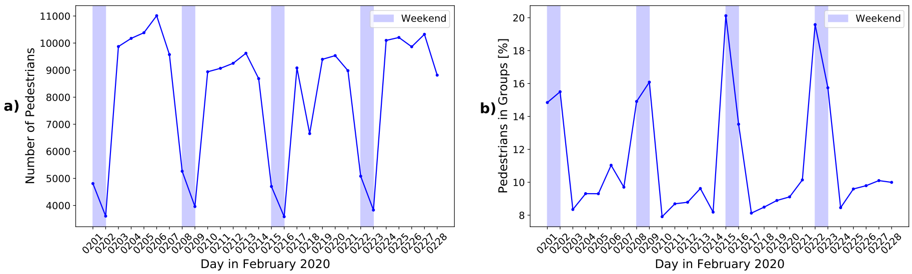

Figure 3: Number of passengers and members of social groups. (**a**) Number of pedestrians during afternoon peak hours from 4 p.m. to 7 p.m. in February 2020 at Zürich Hardbrücke. (**b**) Percentage of passengers who are members of a social group detected by the group detection method. Weekends are marked as blue bars.

pedestrians leaving and re-entering the sensor area, the number of IDs in the sensor area is probably higher than the total number of pedestrians and might differ from passenger counts with other methods. However, in order to improve the readability of the following sections of this paper, the terms "passenger" or "pedestrian" are used as synonyms for "ID".

On workdays between 9000 and 11000 passengers were detected in the observation area during the afternoon peak hours, cf. Fig 3a. On weekends the pedestrian load at the platform was lower and ranged between 4000 and 5000 passengers. The percentage of pedestrians that were identified as members of social groups by the method outlined in section ranged between 9 and 11 % on workdays and rose to 14-20 % on weekends, cf. Fig 3b. Weekday passenger traffic was dominated by individual passengers commuting to their work places, while during the weekends social activities played an important role. Due to the presence of data errors, e.g. incomplete trajectories, the actual number of members of social groups will be higher than the number of detected groups.

While the percentage of pedestrians who are members of social groups varies depending on workdays or weekends, the distribution of group sizes, as shown in Fig 4 does not.

In case of discontinuous trajectories (more than one ID number assigned to the trajectory of one pedestrian) the number of group members could be overestimated. In order to avoid this, the group size is determined as the maximal number of members present simultaneously. About 55% to 70% of all pedestrians assigned to social groups are members of pairs and approximately 20 % of groups of three. Groups with four and more members are less frequent. In accordance with [29], smaller groups are more frequent than bigger groups and each size is less frequent

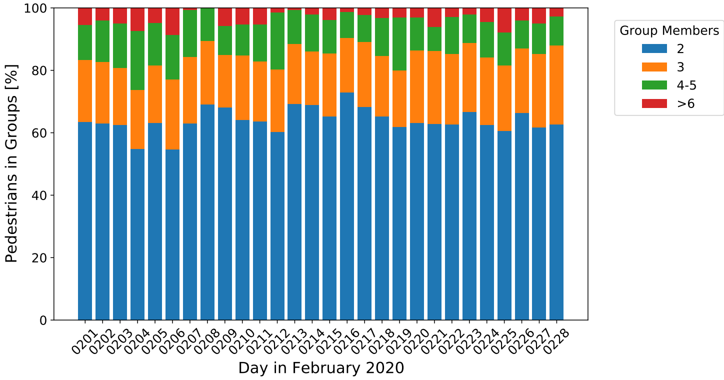

Figure 4: Distribution of group sizes as percentage of the number of passengers assigned to social groups. Each group size is less frequent than the next smaller group size.

than the next smaller group size. A similar analysis of distribution of group sizes was performed by [36] for the time of the first phase of the Covid-19 pandemic in the Netherlands. Comparable to the results for the station in Switzerland more passengers are traveling in groups during the weekends, this seems to be independent of pandemic regulations. Groups with three or members are, however, less frequent in the work of [36] which is also expected due to the pandemic restrictions and contact regulations considered.

In order to determine whether or not individuals and members of social groups show different characteristics in terms of platform usage, the mean speed and waiting places were analysed with respect to group sizes. Since the distribution of group sizes is not affected by weekends and in order to increase the available data of social groups, the data set was accumulated over all days and analysed based on the group sizes. In total 15558 passengers were assigned to groups with two to three members, 1602 to groups with four to five members and 359 passengers to groups with six or more members.

Using Eq (6), the instantaneous speed and its mean were calculated for each pedestrian. In order to analyse the differences in mean speed distribution of group members and individuals, histograms of the mean speed are shown in Fig 5 for (a) individuals, (b) groups of two to three members, (c) groups with four to five members and (d) groups with six or more members. The presence of different types of users, namely boarding and alighting passengers, causes the distribution of mean speed to differ significantly between boarding and alighting [46]. It is noted that only boarding individual are considered in Fig 5a.

While the average mean speed is 0.24 m/s with a standard deviation of 0.33 for members of pairs and trios, the mean value for groups of 4-5 members is 0.1 m/s with a standard deviation of 0.1. For groups with six or more members the speed is only 0.08 m/s with a standard deviation of 0.07. Comparing the histograms, it becomes apparent that the mean speed decreases with increasing group sizes.

Fig 6 illustrates the trajectories of pedestrians in an exemplary six-minute interval. Trajectories of individuals are marked in grey, while the three groups present on the

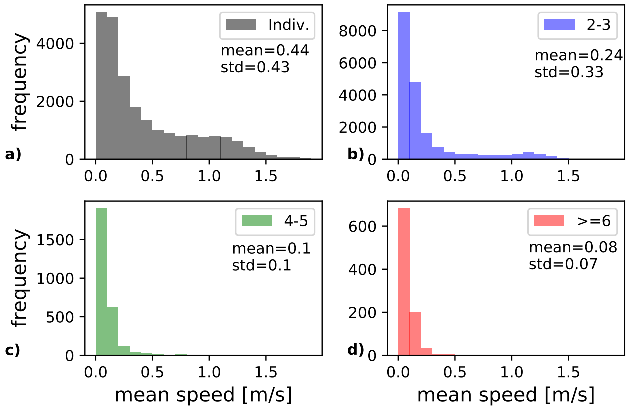

Figure 5: Mean speed of passengers during afternoon peak hours. (**a**) Individuals (boarding only) (**b**) Members of pairs and trios (**c**) Groups with 4-5 members (**d**) Groups with 6 or more members. With increasing group size, the mean speed decreases.

platform in this time interval are highlighted in colour: the group of two in blue, of three in black and the five-member group in red. Due to the chosen time interval, pedestrians' trajectories do not necessarily cover their complete journey through the platform. For example, the two groups with two (blue) and three members (black)

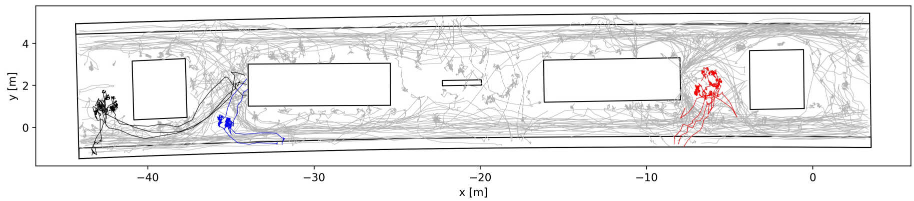

Figure 6: Trajectories of pedestrians at the platform in an exemplary six-minute interval. Trajectories of groups are indicated in colour. Group of two in blue, group of three in black and group of five in red.

enter and leave the platform in the considered time interval, causing their trajectories to begin at the stairs and end at a train door. The group with five members (red), on the other hand, was already located at the waiting spot in front of the entrance at the beginning of the selected time interval. Therefore, the trajectories show their waiting positions and the way towards the train, but not the path they chose to enter the platform. Waiting passengers close to obstacles influence moving pedestrians to walk closer to the platform edges. Therefore, walking ways can be identified as an accumulation of trajectories in the regions in the vicinity to the safety line. The trajectories of individuals (grey) indicate the detours in the regions where social groups are waiting. This is especially prominent with the five-person group, which is waiting in front of the entrance at the right-hand side. Similar detours are observable with the waiting pair (blue). However, due to the lesser space requirements of smaller groups, the impact is smaller. The group of three (black) is waiting at the rearward side of the elevator and therefore seems to have no significant influence on travel paths.

In order to spatially determine differences in the choice of waiting places, a comparison of waiting places of individuals and groups is illustrated in Fig 7. Here, the places where passengers belonging to each group size exhibit a speed below the threshold for waiting were mapped.

For this purpose, the measurement area was divided into tiles with a size of 0.5 by 0.5 metres, in accordance to the average human shoulder widths [7]. The waiting occupation O_{wait} of a tile with the length Δx and the midpoint $\vec{x}_0$ can be calculated as

$$O_{wait} = \frac{1}{N_f} \sum_{f=0}^{N_f} \sum_{i}^{N} \int_{\vec{x}_0-\Delta\vec{x}/2}^{\vec{x}_0+\Delta\vec{x}/2} \delta(\vec{x}_{i,f} - \vec{x}) d\vec{x} \tag{7}$$

with $\vec{x}_{i,l}$ the position of a waiting pedestrian i at the time f, N_f the number of frames, N the number of pedestrians and $\delta(x)$ the Dirac delta function. In words: If a pedestrian assigned to the specific group size is considered as waiting in a certain frame, the value attributed to the tile which the pedestrian is occupying is increased by one. By dividing the resulting values by the total observation time (in this study 3 hours on 28 days, which corresponds to 3024000 frames), the measure gives the percentage of time each tile is occupied by a waiting pedestrian.

