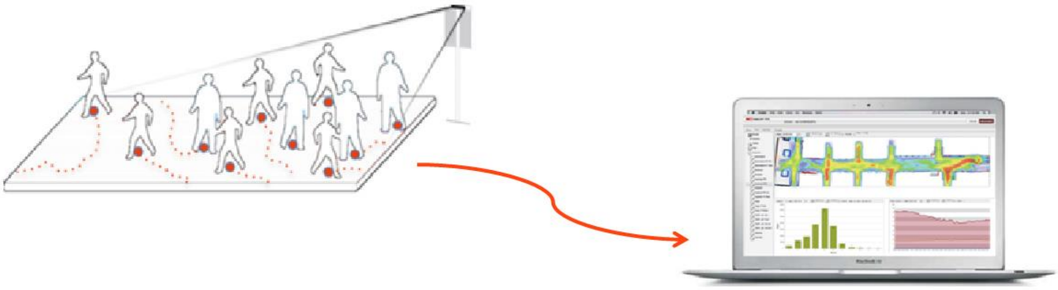

Exploratory analysis of pedestrian flow characteristics in mobility hubs using trajectory data

Marija Nikolić, Transp - OR, EPFL
Bilal Farooq, Transp - OR, EPFL
Michel Bierlaire, Transp - OR, EPFL

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Marija Nikolić
Transp - OR, EPFL
1015 Lausanne

phone: +41 21 693 81 00
fax: +41 21 693 80 60
marija.nikolic@epfl.ch

Bilal Farooq
Transp - OR, EPFL
1015 Lausanne

phone: +41 21 693 93 27
fax: +41 21 693 80 60
bilal.farooq@epfl.ch

Michel Bierlaire
Transp - OR, EPFL
1015 Lausanne

phone: +41 21 693 25 37
fax: +41 21 693 80 60
michel.bierlaire@epfl.ch

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Abstract

Owing to a close collaboration between the Swiss Federal Railways (SBB CFF FFS) and École Polytechnique Fédérale de Lausanne (EPFL), we are able to study pedestrian flows based on disaggregated data collected at the Lausanne train station. People are tracked across the time and precise location in space of every pedestrian is recorded. Based on this remarkable data set, a detailed exploratory analysis is presented in this paper, as an important and necessary step in obtaining the model specification, capable of depicting various aspects of pedestrian motion behaviour. In order to gain an insight into how people use space at the Lausanne train station over time, different aspects (macroscopic and microscopic, both qualitative and quantitative) of pedestrian walking behaviour are explored. The effects of congestion and different spatio-temporal aggregation levels on pedestrian dynamics observables are analyzed in detail. The findings from the analysis will serve to identify limitations of the existing state-of-the-art pedestrian flow models, with the aim to improve research on the pedestrian flow theory. Moreover, on the applied side, it will help us develop operational tools for policy makers that can be used for optimizing pedestrian flow in public spaces.

Keywords

pedestrian mobility data – pedestrian behaviour – exploratory data analysis – visualization – aggregation

1. Introduction

In the context of pedestrians, the term congestion is usually associated with sport, entertainment, cultural or religious events that gather a great number of people in a confined space. In recent years, and mostly due to economic reasons, there has been an observable trend towards an ever-increasing number of people settling in cities. Consequently, it brings a significant stress on the public transportation infrastructure. As an example, let us refer to the train station in Lausanne. Passing through the crowd during the morning rush hour poses a viable challenge for anyone who is in a hurry to catch a train. Moreover, predictions say that by the year of 2030, the number of passengers commuting between Lausanne and Geneva will have increased from 50,000 to 100,000 [15]. A basic question that arises is: what can be done in order to provide efficient management of the predicted increase in number of pedestrians at train stations? The simple application of a particular policy, without previous study of the concrete problem might lead to some very costly trial and error solutions. One solution is therefore to investigate the best approach, which means that the evaluation of the effects of a proposed policy on the pedestrian facilities should be done at an analysis level before its implementation. For such an analysis the tools based on the pedestrian models capable of representing the real phenomena, are necessary. Hence, the understanding of the pedestrian movement behaviour is important both from a practical and a theoretical point of view.

Several pedestrian modelling approaches have already been put forward in the literature. One class represents microscopic or disaggregated models where each pedestrian is modelled separately, as an individual agent, and pedestrian behaviour is explored independently [10]. On the other hand pedestrians are analyzed in groups and crowds, and the state of the system is generally described by mass densities, flows and averaged velocities [8]. The third class of pedestrian models is mesoscopic, acting as a bridge between microscopic and macroscopic modelling approaches. These models don't distinguish each pedestrian individually and report pedestrian characteristics in aggregate terms, but they could describe pedestrian behaviours at a microscopic level usually in terms of probabilities [14]. Nevertheless pedestrian modelling is still a big challenge, due to the fact that pedestrian movements are highly heterogeneous. Different aspects affect their motion:

- personal characteristics of pedestrians (age, gender, size, health, etc.),
- characteristics of the trip (purpose, familiarity with the route, luggage, etc.),
- properties of infrastructure (type, attractiveness, etc.),
- environmental characteristics (ambient, weather conditions, etc.),
- pedestrian density, etc.