The direction in which a pedestrian enters the platform from stairs or the elevators is marked with white arrows. Individuals travelling via Zürich Hardbrücke railway station often choose waiting places close to the sides of stairways or elevators and even wait at the places between the rearward sides of the two stairways in Zürich Hardbrücke (cf. Fig 7a, between x= -15 m and x= -25 m). Groups of two and three show a similar choice of waiting spots, often tending to wait closer to the platform entries (Fig 7b). With increasing group sizes, the preferred waiting places are often chosen in direct vicinity to the entry ways (see Fig 7c and d), while the rearward sides of stairs are only seldom used. Possible reasons for the lower mean speed in larger groups and the tendency to choose waiting places in front of the entries are difficulties in agreements for waiting place optimisations. Social groups choose waiting places that ensure communication between the group members. Therefore, larger groups tend to form circles, which guarantee eye contact between the members. Comparable to the movement of groups in lines perpendicular to the walking direction, cf. [24–26], this leads to higher space requirements. While the area in front of the entry ways at Zurich Hardbrücke is wide enough for a larger group, the way to the less frequented rearward sides of the stair ways necessitates the passing of the narrower parts of the platform. In order to change the waiting place of a group from the entry ways towards less crowded and frequently used places, an active agreement within and a coordination of the group members is needed.

Since the group size is not necessarily the only factor that influences the choice of waiting places, in the following it is analysed how the waiting position is related to the waiting time. The total waiting time for each pedestrian is calculated as the sum of all frames in which the criterion $v_i(t) < 0.4\ m/s$ is meet. Similar to Fig 7, the waiting positions of pedestrians were mapped on a grid with tiles with a size

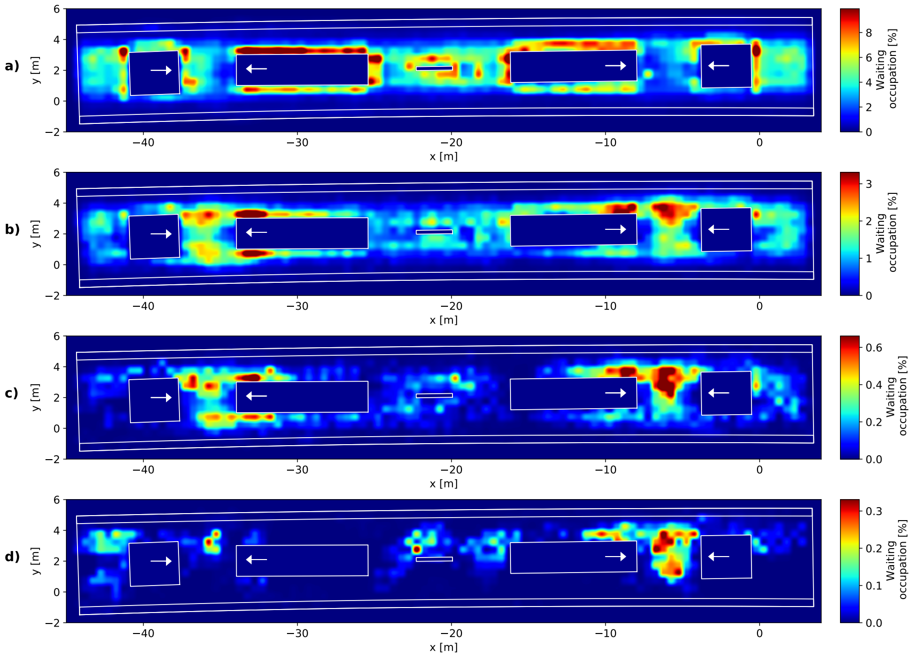

Figure 7: Waiting places of social groups and individuals. (**a**) individuals (**b**) groups with 2-3 members (**c**) groups with 4-5 members (**d**) groups with 6 or more members. Coloured areas indicate the occupation by waiting passengers as percentage of the total observation time.

of 0.5 by 0.5 metres and the portion of the total observation time is given. The results of the mapping are presented in Fig 8, these are given regardless of group membership but with respect to the total waiting time of passengers.

Passengers waiting up to 2 minutes chose locations close to the entry ways (Fig 8a), as those are meant for passengers that arrive only shortly before the train they intend to board. With increasing waiting time (2-5 minutes in Fig 8b and 5-10 minutes in Fig 8c) obstacles with the possibility to lean against, for example the sides of the stairs or the information boards, are used for waiting. Passengers with long waiting times (10 minutes and longer), (Fig 8d) mainly chose waiting places in rearward areas behind the elevators ($x > 0\ m$ or $x < -40\ m$) or between the two stair ways ($-25\ m < x < -15\ m$). These are the places that are least frequently used by walking pedestrians and therefore the least disturbed. Passengers tend to wait in places that allow to turn in the direction of the next intended action. In most cases in the context of railway platforms this is the boarding process.

Pedestrians waiting in front of the entrances are likely to interfere with the passenger flow at the platform, since they narrow the available space for passing pedestrians in an area where the most movements occur. As shown in both Fig 7 and Fig 8 this is likely the case for passengers that are members of larger social groups or that only wait for a short time. This information can be used to optimise the distribution of

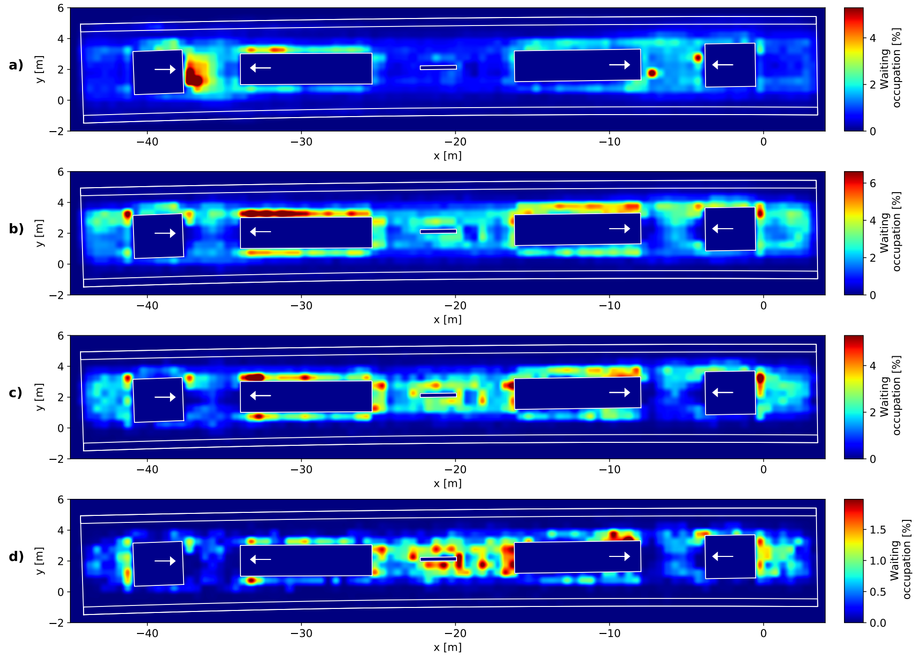

Figure 8: Waiting places of passengers depending on total waiting time. Waiting places of passengers that wait (**a**) up to 2 minutes (**b**) 2-5 minutes (**c**) 5-10 minutes (**d**) 10 and more minutes. Pedestrians with short or intermediate waiting times chose waiting places at the sides of stairs and close to obstacles, with increasing waiting times the rearward sides of stairs are used more frequently.

waiting passengers at railway platforms. Passengers with short waiting time arrive with little head time to the trains and will therefore choose waiting spots close to the entrances. However, social groups likely wait in those areas because of their higher space requirements. The planning of infrastructure modifications would thus do well to consider the requirements of social groups in order to achieve even passenger distributions and ensure the flow at the platform entrances. This is also important for the assessment of comfort of waiting passengers by e.g. level of service concepts.

The discussion of the results of the previous sections leads to the subsequent findings: Passengers tend to choose their waiting places in accordance with the following criteria: (a) short walking distances, (b) possibility to turn towards the next intended action (most likely the boarding process), (c) being undisturbed by other passengers or avoiding disturbing others and (d) ensuring communication. These are very similar to the criteria determined in the context of an inflow in a confined space (like an elevator) [48], where flow avoidance, distance cost and boundary preferences were suggested. The ranking of these criteria and therewith the assessment of comfort differs with varying types of passengers. Passengers with short waiting times choose places with short walking distances close to the expected stopping position of the trains. With longer waiting times the criterion of undisturbed waiting places becomes more important and out-weights the preference of the shortest distances. However, in contrast to individuals, communication is the dominant criterion for social groups. Therefore, social groups do not necessarily wait in places where they do not disturb others. In order to ensure eye contact and communication to all group members, waiting social groups form circles and therefore have higher space requirements, leading them to act as obstacles for passing pedestrians.

5 Conclusion

This paper presented a method that allows the identification of social groups in trajectory data of waiting and standing pedestrians. Social groups were identified by thresholds for inter-personal distances that are present over certain time intervals. In the case of a train station platform, two pedestrians are considered as belonging to a social group, if their distance to one another is smaller than 1.5 m for 85 % of the time in which they are simultaneously inside the observation area and smaller than 1 m for 40 % of that time. The percentages of the time that are needed for pedestrians to be considered as a social group were determined by a parameter study and were checked against a ground truth for validation. The ground truth was established by a visual analysis performed by two independent test persons. However, these parameters need to be reconsidered and validated for different scenarios, e.g. in shopping malls or public gatherings where different dynamics are occurring. The group detection is suitable for scenarios with low densities; the applicability in dense environments cannot be guaranteed as in those cases small distances between pedestrians are caused by congestion or limited available space.