In the literature that deals with pedestrian walking behaviour, the importance of real time observations of pedestrian traffic conditions is stressed ([1], [2], [3], [4], [6] and [8]). In this work we present the individual trajectories based behavioural analysis of pedestrian movement, the aim of which is to improve research on the pedestrian flow theory.

1.1 Paper outline

Firstly, this paper discusses the related work on pedestrian dynamics in Section 2. The main quantitative and qualitative results from the available literature are shown. The focus is on the fundamental quantitative characteristics of pedestrian motion (density, velocity, flow), as well as on the collective behaviour of groups of pedestrians and associated self-organization phenomena. Section 3 describes the data set used for the exploratory analysis and presents the description of the corridors at the train station in Lausanne where the trajectories have been collected. The data set, consisted of microscopic pedestrian data, and allowing for a detailed analysis is going to be dealt with in Section 4. There, the performed analysis of typical trends is going to be shown; qualitative and quantitative, microscopic and macroscopic aspects of the pedestrian dynamics are taken into consideration. It is followed by detailed discussion on the results. Section 5 concludes the main results and findings, and subsequently, some future research directions are proposed.

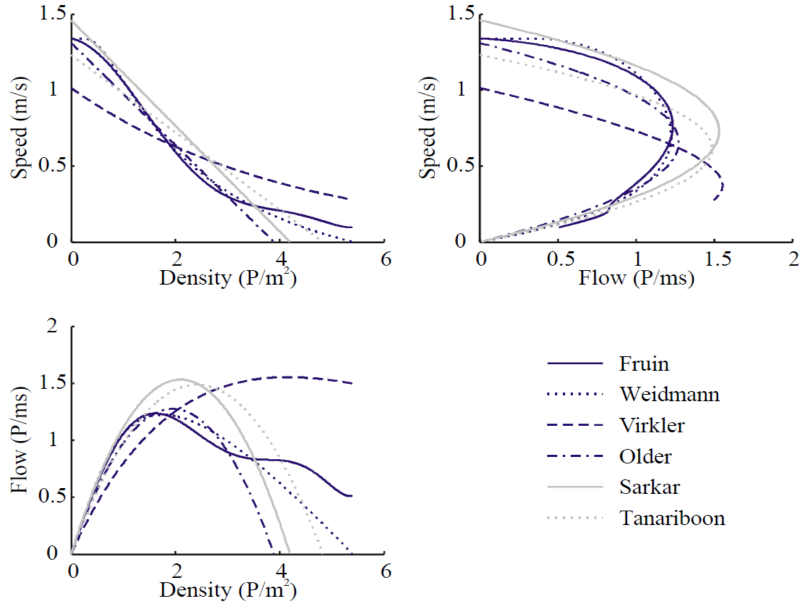
2. Related work

In this section we briefly present an overview of the results on pedestrian dynamics and associated features of the pedestrian movement behaviour, from the aspect of empirical research.

Empirical observations are important when it comes to design and optimization of the public facilities, but should also serve as an initial point for any kind of modelling approach. In [9] the main qualitative and quantitative empirical findings from the literature on pedestrian dynamics are reviewed. Among others, phenomenological observations as a result of collective intelligent behaviour, specific for different types of flow, are summarized (lane formation, density waves, clogging effects, oscillatory changes, etc.). The described collective effects reflect the individuals' microscopic interactions and have to be covered and reproduced by any modelling approach, aiming on realistic representation of real world observations. When it comes to quantitative description of pedestrian dynamics, among others, large differences are present regarding the results on fundamental diagrams. The fundamental diagram is a relation that connects the basic parameters, such as velocity, density and flow to describe pedestrian dynamics. The proposed fundamental relations, present in the literature, were obtained based on different definitions and assumptions, for different cultural and population groups, different types of pedestrian flow and using different measurement methods. Therefore it is not surprising that the reported maximal value of flow goes from 1.2 $(ms)^{-1}$ to $1.8(ms)^{-1}$, jam-density goes from 3.8 ped/m^2 to 10 ped/m^2 and reported maximum flow density range is from 1.7ped/m^2 to 7 ped/m^2 [6]. Examples of the empirical findings of this particular aspect are shown in Figure 1.

In recent years, several well-controlled pedestrian experiments were performed by researchers in order to extract the characteristics of pedestrian dynamics and to identify the reasons for the uncertainties of fundamental diagrams ([3], [4], [5], [6] and [7]). An approach to investigate the influence of the measurement method of fundamental pedestrian flow characteristics on the resulting fundamental diagram for different types of pedestrian flows is described in [4]. Even for this particular factor and the most regular and simplest system, namely the unidirectional movement, different conclusions have been derived in this work compared to the results presented in [6].