The group detection method was applied to a data set taken from the afternoon peak hours during February 2020 in Zürich Hardbrücke, Switzerland. During working days about 9-10 % of the pedestrians waiting at the train station platform were members of social groups; the portion increases to up to 20 % during weekends. The most frequently observed group size was pairs, each size is less frequent than the next smaller size. Distributions of group sizes showed no correlation to whether it was a working day or weekend day. With increasing group size, the members mean speed decreased. While individuals often waited at the sides of stairs and elevators, social groups were found to be more likely to choose waiting places that provide enough space for members to position themselves in such a way that enables communication within the group. Typically, this is the case in the vicinity of the platform entrances. This behaviour was shown to be more prominent with increasing group size. Moreover, waiting places were influenced by the total waiting time of the passengers. Pedestrians with short waiting times (less than 2 minutes) waited close the entrances. For longer waiting times places at the undisturbed rearward sides of the stairs were used.

The waiting places chosen by individuals and groups highlight the different needs in terms of comfort. The waiting places were chosen based on a ranking of the criteria of short walking distances, the direction of the train arrival, undisturbed waiting places and ensured communication. Depending on the types of users and the waiting time those criteria were prioritised differently. Passengers with long waiting times prefer undisturbed waiting places even if the distance was longer. While individuals chose undisturbed waiting places in areas where they do not hinder the movement of others, social groups prioritised the possibility to communicate even if the position was close to the highly frequented entry way. The results could be used to assess the comfort of different types of users by level of service concept including waiting passengers and to optimise space usage at railway platforms by increasing the robustness of performance during peak load by optimising the pedestrian distribution.

Acknowledgments

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Data Availability

The trajectory data used for this study are the property of Swiss Federal Railways (SBB AG). The data is available upon request addressed to the Swiss Federal Railways (Contact: entwicklung.bahnhof@sbb.ch) and after signing a confidentiality agreement (as it was done by the authors).

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PUBLICATION III

Waiting in crowded places - influence of number of pedestrians, waiting time and obstacles

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Waiting in crowded places - influence of number of pedestrians, waiting time and obstacles

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Abstract

At crowded places, like railway platforms at rush hour, the spatial distribution of waiting pedestrians has a significant influence on performance and level of comfort. However, the choice of waiting places and the resulting spatial distribution of the crowd have rarely been studied. This study investigates the effects of obstacles, number of passengers and waiting time on the distribution of waiting passengers. Laboratory experiments were performed using a mock-up platform with three setups: without obstacles, with a narrow and a wide obstacle. Density profiles determine preferred waiting places. While the space usage by waiting passengers is inhomogeneous, the distances between the individuals show surprisingly small variations, regardless of obstacles and number of passengers. This suggests a robust collective optimisation of the crowd when searching for waiting positions. In doing so, and without necessity, the participants chose distances to each other extending into the personal zone specified in classical personal-space-concepts. These results indicate necessary refinements of the concept by considering context and collective behaviour. The findings are transformed into floor-fields modelling the space usage by a superposition of attractive or repulsive areas which consider optimisation of distances and comfort. This model does not only reproduce the waiting places at platforms but can be adapted for other use cases.

Keywords: experiment; pedestrian; waiting; train station

1 Introduction

The research field of pedestrian dynamics studies the movement and behaviour of pedestrians. For an overview the reader is referred to the biannual conference series [1, 2], the reviews on the topic, e.g. [3–5] and the glossary on human crowd dynamic research [6]. While most studies are focused on pedestrians walking through e.g. corridors, bottlenecks or in evacuation scenarios, situations in which pedestrians are waiting or standing still for a while were subject of fewer investigations. However, standing or waiting pedestrians are present in many daily situations, such as at public transportation facilities where passengers wait at railway platforms or inside trains.

Especially under the assumption of an expected increase of passenger numbers in public transport facilities in central Europe in the near future, the waiting behaviour and distribution of boarding passengers is of interest as standing pedestrians narrow the available space and influence the overall performance of the station. At train station platforms the boarding passengers usually spend some time waiting and thereby show a different space usage than moving pedestrians. The distribution of passengers along the platform is of importance for this matter as uneven distributions of passengers lead to non uniform uses of the train doors in the boarding process, which can increase the train's dwell times and influence the performance of the station [7–9].

Previous studies on passengers waiting behaviour at railway platforms found that the passenger distribution is not uniform along the platform but influenced by the location of the entry ways [10–14] and stopping positions of the trains [15]. Passengers tend to cluster around the entrances (cf. [11, 16–18]) or infrastructure elements (like seating arrangements or vending machines [19–21]), beginning with the ones closest to the entrance. Waiting places close to obstacles were found to be preferred as those offer the possibility to lean against them cf. [22, 23]. In regions close to obstacles passengers accept higher densities while waiting [22, 24]. At a two-sided platform usually only regions at the platform side of the expected train arrival are occupied [24]. Spaces close to the platform's edges are avoided [25].

Moreover, different types of passengers exhibit different preferences for their waiting locations. Passengers travelling in social groups often choose waiting places that are wide enough for the whole group to fit and ensure the groups communication. This is often the case in areas directly in front of the entrances leading to possible bottlenecks and congestion [26]. Passengers with short head time to the expected train arrival stand in region close to the entrances while passengers with longer waiting times prefer undisturbed spaces and even walk to farther platform areas or use the rearward sides of stairways [26]. Commuters often develop individual strategies in order to minimise the distance to the exits at their destination [27].

The studies introduced in the previous paragraphs highlight findings obtained in field observations on passengers using platforms at railway or underground stations. If this situation is abstracted, it can be described as pedestrians entering a space through an entrance, waiting for a certain amount of time and then leaving the space through an exit. This situation is comparable with pedestrian's inflow into confined spaces and happens in daily life e.g. in elevators, waiting rooms or terminals at airports. Laboratory experiments, which can reduce the complexity of influencing factors, aiming at investigating pedestrian's waiting behaviour and distribution inside confined spaces were performed and analysed by [28–33]. In contrast to situations in which the walking direction is predefined (and e.g. given by the experiment's instructions or set by the goal that should be reached), in inflow situations pedestrians can freely choose their walking direction and waiting place. Upon entering a room, a pedestrian needs to decide on a waiting place taking into account the current situation which is, among some potential personal preferences, composed of the current position of other pedestrians, the expected filling of the room (by further entering persons) and the expected exit from the room.

Experimental studies on inflow processes into a room were previously performed with two different setups: a) for square rooms (approx. 4x4 m) with one door that serves as both entry and exit (like e.g. an elevator) [28, 29] and b) for a rectangular room (approx. 2x10 m) with separate entry and exit doors [30–33].

- In setup a) it is reported that the filling of the room starts at the boundaries beginning with the wall on the opposite side of the door. Subsequent persons fill the room forming an arch around the boundaries. The reasons proposed for those boundary preferences are the option to lean against the walls and less repulsion and contact to other pedestrians [29]. With increasing number of pedestrians inside the room the middle parts are used and the final distribution of participants in the room is uniform with only slight variations in Voronoi cell sizes [28]. After reaching their stopping positions pedestrians turn towards the exit and are thus facing subsequently entering persons. It was observed that pedestrians mostly remain standing at the position in which they first stopped inside the room and only small fluctuations occur [28]. The authors of [28] identified four main factors which influence the decision making process in inflow situations. These were named: flow avoidance, distance cost, angle cost and boundary preferences.

  While these findings refer to non competitive situations, [29] showed that the distribution of participants changed significantly when including a first-out-award. In this scenario pedestrians gather close to the exit and the average distance to the nearest neighbour decreases. The participants entering first can minimise their distance to the door in order to obtain an advantageous exit position, which leads to interference with subsequently entering pedestrians.

- In setup b) the rectangular room has a separate exit door located near the middle of the longer wall. Pedestrians entering first chose a position close to the exit doors [32]. In contrast to the observations in setup a) no boundary effect was reported in the setup with a separate exit door. However, in the images shown in [31–33] the barriers used to mark the experimental setup in scenario b) appear to be soft (traffic cones and ropes) and therefore would probably not offer the same function as solid walls which can provide comfort through the possibility to lean against them and safety as those will decrease the number of neighbouring pedestrians, especially of those standing directly behind. The final distribution of participants in the room was not uniform, as participants gathered in the middle of the room between the entry and exit doors and hence higher densities are reported in those regions [30, 32, 33]. The far side of the room was not used [31]. This results in a spatial distribution that is not evenly throughout in the whole available space.

The first proposed explanation for these findings is that the distribution of waiting passengers is related to the personal space as participants perform a trade-off between the desire to optimise their distance to the exit and to preserve their privacy [32, 34]. The preservation of privacy is described by psychologists in the concept of personal space. E.g. [35, 36] characterise this as the area in which the entering of other persons causes discomfort. The area surrounding an individual is divided into different zones: the intimate ($d < 0.45\,m$), personal ($0.45 < d < 1.2\,m$), social ($1.2 < d < 3.6\,m$) and public ($d > 7.6\,m$) zones [35, 36]. The personal distance ($0.45 < d < 1.2\,m$) is in this context often described as the distance that individuals try to maintain between themselves and others [36] and is used in many approaches to model the movement of pedestrians and crowds. The distance zones in these concepts were determined between persons of varying degrees of familiarity (e.g. friends or strangers) standing face to face in different settings (e.g. office, street corner) [35]. Goffman investigated the relation of people in public spaces [37] and describes the process as follows: pedestrians entering first can freely choose their waiting location but afterwards each newly entering person causes the others to shift position and relocate sequentially. With an increasing number of pedestrians inside a space, the amount of free space decreases and pedestrians are distributing more uniform, eventually reaching a state of equal-distances. Those equal distances are achieved by self-organisation processes, which were previously described as a weighting up between the desire to allocate the space equally and to maximise the distance to others. However, recent studies found that increasing densities and the associated violations of personal space do not simply increase the discomfort perceived in those situations. In low densities, where the available space is higher, the discomfort caused by invasion of personal space is higher [38].

Comparing the studies on waiting passengers at railway platforms and in inflow situations, the behaviour of the pedestrians shows many similarities. In both cases short distances (to the entrances or destinations) are preferred, and waiting places are often located close to the boundaries. However, at railway platforms the boundary preferences correspond to obstacles or other infrastructural elements rather than the platform's edges. In contrast to boundaries of spaces enclosed by walls, the platform edges are hazard zones and therefore avoided by passengers. As far as distances to destinations are concerned, usually in enclosed spaces the exact location of the door is visible and known. On platforms, the exact location of the targets, in this case the train doors, may be unknown due to the unpredictable stopping points of the trains.

Passengers' waiting behaviour at railway platforms was until now studied using field observations. As reviewed in the section above a large variety of factors (e.g. location of entrances, infrastructural elements, stopping position of trains etc.) was found to have an influence on passengers choice of waiting positions. However, in observations of real-life situations it is not possible to distinguish the influences of different factors separately. Therefore, this study investigates the influence of obstacles, waiting time and number of passengers on the distribution at railway platforms by performing laboratory experiments. These factors were chosen as they were expected to have a relevant influence on the distribution of passengers and were technically possible to investigate within the framework of a given set of laboratory experiments (for details see methods section and [39]).

After an introduction of the experiment procedure and the data preparation, trajectories and density profiles are presented in order to show passengers waiting places and distribution along the platform. The distances kept by waiting participants and the perception of the experimental runs are shown. Based on the results obtained from this analysis a floor-field model for waiting places is developed which can also be adapted for other scenarios than train station platforms.

2 Results

2.1 Experiments and data collection

The experiments were performed by using a mock-up train station platform (for details see Methods section). The platform was either equipped with no obstacle, a narrow or a wide obstacle as seen in Fig. 1. Each setup was tested with 40 and 100 participants. Participants entered the platform through stairs at the right hand side of the platform (see Fig. 1d), and waited for a train that was to arrive at the platforms lower side. In runs with 40 participants the waiting time, which started after the last participant of the run had entered the platform, was either 2 or 4 minutes; in runs with a higher number of participants the waiting time was 2 minutes. After the waiting time was completed, the train arrival was announced, movable stairs, which acted as train doors (see Fig. 1d left-hand side), were positioned and the participants left the experimental side. Each scenario was repeated three times with different participants. After each run participants were asked to use a mood

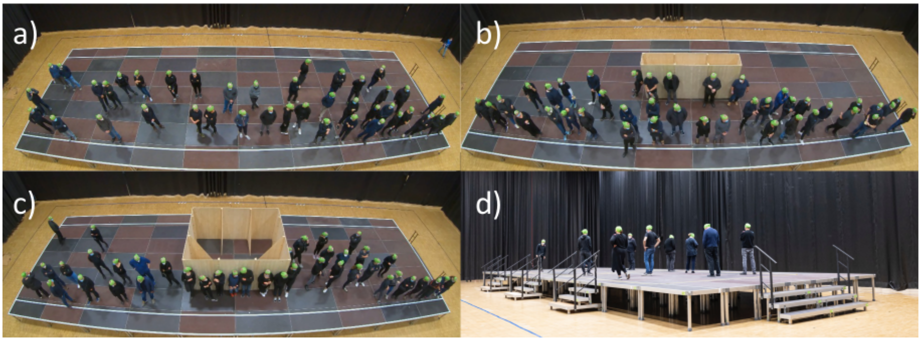


Figure 1: Experimental setup and participants' positions at the end of the waiting time shortly before the time of announcing the trains' arrival. (**a**) platform without obstacle, (**b**) with narrow obstacle, (**c**) with wide obstacle. (**d**) Side-view of the experimental setup. At the right-hand side the entrance is located, at the left side the movable stairs that act as train doors are visible.

button terminal to express how they felt during the experiment. After selected runs questionnaires were distributed, see Table 1 for an overview. Participants' head trajectories were automatically extracted following [40] using the software PeTrack [41], which is achieved by recognising and tracking of green caps worn by the participants. For details on procedure and data collection see Methods section.

Table 1: Overview of the experiment runs

Setup	Number of Participants	Waiting Time [Minutes]	Questionnaire
no obstacle	40	2	no
no obstacle	40	4	no
no obstacle	100	2	yes
narrow obstacle	40	2	yes
narrow obstacle	40	4	yes
narrow obstacle	100	2	no
wide obstacle	40	2	yes
wide obstacle	40	4	yes
wide obstacle	100	2	no

2.2 Trajectories

The exemplary images from an overview camera seen in Fig. 1 a)-c) show a time frame at the end of the 2 minutes waiting time for runs with 40 participants and the three different platform setups. Observable in all setups is that the participants do not distribute evenly along the platform, but cluster at the lower side. Also their viewing direction is turned towards that side, which is caused by their awareness of the side of train arrival.

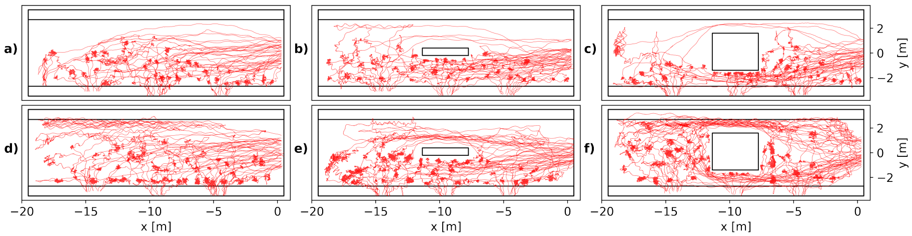


Figure 2: Trajectories for exemplary runs with 40 participants for the three different setups, a platform without obstacle, a narrow or a wide obstacle. Waiting time was either 2 minutes (**a-c**) or 4 minutes (**d-f**).

Fig. 2 shows the trajectories of exemplary runs with 40 participants for the different setups; in the upper panel (a-c) the waiting time of 2 minutes, in the lower panel (d-f) runs with 4 minutes waiting time. In runs with 40 participants and 2 minutes waiting time, the upper side of the platform is only used for walking to the desired waiting spots. Waiting places can be identified in the trajectories as "knots", since standing pedestrians still show slight head movements. Those waiting places are mainly located at the side of the lower platform, where the train is expected to arrive. This phenomenon is more pronounced in runs with obstacles than in runs without obstacles. With an increased waiting time of 4 minutes (Fig. 2 d)-f)) the area covered by trajectories increases, as some participants start to walk around instead of waiting at a fixed position. The moving participants can be identified by the wave-like trajectories, which are mainly located at the side of the platform which is free from standing participants. In all runs with obstacles, independent from waiting time, participants waiting at a fixed position can be observed to lean against the sides of the obstacles. However, the obstacles' sides facing towards the side of train arrival are used more frequently than the sides facing towards the smaller sides of the platform.

It should be noted that in all runs the safety line is only rarely crossed and no participant waited in the area between the safety line and the platform's edge, even though participants were not told to pay attention to these lines indicating danger zones.

2.3 Density profiles

The density was calculated using the Voronoi method following [42]. For each pedestrian i a Voronoi-cell is defined as the area that is closer to the given pedestrian than to all others. The Voronoi cells are cut at the edges of the platform, therefore no open cells are existing at the boundaries. The density ρ corresponds to the inverse of the area of the Voronoi cell A_i and is calculated for each frame:

$$\rho_{xy} = \frac{1}{A_i} \, if \, (x, y) \in A_i \tag{1}$$

Voronoi density ρ_V of a measurement area A is then calculated as

$$\rho_V = \frac{\iint \rho_{xy} dx dy}{A} \tag{2}$$

To perform a spatial analysis of the data, as introduced by [43], the measurement area is parcelled into tiles with the size of 0.2 x 0.2 m. For each frame within the waiting time, the Voronoi densities were calculated and integrated over time for each tile. The calculation of Voronoi densities and profiles was carried out using the Python library PedPy [44] and the software JPSreport [45]. Density profiles were calculated for the waiting time in each of the three repetitions of the experimental runs and averaged over the number of frames of the waiting time.