Figure 1 Fundamental diagrams from literature



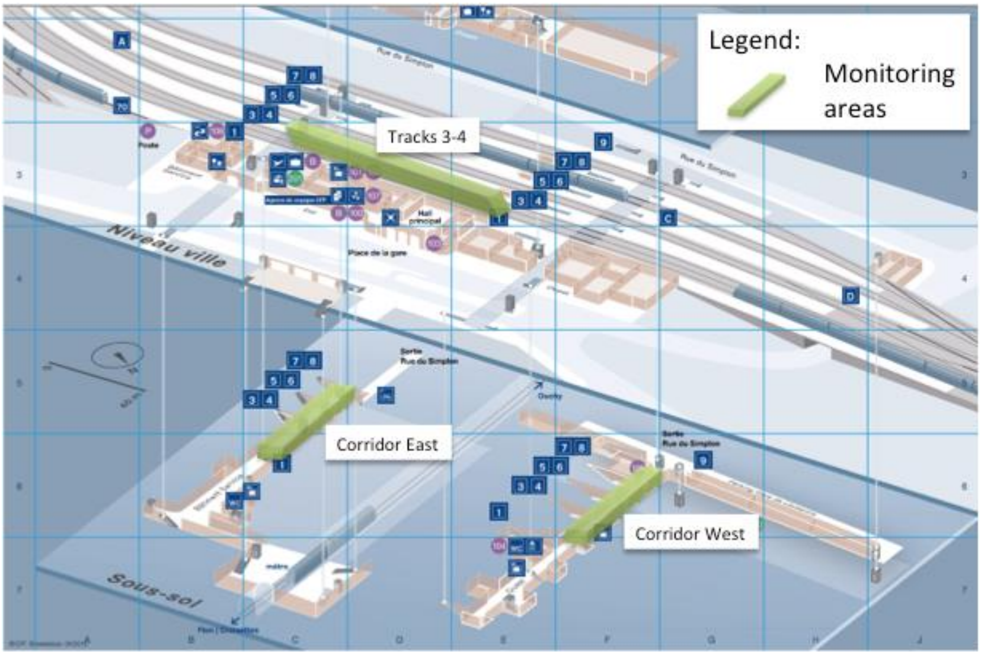
Source: [1]

The conclusion arising suggests that pedestrian movement behaviour is still not well understood. Therefore the development of the better data analysis methods based on precise field data becomes significant, in order to obtain reliable qualitative and quantitative properties of pedestrian movement behaviour.

3. Data collection

Owing to a close collaboration between Swiss Federal Railways (SBB CFF FFS) and École Polytechnique Fédéralede Lausanne (EPFL), we are able to study pedestrian flows at the Lausanne train station on the basis of disaggregated or microscopic pedestrian data. Visiosafe is a spin-off from EPFL which offers cutting-edge sensors for tracking people [16]. 76 smart sensors capture flow anonymously without any physical tags in Lausanne train station's corridors West/East, and tracks 3-4 (Figure 2).

Figure 2 Monitoring areas in Lausanne train station where pedestrian flows are captured by Visiosafe network of smart sensors



Source: [16]

The sensor system allows an automatic capture of human behaviour in extreme conditions; pedestrians are automatically located in 3D and tracked across time. As shown in Figure 3, for each time point the precise date and time are recorded (date), as well as the zone identifier (zone_id), the pedestrian's x, y position and the unique identifier (traj_id).

Figure 3 Screen shot from the data base

	data	zone_id	x	y	traj_id
904	2012-09-19T06:40:50:348	PIW	98105	11014	1412
905	2012-09-19T06:40:50:848	PIW	98227	11021	1412
906	2012-09-19T06:40:51:348	PIW	98350	11027	1412
907	2012-09-19T06:40:51:848	PIW	98473	11034	1412
908	2012-09-19T06:40:52:348	PIW	98596	11040	1412
909	2012-09-19T06:40:52:848	PIW	98719	11047	1412

Based on such remarkable data source, plenty of analysis can be performed in order to get an insight into pedestrian walking behaviour in mobility hubs:

- interaction with moving and static objects (other pedestrians, obstacles),
- collective behaviour and self-organization of pedestrian groups,
- flow characteristics and spatial usage.

On one hand, individual trajectories contain important information for the optimization of location of mobility infrastructure and services. On the other hand, they also describe the essential parts of the pedestrian motion behaviour. Last but not the least dimension of the importance of individual trajectories is their usage in model calibration and validation processes.

The process of data collection lasted for four months. From June twenty-second to October twenty-second of 2012. The individual trajectories were collected every day from 6 hours in the morning till midnight. Our analyses are based on data collected during the period from September eighteenth to September twenty-first 2012, mainly for the West corridor, for which the higher traffic volume is observed.

4. Exploratory data analysis

For anyone who aims at modelling and simulating pedestrian dynamics, the very first step should be the analysis of the empirical data in order to understand pedestrians' behaviour and their interactions. Exploratory data analysis presented in this section aims at better explaining of the pedestrian walking behaviour in normal situations.

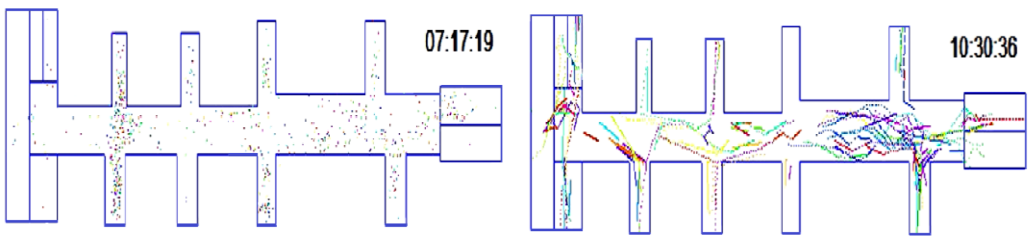
We start with the analysis of time-space patterns, based on trajectories for the corridors East and West.