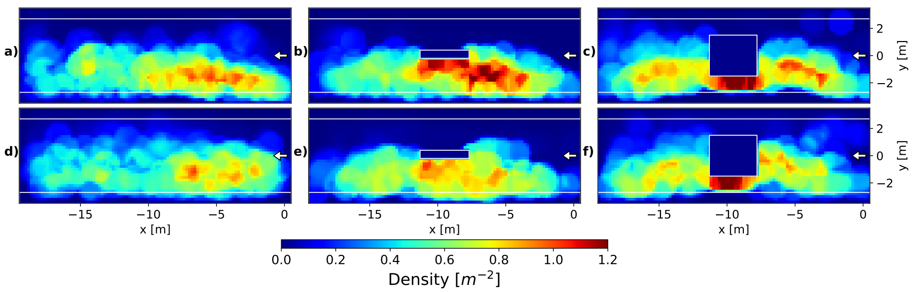


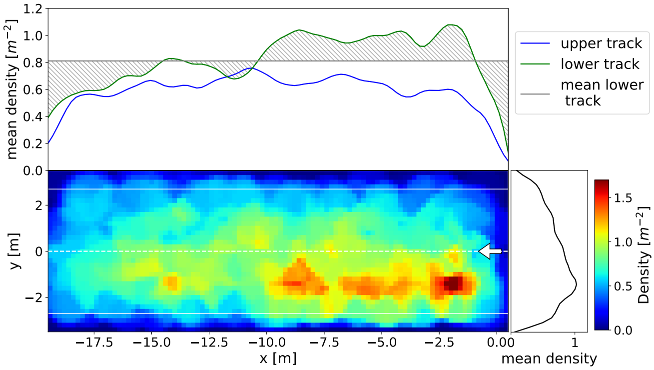
Figure 3: Density profiles for N=40 participants. (**a-c**): 2 minutes waiting time; (**d-f**): 4 minutes waiting time. The location of the entrance is marked with a white arrow.

In experiments with 40 participants, see Fig. 3, the side of the expected train arrival is visible for all configurations as participants mainly distribute themselves along the lower platform side. In case of 2 minutes waiting time (Fig. 3a-c), the areas of highest densities for a platform without obstacle are shifted towards the entrance at the right. With obstacles the density distribution becomes more even in x-direction. In these runs the highest densities are found close to the obstacles. Compared with the profiles for runs without obstacle, more space farther away from the entrance is covered and concurrently the side facing towards the entrance is used more often.

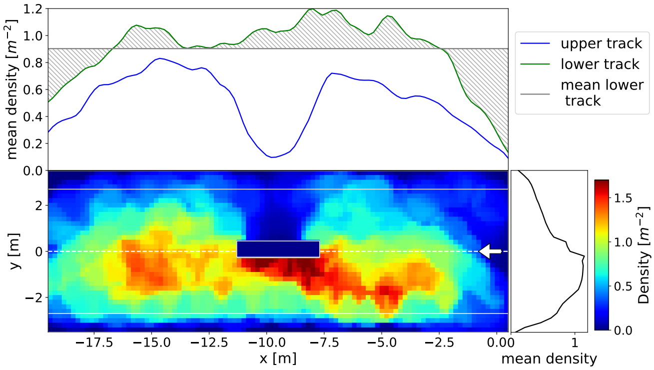
The sides of the obstacles facing towards the lower track exhibit the highest densities with up to 1.3 m^{-2}. In the setup with the wide obstacle, those areas extend towards both sides of the obstacle along the platform. It is pointed out that the differences are clearly discernible but small ranging between approximately 0.6 and 1.3 m^{-2}. Comparing the runs with shorter (2 min) and longer (4 min) waiting times it seems that for the latter the density becomes more homogeneous and more space is covered, cf. Fig. 3d)-e). With an increased waiting time of 4 minutes some participants start to walk slowly instead of waiting at a fix location, see Fig. 2 d)-e). Consequently, and regardless of the presence of obstacles, the densities decrease as the participants cover more of the available space. To analyse the inhomogeneity of the density, the density profiles for runs with 100 participants as well as the density distributions along the x- and y-axis are shown in Fig. 4. Density distributions are calculated as a sum of densities for the tiles in the corresponding direction and averaged over the number of accessible tiles. Since the knowledge of the side of train arrival structures the distribution of densities along the platform, the density distributions (upper plots) are separated into the lower track (green line) and the upper track (blue line). The mean density at the lower platform side is illustrated as grey horizontal line and the deviation of the density distribution of the lower track from the mean density as grey area. This means that grey areas above the line of mean density indicate that a platform region is showing a density above average.

Comparable to the runs with 40 participants the highest densities for the platform without obstacle are located at the side of the entrance on the lower track, causing the density distribution to show a positive deviation from the mean density. The distribution at the upper track is more even.

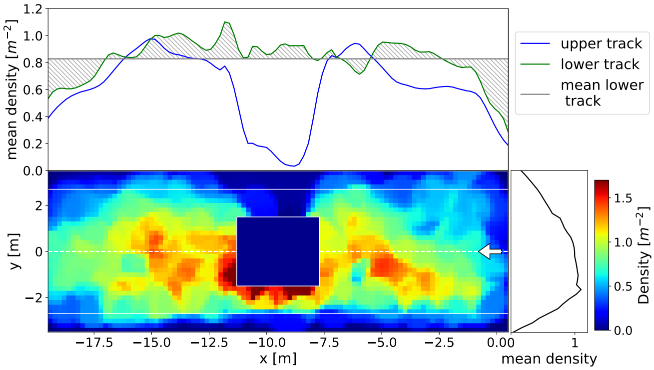
In the runs with obstacles (b-c) the sides of the obstacles were preferred waiting locations and therefore shift the density distribution towards the lower side of the track. This is most distinct for the narrow obstacle (4b) right side). In case of the wide obstacle in runs with 40 participants mainly the sides facing towards the lower track were used for waiting. With an increasing number of participants the sides facing towards the smaller sides of the platform (left and right in Fig. 4c) became more attractive as waiting places. This leads to a more even distribution along the platform. However, the rearward sides of the obstacles (which are facing towards the opposite track) are unattractive and the density distributions exhibit a distinct drop in the curves of the upper track (blue lines) at the location of the obstacles. Those areas are unattractive because there is no direct line of sight to the next expected action, which was the “boarding” of the train at the lower track. Hence, narrow obstacles structure the distribution of densities towards the lower platform side as those visually separate the track sides, while in the case of wide obstacles more space along the platform (in x-direction) is covered. This causes obstacles to



(a) no obstacle



(b) narrow obstacle



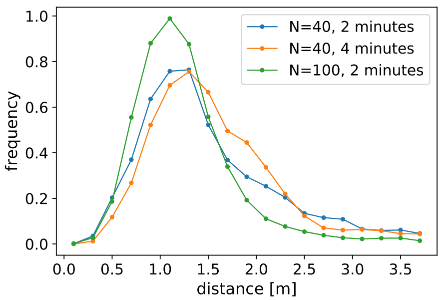
(c) wide obstacle

Figure 4: Density profiles and mean density in x- and y-direction for runs with 100 participants. Mean densities in x-direction (upper panel) are separated into the different track sides. For the lower track (side of train arrival) the mean density is indicated as gray line, the density deviation from the mean is highlighted as grey area for (**a**) the platform without obstacle, (**b**) with narrow obstacle and (**c**) with wide obstacle. The location of the entrance is marked with a white arrow.

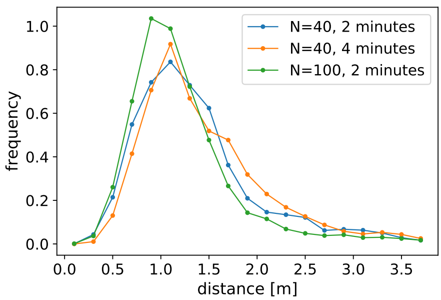
have a two-sided effect: the side facing towards the lower side of the platform (train arrival) is attractive while the opposite side acts as repulsive. Despite the density variations along the platform, a once chosen waiting place is only seldom changed even if the density in other regions is lower.

2.4 Distribution of distances

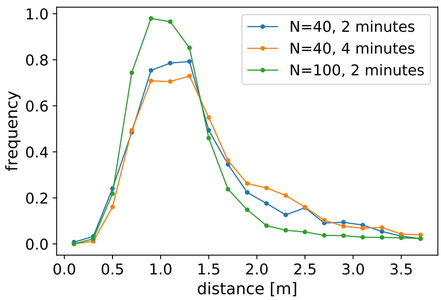
Concerning the distribution of pedestrians two different definitions on uniform distributions can be given: pedestrians can be evenly distributed in space, which would be characterised by a coverage of the whole available space and concurrently by equal sizes of Voronoi-cells. However, the results presented in the previous sections show that in case of a railway platform the awareness of the train arrival causes the participants to congregate at one side of the platform and therefore the distribution is non uniform in space. Nevertheless, the distribution of participants inside the crowd can still be uniform, which is identified by equal inter-personal distances without completely covering up the available space.



(a) no obstacle



(b) narrow obstacle



(c) wide obstacle

Figure 5: Histograms of distances between participants for (**a**) the platform without obstacle, (**b**) with narrow obstacle, (**c**) with wide obstacle. Distances were calculated with Delaunay triangulation during the waiting time.

The distances between neighbouring participants, identified using Delaunay triangulation, were calculated for each frame within the waiting time and visualised as histograms, see Fig. 5.

For each setup (no, narrow or wide obstacle) the distances were determined for runs with 40 participants and 2 minutes waiting time (blue), 4 minutes waiting time (orange) and for 100 participants (green). The distribution of distances differs in runs with 40 participants for the two waiting times. Tukey tests reveal that this difference is significant ($p < 0.001$). For all setups the difference becomes visually apparent in the interval of distances between 1.6 and 2.5 m. (Fig. 5 a-c). For 4 minutes waiting time these distances are more frequent, as those correspond to pedestrians that walk slowly instead of waiting at a fix position.

The distributions of distances for runs with 100 participants differ significantly from the runs with a lower number of participants ($p < 0.001$). With an increasing number of persons the histograms become more symmetric around a mean value of about 1.0 - 1.2 m with only small fluctuations (standard deviation $\approx 0.25\,m$). The skewness to the right, corresponding to larger inter-personal distances, becomes smaller with increasing passenger numbers. This can be quantified as for 40 participants and two minutes waiting time a portion of about 30% of the distances are greater than a threshold of 1.6 m, while with an increasing passenger number this portion decreases to 15 %.

Assuming theoretically that the persons would be evenly spaced out like aligned on a grid over the whole available area, the inter-personal distances would be 1.9 m for runs with 40 participants and 1.18 m for 100 participants. However, all histograms of distances show distributions around 1.0 - 1.2 m. Despite the larger available space per person the participants do not use this space, see the density profiles in 2.3. It is unclear whether the inter-personal distances will also be in this range if the number of participants is increased even further or decreased to fewer than 40 participants. As previously discussed in section 2.3, the density ranges mainly between 0.6 and $1.2\,m^{-2}$ and therefore corresponds to a range of distance of 1 m to 1.4 m, respectively.

The above findings and discussions imply that in these experiments the inter-personal distances are uniform, mostly independent of the global density, number of passengers and the complexity of the waiting areas. Even in situations in which wide obstacles or other pedestrians block the view, waiting pedestrians achieve uniform inter-personal distances. The preference of pedestrians to maintain equal distances between each other is already described in [37]: Passengers in public environments are expected to keep a distance from one another and thus cover the space equally. Following the zones of inter-personal distance introduced by [36], the distances observed in the experiments are without any need inside the "personal zone" $0.45\,m < d < 1.2\,m$ and hence smaller than expected for a public environment with a social distance of $1.2\,m < d < 3.6\,m$. This is an indicator for a superposing effect which seems to surpass the desire to maintain the personal distance to other pedestrians. In the experiments the awareness of the next action seems to cause the reduction of the distance to exit and the concept of maintaining the personal space does not appear to be the predominant factor in these situations. However, the thresholds determining the extent of the personal space by [36] were set for situations between a pair of pedestrians facing each other. In the case of waiting passengers at a train station, the passengers are aligned behind each other, usually facing towards the side of the train arrival. It is therefore questionable if these distances can be adopted for waiting situations or whether a refinement of the concept of personal space is necessary. As these concepts are widely used in the modelling of pedestrian movements, this should be further investigated.

2.5 Rating of experiments: questionnaires and mood button terminals

Runs with obstacles for 40 participants and runs with 100 participants without obstacles (cf. Table 1) ended with the participants being asked to answer questionnaires. Participants were asked to indicate their perception of the density and available space during the experiment. Despite the varying number of participants the rating of density and available space is always very positive and does not exhibit suitable variances. This might indicate that the density differences achieved in the experiments were not high enough to cause discomfort among the participants.

While the questionnaires were specifically asked for the participants' perception of density and space, the mood button terminals (Fig. 6a)) asked about the overall perception of the experimental run. This could include ,for example, the perception of e.g. waiting time or boredom of a single experimental run or the tiredness due to the running time of the sets of experimental runs.

In order to analyse the participants' overall assessment of the runs, see Fig. 6 b), the experiments were divided into three groups: a) runs with 40 participants and 2 minutes waiting time, b) 40 participants and 4 minutes waiting time and c) 100 participants and 2 minutes waiting time. Each of these groups contains runs of the three different setups (no, narrow and wide obstacle). The effects of setup and waiting time (between group a and b) and setup and number of participants (groups a and c) were analysed using ANOVA. To facilitate the analysis, numbers were assigned to the Smiley-buttons (cf. 6a) starting with "1= very unhappy" and ranging to "4 = very happy". For runs with 40 participants the waiting time has a significant effect on the rating ($F_{1,694}$=13.53, p=0.0003), while the setup has no significant effect. This indicates that an increasing waiting time leads to less positive ratings. However, mean values higher than 3.0 are still assigned to the "happy"-side of the scale.

In runs with 2 minutes waiting time (groups a and c), both number of participants ($F_{1,1030}$=50.98, p=0.000) and setup ($F_{2,694}$= 6.92, p=0.0001) have a significant effect on the rating. Their interaction effect is also significant ($F_{2,1030}$=4.22, p=0.0001). Therefore, an increase of the number of participants decreases the rating. A post-hoc test revealed significant pairwise differences between the setups with the narrow obstacle to both other setups. In runs with 100 participants the setup with the narrow obstacle (M= 2.94, std = 0.88) was rated significantly poorer than the runs without obstacles (M=3.26, std=0.73, p = 0.001) and with wide obstacle (M=3.17, std=0.74, p= 0.004). A mean value smaller than 3.0 for the narrow obstacle places the participants' assessment of these runs on edge towards the "unhappy" -side of the scale.

Hence, the mood button terminals reveal that both an increasing waiting time and an increasing number of participants (here by more than a factor of two) have a comparable negative influence on the participants' overall perception of the exper-

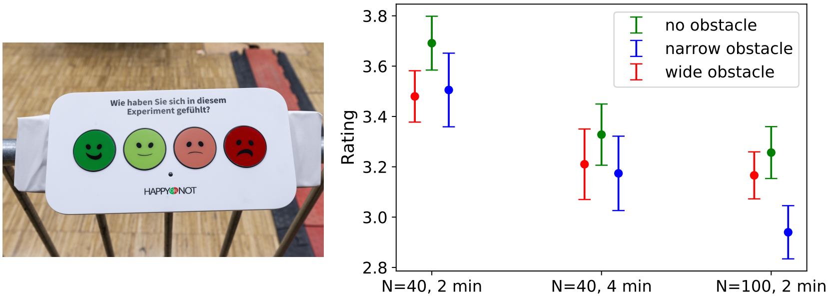


Figure 6: (**a**) Mood button terminal: Participants were asked to rate the latest experiment using the smiley-buttons. The question on the terminal was (translated from German): "How did you feel during this experiment?" (**b**) Rating of perception of experiments: "4 =very happy", "3=happy", "2 =unhappy", "1 = very unhappy" (error bars: 95% confidence interval)

iments. The three setups (no, narrow and wide obstacle) have no significant effect on the rating in runs with 40 participants. However, the narrow obstacle shows significantly lower ratings in runs with 100 participants. Possible reason for this is the structuring effect of the wall-like obstacle which causes the participants to mainly wait at the lower side of platform. It should however be noted that the experiments with 100 participants and the narrow obstacle were performed directly before participant's lunch break and therefore a tiring effect can not be ruled out.

2.6 Floor field model for waiting

Based on the results shown in the previous sections, pedestrians are expected to choose their waiting positions based on a trade-off between different factors, which can either act as attractive or repulsive. As an extension of the approaches introduced in [28] and [46], the following factors (as illustrated in Fig. 7) were identified to influence waiting pedestrians at a platform. These factors are transformed into floor fields which were calculated by equations and functions designed to represent the results obtained in the experiments. The equations of the floor fields were estimated qualitatively as educated guesses and do not claim general validity. The model is a first approach to test qualitatively if it is possible to describe the attractiveness of waiting places using a superposition of floor fields. Due to the necessary simplifications that were used in the experiments, the model in its current form does not claim to be complete with respect to real platforms, since several factors such as e.g. lightning, seating arrangements or information boards are not included. These would influence certain pedestrians individually, resulting in the need to adapt the floor fields for different passengers. As the conflict between parsimony and accuracy becomes larger with more complex models, the floor fields were not validated or quantified by simulations but should act as first attempt of a floor model for waiting places.

a) Distance to entrance (Fig. 7 a): As already shown in previous studies (cf. [10–14, 16–18]) and also observable in the laboratory experiments, passengers prefer

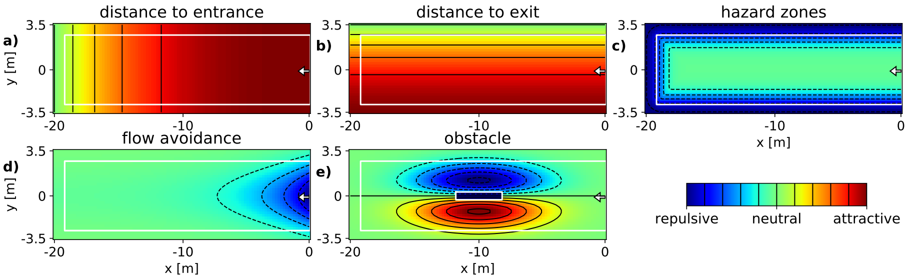


Figure 7: Schematic illustration of influencing factors: (**a**) distance to entrance (**b**) distance to exit (**c**) repulsion of hazard zones (**d**) flow avoidance (**e**) effect of obstacle. Colours indicate the attractiveness as waiting place with blue marking areas as repulsive and red marking areas as attractive. The location of the entrance is marked with a white arrow.

staying close to the entrance and do not walk to the far side of the platform. This behaviour is also reported by [28] for inflow situations into confined spaces and leads to an increased attractiveness of areas in the vicinity of the entrance. The equation used to calculate the distance cost was chosen to be maximal at $x = 0$ (position of the entrance) and decreasing as x^3 towards the end of the platform. The power of three was chosen in order to describe a decay in attractiveness of places at the far platform side, while still rating regions in the middle of the platform as attractive. Following the principle of Occam's Razor the most simple equation was used to describe this behaviour.

$$D(x) = (x + x_{min})^3 \tag{3}$$

where x_{min} is the position of the end of the platform. The y-coordinate of the entrance was left out for simplification as the entrance is almost as wide as the setup.

b) Distance to exit (Fig. 7 b): In the context of railway platforms the location of the exit is known to the passengers as the side of the next intended action (usually the boarding of a train). Therefore, waiting places on the corresponding side are more attractive than on the opposite side of the platform. The attractiveness based on the side of train arrival is calculated as

$$T(y) = (1 + exp(-a \cdot y))^{-1} \tag{4}$$

with a being a positive constant. Waiting places at the side of train arrival are consequently assessed equally, while the attractiveness decreases exponentially from the middle towards the opposite track. As the side of train arrival but not the exact position of the doors is known, the x-coordinates of the doors are not part of the equation. In case a platform with installations such as platform edge doors or other visible indications for the exact location of train doors is modelled, this field will probably need to be modified accordingly.