Next, the performed descriptive or qualitative analysis of people motion behaviour is presented. Microscopic (how people use the space based on individual trajectories) and macroscopic aspects (collective behaviour), emerging out of individuals, are analysed in details. The detailed analyses of several scenarios typical for a train station, such as the stairs, the ramps, and the corridors are presented.

Finally, the quantitative analysis of microscopic and macroscopic aspects is given. It includes the analysis of the fundamental quantities of pedestrian motion behaviour such as velocities, densities, distances and travel times for the corridor scenario. The quantities are extracted directly from pedestrian trajectories and their relationships are derived. One of the goals is to investigate the effects of different spatio-temporal aggregation on obtained results which describe the pedestrian dynamics.

To support our perception, cognition and reasoning, when it comes to handling and analysing the large amount of movement data, a visualization tool for pedestrian space-time motion has been developed (Figure 4). The main purpose of the visualization tool is to provide us with an ability to gain an insight into how people behave over time, depending on various circumstances at the train station, by investigating different aspects (unidirectional, bidirectional, cross flows) and phenomena in pedestrian dynamics.

Figure 4 Visualization tool output – (a) pedestrians' positions without trail; (b) pedestrians' positions with trail;



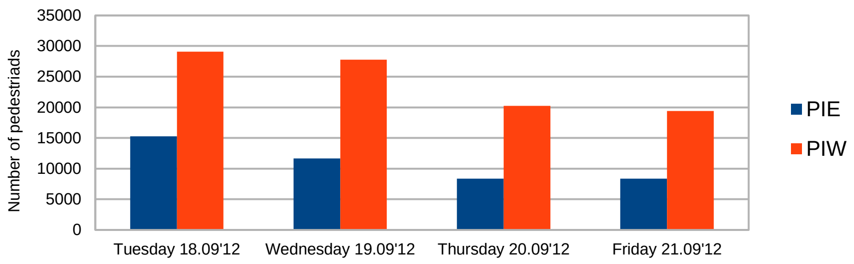
(a) (b)

4.1 Analysis of time-space patterns

In order to identify the most frequently used areas, the congested and uncongested periods for the corridors East (PIE) and West (PIW), the basic pattern analyses are performed, the results of which will serve as a benchmark for further analyses.

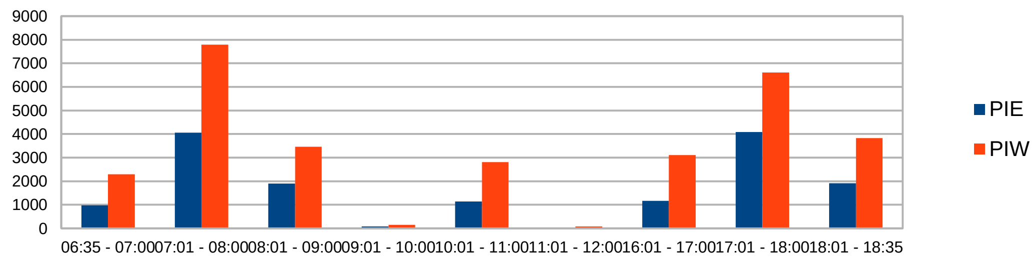
By analyzing the number of people over time for both corridors, the higher rate of traffic is observed for corridor PIW, compared to PIE. In both cases the critical day, in terms of traffic volume, is Tuesday 18.09.2012. Results are summarized in Figure 5.

Figure 5 Traffic for all days



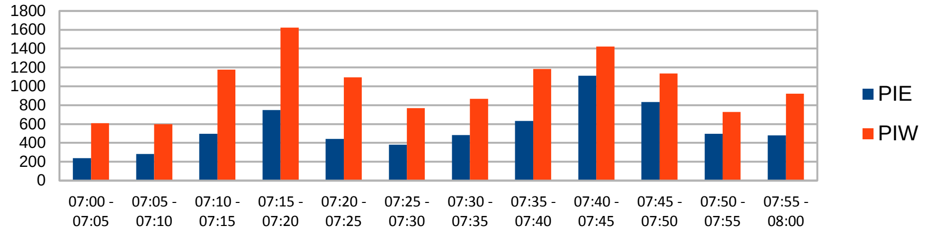
From Figure 6 it is obvious that two critical periods (congested conditions) of time are from 7 to 8 in the morning, and from 17 to 18 in the afternoon. The results are as expected, taking into account the fact that for the people whose purpose of commuting is work related these periods are very common.

Figure 6 Traffic over the peak day



During the morning rush hour the most critical periods (congested conditions) are from 07:10 to 07:25 and from 07:35 to 07:50 (Figure 7). This phenomenon reflects the rhythm of the train schedule.