The factors a) and b) are both optimisations of distances which are generally applicable in different setups like at train platforms, elevators or rooms/corridors. To a certain extent in all these scenarios the distances to the entry and exit will influence the distribution. The distance to the exit is expected to have a greater influence than the distance to the entrance, as pedestrians usually know that they will leave at a certain time and therefore the distance to the exit must to be covered anyway. Additionally, a waiting place close to the expected location of the train's doors might improve chances to get a seat on the train. Besides the optimisation of distances also the comfort is an important factor. Here the context of the situation gains in significance.

c) Repulsion of hazard zones (Fig. 7 c): In contrast to waiting in enclosed spaces, where the boundaries are preferred places [28, 29], the platform's edges have a repulsive effect. Due to the risk of falling passengers in the experiments kept a distance to the edges and did not wait in the area between the white safety line and the platform's edge, even though they were not instructed to respect the safety line. The floor field of the edges depends on the distance to the safety line,

$$E = (1 + exp(-b \cdot B_{ij}))^{-1} \tag{5}$$

where B is a field containing the distance to the safety line and b a positive constant. Hence, the repulsion effect of the platform's edge decreases exponentially from the safety line towards the inner part of the platform and has no effect in the middle of the platform.

d) Flow avoidance (Fig. 7 d): As passengers prefer places where they do not get in the way of others and are not perceived as an obstacle, the area directly in front of the entrance also has an repulsive effect. In real-life field data this effect will be more pronounced than in the laboratory experiments discussed here, as usually passengers will arrive continuously, while in the experiments no new participants entered the platform during the waiting time. As introduced in [28], the flow avoidance can be described as

$$F(x, y) = (-c \cdot exp\left(\frac{-(x - x_0)^2}{d^2} - \frac{(y - y_0)^2}{e^2}\right) \tag{6}$$

with c, d and e being positive constants and x_0 and y_0 the location of the entrance.

e) Stationary obstacles (Fig. 7 e): Obstacles have a two-sided effect on waiting passengers. The side facing the expected boarding direction is an attractive waiting place, while, due to the restricted line of sight, the opposite side acts as repulsive. Hence, the resulting floor field depends on the location of the obstacle whose corner coordinates are given as x_1, x_2, y_1 and y_2.

$$O(x, y) = f \cdot \left(y - \frac{y_1 - y_2}{2}\right) \cdot exp\left(-\frac{(x - x_1) \cdot (x - x_2)}{g^2} - \frac{(y - y_1) \cdot (y - y_2)}{h^2}\right) \tag{7}$$

with f, g and h being positive constants. The function is designed to generate negative (repulsive) values for the area behind the obstacle and positive (attractive) values directly in front of the obstacle. With greater distance to the obstacle its influence decreases to neutral values.

Using a superposition of these factors, a rough estimate of attractiveness of waiting places at railway platforms can be generated. Therefore, the floor fields shown in

Fig. 7 were summed up as $A = w_1 \cdot D + w_2 \cdot T + w_3 \cdot E + w_4 \cdot F + w_5 \cdot O$ using different weights w_i so that different strengths can be assigned to the factors depending on the context.

The resulting superposition is illustrated in Fig. 8, where a) shows the platform without obstacles and b) the platform with a narrow obstacle. The weights were set

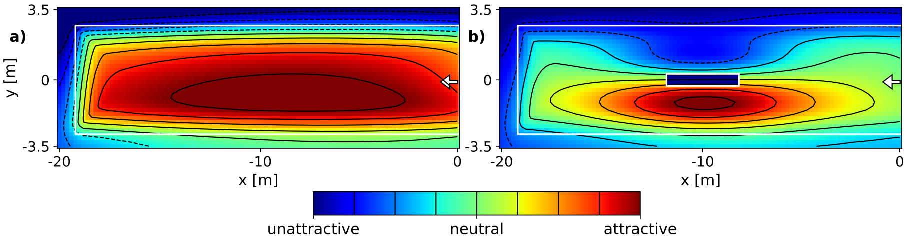


Figure 8: Floor field of attractiveness of waiting positions obtained as superposition of effects from Fig. 7 (**a**) platform without obstacle (**b**) platform with narrow obstacle. The location of the entrance is marked with a white arrow.

as $w_1 = 1$, $w_2 = 2$, $w_3 = 3$, $w_4 = 1$ and $w_5 = 0$ for Fig. 8 a) and $w_5 = 3$ for Fig. 8 b). Regions are coloured based on their attractiveness, with red colours marking attractive and blue colours unattractive waiting places. Even though the weights and floor fields were only determined as educated guesses, the resulting patterns are comparable to the results of the experiments. The weights chosen in this example do not claim general validity, but indicate that the distance to the exit and the hazard zones are likely to play a stronger role.

The suggested floor fields can be used to get a qualitative impression on the final waiting positions, but do not claim to reproduce the dynamics and relocation during the filling processes. In a real environment, the individual factors discussed in the beginning of this section should be added. The floor field can act as a basis for simulation studies to determine pedestrians' positioning goals. In order to model the distribution of pedestrians along these fields, additionally the interactions between the pedestrians, such as collision avoidance or keeping personal distances, need to be considered. With the work presented here, an example of a floor field of the pedestrians' desired waiting places is given.

3 Discussion and conclusion

This study investigated the influence of obstacles, number of passengers and waiting time on the distribution of waiting pedestrians. As the participants were informed about the side of train arrival, their attention was drawn towards this side and their viewing direction was aligned towards the expected train arrival.

Obstacles were identified to structure the distribution of waiting passengers as their side facing the side of train arrival has a pulling effect while their opposite side acts as repulsive. Reasons for the attractiveness of obstacles are the comfort that can be achieved by leaning against the obstacle. These positions also reduce the number of neighbouring pedestrians especially those standing behind, as well as the feeling of leaving space for passing pedestrians as the space directly next to the obstacle cannot be used for walking. Due to the limited line of sight, the rearward side of obstacles is an unattractive waiting place. Especially narrow obstacles structure the platform visually into two sides and thus guide passengers towards the side where they intend to board the train. The wide obstacle, despite blocking the direct view to the far side of the platform, did not lead to an accumulation of passengers at the side of the entrance, and in contrary lead to a more even distribution of participants along the platform. Hence, despite the intuitive assumption that obstacles narrow the available space, they can be used to guide passengers towards waiting places that are further away from the entrance.

In runs with 40 participants the waiting time was varied. With an increased waiting time some pedestrians were observed to start walking around instead of standing at a fixed position. This behaviour was not observable in runs with a shorter waiting time, indicating that in case of longer waiting times the desire to optimise the available space becomes more important to certain pedestrians. Over all, an increase of waiting time decreases the comfort of participants. As the runs with 100 participants were only performed with a short waiting time, no clear statement can be made about the influence of waiting time on larger groups of pedestrians. It is however to be expected to decrease the comfort as well. Whether participants still have enough space to walk around while waiting in a larger group is unclear. An increase of waiting time, however, has nearly the same effect on passengers' evaluation of comfort as a significant increase, here a factor larger than two, of the number of passengers at the platform.

The choice of waiting positions was found to be influenced by different factors, which are identified as staying closer to the entrance rather than walking to the far end of the platform (distance to the entrance), waiting at the side of the next intended action (distance to the exit), keeping a safe distance from the platform's edges, avoiding places that are often disturbed by newly arriving passengers (flow avoidance) and the repulsive and attractive influence depending on the side of obstacles. A superposition of these factors generates a suitable floor field of attractiveness, that can benefit in the modelling and simulation of waiting passengers at train station platforms. However, this model does not yet take into account that passengers tend to distribute along the platform so that the distances between neighbouring passengers are evenly distributed.

Waiting passengers do not cover the whole available space but favour certain areas. However, inside the crowd the inter-personal distances between neighbouring persons were remarkably similar. Despite the fact that the available space for each person is larger in runs with 40 participants than with 100 participants, the inter-personal distances for all runs are distributed around 1.0 - 1.2 m. In other words, in the limit of the variations [N=40 and N=100], the distance is independent of the number of passengers on the platform. This leads to the seemingly contradictory statement that the distance between pedestrians is independent of the global density. Whether this finding is valid for higher densities and other geometries as well is an open question. According to the concept of personal space introduced by [36], inter-personal distances between unacquainted pedestrians are expected to be larger than 1.2 m. However, the distance zones in [36] were derived for face to face situations while waiting passengers stand aligned behind each other. It is therefore likely that these distance zones need to be adapted depending on the context of the situation. The equal distances determined in this study are consistent with the observations for public spaces by [37]. How this is achieved over large distances (here 20 m) and in complex structures (with obstacles) and which dynamic processes lead to this distribution is unclear. Due to the limited variations in the experiments no statement can be given whether a longer waiting time would lead to a uniform space usage and coverage of the whole available space.