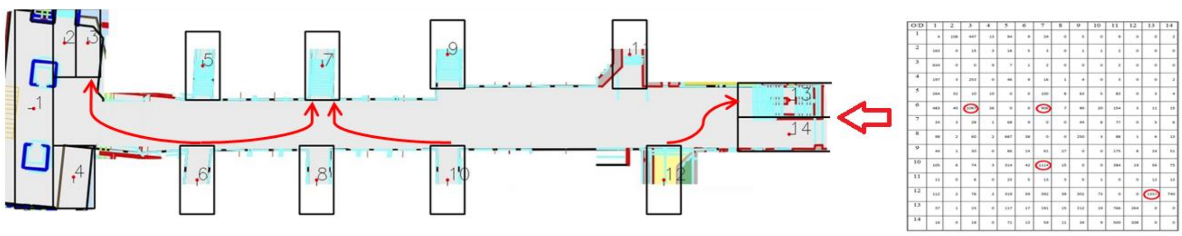
Figure 7 Traffic over an hour (peak day)



Based on these findings, the following analyses will be based on individual trajectories collected at the corridor PIW for Tuesday 18.09.2012, and mainly for the morning peak hour. The reason is that the highest traffic rate is observed for the PIW for the mentioned time interval. More precisely, during the morning peak hour conditions with lower, medium and higher levels of congestion are observed at PIW, making this period convenient for the baseline analyses.

Figure 8 shows the most taken paths (hot paths), whereas in Figure 9 the most frequently used areas (hot spots) at the Lausanne PIW for Tuesday 18.09.2012 are presented. The zones marked as 5, 7, 9, 11 and 6, 8, 10, 12 are stairs and ramps respectively, providing the access to the platforms. Additionally, the zone 12 provides the way to the main train station's hall. The zones 13 (stairs) and 14 (underground entrance/exit) provide the way to the city, metro and bus stations. The zones 1, 2, 3 and 4 are the shopping and parking areas.

Figure 8 The most taken paths at the Lausanne PIW for the peak day: left – PIW corridor with marked most taken paths; right – OD matrix for the peak day

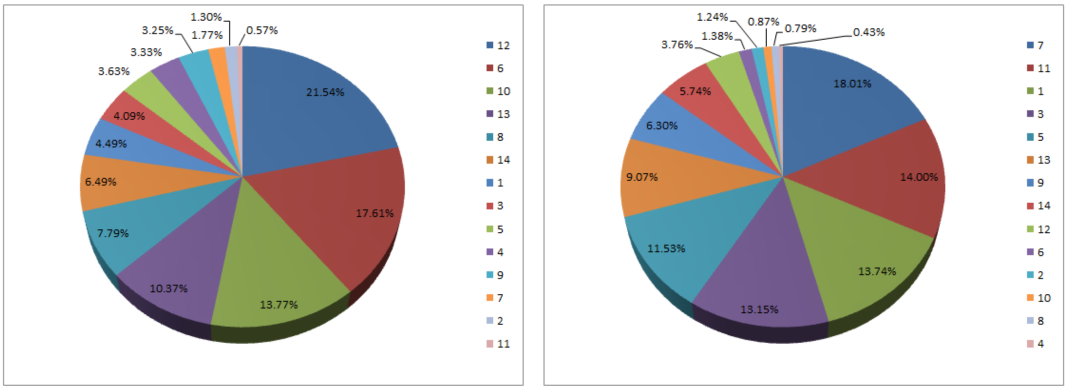


As a result of the scheduled arrival and departure times of trains and purpose of the specific zones, as it is already explained, the most used paths at PIW are:

- zone 6 to zones 3 and 7,
- zone 10 to zone 7,

- zone 12 to zone 13.

Figure 9 Origins (a) and destinations (b) for the peak day



(a) (b)

As it is shown in Figure 9, the zones 13 and 14 (considering both together) are observed as frequently used areas, which is as expected, taking into account their purpose - they provide the way to the city centre, metro and bus stations. The frequently used area as origin is the zone 12 that connects PIW with the main train station's hall, where, among others, ticket machines, information stands, exchange offices and the main information board are located. The zones 6 and 10 appear as frequently used origins too, which is caused by the fact that they provide the access to the platforms with the highest frequency of inter-regional (IR) and so-called euro-city (EC) train arrivals/departures [17]. The zone 11 attracts a significant number of pedestrians because of the presence of the ticket machines and lockers in this area. The frequently observed destinations are the zones 1 and 3, representing the shopping and parking areas. For the rest of the zones, the rhythm of the train schedule is observed.

These findings will serve to explore the changes in pedestrian flow characteristics and walking behaviour over time, depending on various circumstances at the train station (periods of time with higher and lower level of congestion, different areas, etc.). In such a way the identification of the limitations of the existing state-of-the-art pedestrian flow models becomes possible.

4.2 Qualitative data analysis

The analyses presented in this subsection are based on individual trajectories for the peak day in the case of the PIW corridor. The aim of the analyses is to identify the impact of certain factors, such as the geometry of the infrastructure, the level of congestion, etc., on the pedestrians' walking behaviour. We have found that pedestrian trajectories show a certain level of both, temporal and spatial regularity.

4.2.1 Microscopic data analysis – individual trajectories

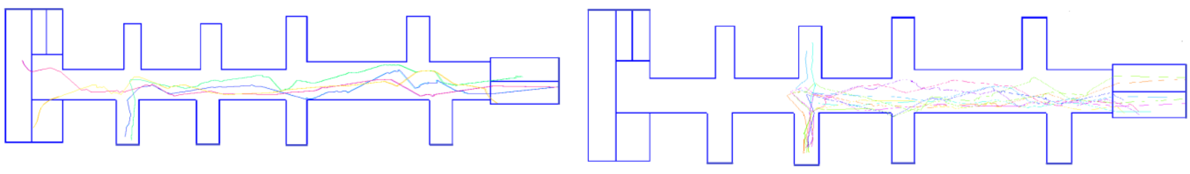
4.2.1.1 Corridor scenario

In this subsection we present the conclusions derived for the pedestrian motion behaviour in the case of corridor, obtained with the aid of visualization tool [18].

Figure 10 shows only those trajectories, for two chosen time intervals (less congested – left; more congested - right), whose destination is the PIW northern exit, providing the way to the metro stations and the city.

Comparing to the trajectories from Figure 10 (a) and Figure 10 (b) it is noticeable that in the case of lower congestion, pedestrians deviate less from the desired path, which means that higher level of congestion prevents pedestrians from walking in a straight line. In the case of higher congestion speed is reduced, hence, pedestrians have to either wait to continue their movement or to deviate from the desired path. Another point to be stressed is an observation that pedestrians use space more efficiently when the congestion level deteriorates, occupying the whole available walking area. From Figure 10 it is clear that trajectories at the ramps and stairs are quite smooth, whereas those along the corridor are more tortuous with pronounced lateral deviations.

Figure 10 Individual trajectories - (a) lower level of congestion 10:30-10:32; (b) higher level of congestion 07:16-07:18



(a) (b)

4.2.1.2 Ramps and stairs scenarios

Due to the reduced dimensions of the stairs and ramps, compared to the rest of facility, as well as due to the well-known fact that the walking speed is also reduced, these two entities can be considered as an example of the bottlenecks in the system [8]. When it comes to reduced walking speed, one should distinguish between upward and downward movement, and its geometry, current conditions (normal or dangerous) and social characteristics of pedestrians (age, sex, health, etc.) should be taken into account.

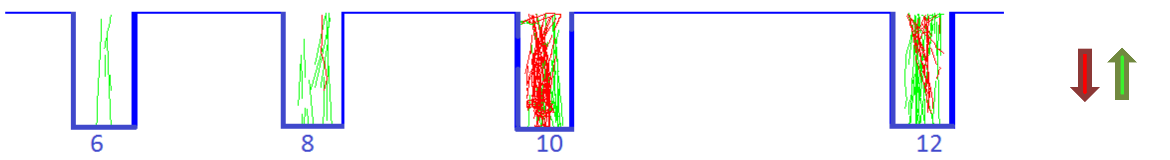
On the basis of the foregoing and the available data, in this subsection we present the conclusions derived for the pedestrian motion behaviour in the case of stairs and ramps, obtained with the aid of visualization tool ([19] and [20]).

A general conclusion is that pedestrian trajectories for the ramps and stairs are smoother than the ones along the corridor suggesting that in shorter segments, pedestrians are able to walk in a straighter line. It is also observed that pedestrians tend to use the shortest path and tend not to deviate too much from the desired one. In the case of narrower stairs and ramps the available walking space is more efficiently used which is especially obvious when congestion conditions deteriorate.

As shown in Figure 11, for an unidirectional flow and a lower level of congestion pedestrians' trajectories, which are quite smooth, are placed in the middle of the available walking area (zone 6). It indicates that people tend to increase the distance between themselves and walls if possible. For the same type of flow but a higher level of congestion, this is no more the case, and the whole walkable area is used (zone 8).

In the case of a bidirectional flow, the same conclusions are derived for both higher and lower level of congestion, noting that there are certain differences depending on the flow balance. Namely, when flow is bidirectional and mostly balanced (approximately equal in both directions) whole available walking area is used and pedestrians form groups of people walking in the same direction rather than lanes. Groups are dynamically formed and they are not stable over time. It is also observed that slower pedestrians (based only on visual impression) have a tendency to walk closer to the handrails. The reason for this is most likely of psychological nature – slower pedestrians walk closer to the walls, thus protecting themselves, given the fact that such behaviour provides the sense of greater safety. On the other hand, when the flow is bidirectional but unbalanced, the dominant flow tends to use the middle part of an available walkable area, and those people that constitute the opposite flow form groups that use the rest of the available space. When the congestion level is higher, paths are no longer smooth; certain lateral deviations can be observed.

Figure 11 Pedestrian trajectories at ramps: red – upward flow; green – downward flow



4.2.2 Macroscopic data analysis – collective behaviour and self-organization

In this section we refer to the terminology used in [9].

Collective intelligence: Emergent functional behaviour of a large number of people that results from individual reasoning or global optimization.

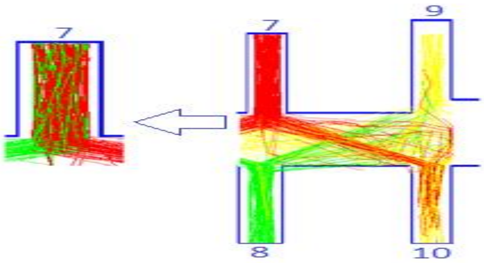
Self-organization: spontaneous organization (i.e. formation of ordered patterns) not included by initial boundary conditions, regulations or constraints. Self-organization is a result of non-linear interactions between many objects or subjects, and it often causes different kinds of spatio-temporal patterns of motion.