The results obtained by this experimental study can be transferred to real-life train station platforms under consideration of certain factors. While the experiments were conducted using a two sided platform where only one train was expected to arrive, in real life scenarios usually both sides of the track are used for boarding and alighting. Therefore, the waiting phases of passengers waiting for their trains at opposing sides will overlap. The interaction effect between the passengers waiting for trains at different platform sides was not part of this study. Since the length of the experimental platform was much smaller than a real platform, the results cannot be applied to whole platforms but only to certain areas. Due to the simplifications that were necessary in the experiments, at real platforms the various installations such as information boards, signs indicating the next trains, etc. and their repulsive or attractive influences, must to be taken into account. The preferred inter-personal distance of 1.2 m can be used to determine the maximum number of passengers in certain waiting areas which still ensures the passengers' comfort. Assuming that persons are standing aligned on a grid, inter-personal distances of 1.2 m would lead to Voronoi densities of approximately 0.7 m^{-2}. This density value can be an indicator during the planing of waiting areas on platforms.

The results of this study can be used to optimise the pedestrian distribution at railway platforms and thereby increase the robustness of the system during peak loads. The factors influencing pedestrians' waiting behaviour and distribution are not solely applicable in the context of railway platforms, but can also be derived for other scenarios. It was shown that the key concepts obtained on inflow experiments into small rooms can be extended to reflect the situations at railway platforms. A further expansion will most likely make these concepts suitable for varying fields of applications.

The experiments using a mock-up train platform have shown that even when pedestrians are waiting in such simple spatial structures, complex phenomena can be observed which can only be described by a superposition of several factors. Furthermore, deviations and complex correlations to basic assumptions in pedestrian dynamics are revealed, especially in the relative positioning of passengers between each other. These findings indicate that concepts widely used in pedestrian dynamics, such as the personal space zone described in [36], need to be expanded. When people are aligned, self-organisation phenomena lead to equal inter-personal distances which, moreover, are found to be independent of the global density. In particular, it is unclear how pedestrians manage to globally adjust this equality over a distance of 20 metres. Since visual signals or globally acting stimuli or instructions can be excluded, it must be a local balancing process which surprisingly leads to a global equal distribution.

4 Methods

4.1 Experiments

The experiments in this study were conducted from 8 to 10 October 2021 in a multi-purpose hall in Düsseldorf, Germany. On each of the experiment days the participants were divided into three groups and interchanged between three different experimental sides inside the hall periodically. Therewith, three different experiments were performed simultaneously. This article only considers experiments from one side. Details on the other experiments and the overall procedure can be found in [39]. The experiments were conducted during the Covid-19 pandemic and in order to minimise the risk of infection all participants were tested prior to entering the hall and were requested to wear masks at all times. In addition to all safety precautions (rapid test, masks etc.), the participants were getting used to crowded situations by an "icebreaker experiment". They were not informed about this experiment as it was a part of their walking way towards the first experiment side. In the morning each group was led inside a corridor with two doors on their way to the first experiment. Once all participants were inside, the doors were closed (inside the corridor were densities of about 1 ped/m^2). After a waiting time of a few minutes the participants were then led to the first experiment. This way the participants experienced dense situations prior to the first experiments. To estimate the extent to which the participant's behaviour was influenced by the pandemic, they were asked to indicate this in a questionnaire after the last experiment of the day. The questions were answered using a 7-point scale ranging from "strongly agree" (1) to "strongly disagree" (7). Among other questions participants were asked to self-report whether they would have behaved differently before the pandemic. Participants indicated that they did not act differently than they would have before the pandemic (M=2.69) and had already been inside crowds elsewhere since the pandemic had started (M=4.02). A more detailed description on the ice-breaker experiments and the questionnaires regarding pandemic influences can be found in [39]. In total 1038 participants took part in the experiments, with ages ranging from 18 to 85 years (median: 31 years). 47 % were male and 51% female. They were paid for participation. In order to automatically extract participants head trajectories, the wearing of green caps was mandatory. Each cap was equipped with an individual code, which is assigned to the participant's data instead of the real name. At the beginning of the experiments participants were asked how often they use public transportation and 80% of the participants stated they use public transportation on a regular basis at least several times per month. Therefore, participants can be expected to be familiar with the setup.

4.2 Experimental setup

The experiments were performed by using a mock-up train station platform with a size of 7 x 20 m and a height of 0.8 m as seen in Fig. 1. Comparable to typical railway platforms in Central Europe, a safety line marked the hazard zone in a distance of 0.8 m from the platform's edges. The platform was either equipped with no obstacle, with a narrow or a wide obstacle. The obstacles were located in the middle of the platform. The narrow obstacle was 0.6 m x 3.6 m in size and the wide obstacle 3 m x 3.6 m. Both had a height of 2 m. Obstacle sizes were chosen to represent common platform structures, such as information boards or elevators. The experiment side was separated from other parts of the hall by black curtains so that participants did not see the setup beforehand. In order to reduce disturbance and to simulate a typical railway environment a speaker box with a recording of train station sounds was placed below the platform. Participants entered the platform through stairs with a width of 3 m attached to the platform's smaller side (right-hand side in Fig. 1). The arrival of a train was simulated by three movable stairs with a width of 1.5 m, which were manoeuvred to their positions for safe attachment at the larger side of the platform (left side in Fig. 1d). The exact position of these stairs was unknown to the participants. Each setup of the platform, with or without obstacle, was tested with 40 and 100 participants. In runs with 40 participants the waiting time, which started after the last participant of the run had entered the platform, was either 2 or 4 minutes; in runs with a higher number of participants the waiting time was 2 minutes. Each participant took part in one run with 40 and one run with 100 participants. Over the course of the three days of the experiments each scenario was repeated three times with different participants, cf. [39].

Choice of experimental conditions

The experimental setup was designed as a compromise between a realistic configuration and technical feasibility. It was therefore necessary to limit the focus of the study to the factors that were expected to be most relevant and technically possible to investigate. This lead to a downsizing of the platform due to the technical effort to cover the complete area by the field of vision of the camera system and the costs of installing technical equipment and the platform itself. The obstacles were chosen as simple as possible but comparable to real life platform infrastructure. In order to ensure the coverage of the whole experimental platform by the video cameras, the obstacles were placed in the middle of the platform, cf. [47]. The number of participants was planned to be higher, but despite ensuring payment for the participants and publicly advertising of the experiments, it was not possible to find more volunteers, which might be caused by the fact that the experiments were performed during the pandemic. Additionally, temporal constrains (e.g. number of experimental days, work load for extraction of trajectories and analysis) and the costs (e.g. technical equipment, payment of staff and participants, platform parts) were limiting the number of possible repetitions of the experimental runs and therewith the number of factors that could be investigated.

4.3 Experimental procedure

Before the experiment, participants were guided to a waiting area separated from the experimental setup by black curtains. Depending on the run (for an overview see Table 1) a certain number of participants were given the following instructions (translated from German): "Imagine you are at a train station. Behind those curtains is the platform, which you will enter through the stairs. You plan to take the train that will arrive in a few minutes at the platform at the left-hand side." After the instructions, the participants' inflow to the platform was regulated so that approximately one person entered the platform every 3-5 seconds. Participants then waited for a predefined waiting time (either 2 or 4 minutes; see table 1). After the waiting time was completed, the train arrival was announced, the movable stairs were positioned and the participants left the experimental side and were guided in a different waiting area. In this second waiting area a mood button terminal was placed, which participants were asked to use after each run. A mood button terminal is a tablet with four smiley buttons, which people passing by can use to express a feeling by pressing one of the buttons. The question displayed on the terminal was "How did you feel during this experiment?" (translated from German). The terminal saved a timestamp and the pressed mood button, which had to be chosen from "Very Happy", "Happy", "Unhappy" and "Very Unhappy". In order to ensure that participants used the terminals, they were actively reminded to do so after each run. In runs in which questionnaires were to be filled out (as indicated in table 1), those were distributed in the second waiting area. Questionnaires were either distributed for both runs with 40 participants (for the setups with narrow or wide obstacle) or for the runs with 100 participants (for the setup without obstacle). Participants were asked how they rated the following items (translated from German): 1) I perceived the space available for me as sufficient. 2) I perceived the density at the platform as unpleasant. The rating was a 7 point-scale ranging from "1 =strongly disagree" to "7 = strongly agree".

4.4 Data collection and preparation

The trajectory data were collected by filming the experimental setup with three cameras facing straight down. Two of these cameras were used to cover the platform with an overlap of camera views in the middle; the third camera filmed the entrance staircase and was used to read the individual code markers on the participants' heads. A detailed description on camera configuration and techniques can be found in [39]. Participants' head trajectories were automatically extracted following [40] using the software PeTrack [41], which is achieved by recognising and tracking of the green caps. Trajectories of all runs were then manually corrected and the different camera views were combined to result in one complete trajectory set for each run. The resulting trajectories consist of an unique ID number (the number of the marker on the participants' cap) and the x and y positions at a given time frame. In this study the frame rate is 50 frames per second. The obtained trajectories were then used for the analysis outlined in the next section.

Data Availability

All raw data, i.e. video recordings and head trajectories, are available through the Pedestrian Dynamics Data Archive hosted by Forschungszentrum Jülich and can be found here:
`http://ped.fz-juelich.de/da/2021train_platform`

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Ethics statement

The application of ethical approval for the experiments was submitted by A. Sieben to the German Psychological Society (DGPs, the Society) and approved in December 2019 (file reference SiebenAnna2019-10-22VA). Written consent was obtained from all participants who took part in the experiments.

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