In accordance with the mentioned terminology, the typical example of self-organization, namely the lane formation, in the case of higher congestion (07:19-07:22), is observed and shown in Figure 12. The lanes are formed in the case of cross flow and this phenomenon is not caused by external directives - on the contrary, it is an effect of spontaneous pedestrian interactions. We hypothesize that this kind of emergent collective behaviour phenomena may be the result of the fact that such formations allow for a more comfortable flow for people who walk in the same direction. The improved comfort is due to the reduced interactions with people walking in the opposite direction who are therefore able to perform walking at a higher speed.

By analyzing the output of the visualization tool for the whole time interval of the interest (07:19-07:22), the form of stripes composed of pedestrians walking in the same direction has also been observed.

The same figure shows a zoomed part of stairs 7 where merging flow is observed. Two streams aggregate forming one main stream that moves upwards and occupies the whole available walking area. From trajectories, congestion in front of the stairs 7 can also be noticed.

Figure 12 Left - merging flow: green - pedestrians coming from the left side, red-pedestrians coming from the right side; Right - cross pedestrian flow: red – pedestrians going towards stairs 7, green – pedestrians going from ramp 8, yellow – the rest flow



4.3 Quantitative data analysis

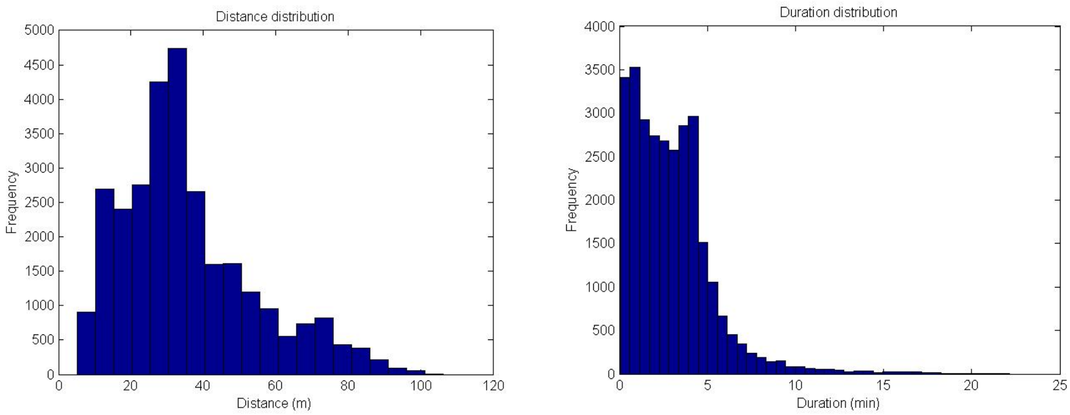
Before we present the results of the quantitative analyses, let us introduce the observables used for pedestrian movement behaviour studies for the peak day in the case of the PIW corridor, discussed in this subsection.

There are different ways to quantify the pedestrian load of facilities. The most used are based on the fundamental flow quantities, such as velocity, density and flow, and on their relation - the fundamental diagram. However, another analysis can be performed linking the distances travelled within the facility and total time needed to perform the desired walking. In this context time and space representation are essential aspects that affect the pedestrian dynamics analysis.

4.3.1 Distances and durations

In order to gain an insight into how the space of our interest (PIW corridor) is used the analysis of the duration and distance observables can be considered as shown in Figure 13.

Figure 13 Distance (a) and duration (b) distribution for the peak day at PIW corridor



(a) (b)

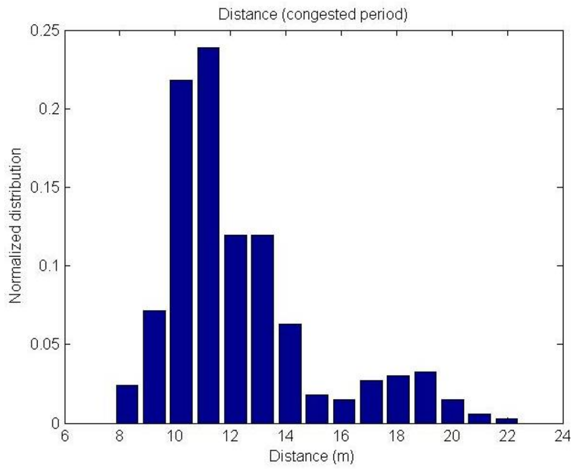
Based on the distance and duration histograms, the majority of people in the corridors travel distances longer than 35 meter, and remain there up to 5 minutes. The average transit time is about 3 minutes.

A more useful analysis is the one which gives us the relation between travelled distances and durations for congested and uncongested intervals for a specific area. In this regard, in the following subsection, we are focused on the mentioned analysis for the case of the most widely used path at the PIW corridor.

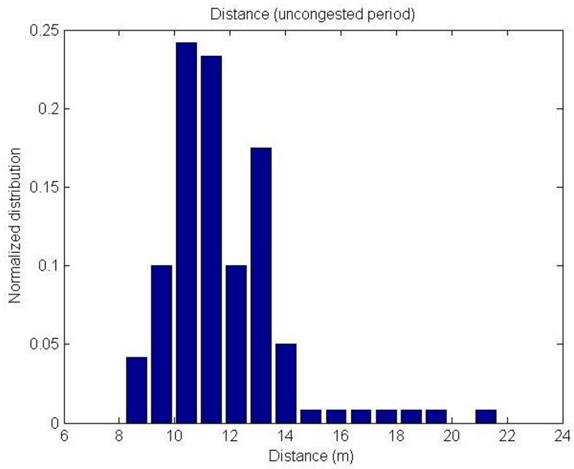
4.3.1.1 Impact of congestion on distance and duration observables

An indicator of the level of service of the system, such as the PEW corridor in our case, is certainly the information regarding the travelled distance and time spent on this activity. Our hypotheses are that the congestion has an impact on the travelled distances and that for the same activity more time is needed when traffic conditions deteriorate. In this context, we analyze the impact of congestion on the distance and duration observables in the case of the higher (07:00 – 08:00) and lower (10:00 – 11:00) level of congestion (Figure 6). The analyses are performed for the most frequently used path (zone 12 to zone 13) and the differences for the distance observables are not very high in terms of the values. The minimum distance travelled in congested and uncongested periods are 7.78m and 8.17m. Whereas, the maximum distances are 22.46 and 21.68m. The average distances are 12.3m and 11.72m for the more and less congested periods respectively. The observation that the minimum distance for the uncongested is longer than for the congested period might suggest that people walk more efficiently in congested periods, but certainly requires further analysis. In the case of a duration indicator, the observed minimum values are 9s and 8.5s, observed maximum values are 157s and 140s, and the average observed durations are 64.7s and 35.3s, for the more and less congested periods respectively. Based on these indicators, particularly on the duration, the impact of the congestion on pedestrians' flow along the corridor is evident. The impact becomes even more evident if we analyze the distribution of the indicators (Figure 14 and Figure 15) for the desired time period rather than the average values.

Figure 14 Distance distribution for path zone 12 - > zone 13 for (a) congested period (07:00 – 08:00) and (b) uncongested period (10:00 – 11:00)



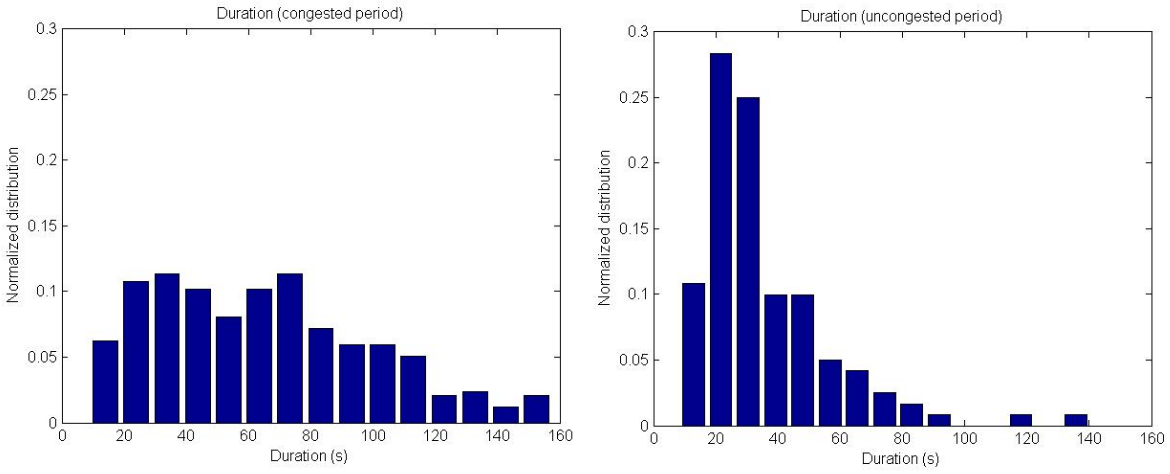
(a)



(b)

During the periods of lower traffic congestion, distances greater than 14m are less common than in the case of the higher congestion level, while the presence of distances less than or equal to 10m is more often, which is as expected. Additionally we have analyzed the deviations from the straight-line path between two zones in the congested and uncongested conditions. The straight-line is defined as the path between the x-axis midpoint of the zone 12 entrance and the y-axis midpoint of the zone 13 entrance, which is 8.7m. With respect to the straight-line distance, presence of distances up to 22m can be associated with pedestrians' familiarity with the environment, with the impact of the attractors such as shops, billboards and storages for personal belongings present along the corridor. Certainly greater proportion of the distances greater than 14m, in the case of higher congestion, is associated with the impact of congestion that prevents pedestrians to achieve the movement in form of the shortest path.

Figure 15 Duration distribution for path zone 12 - > zone 13 for (a) congested period (07:00 – 08:00) and (b) uncongested period (10:00 – 11:00)



(a) (b)

Clearly, from Figure 15, two different types of pedestrians can be observed: the slow and the fast movers. These types are more visible in the uncongested case, due to the fact that both can walk at desired speed. The analysis based on the normalized duration histograms, for both time intervals shows an evident shift of distribution to the left in the case of the lower level of congestion where the highest proportion of duration values is grouped around 20s. There is an observable decrease in the average time needed to traverse the path from the zone 12 to the zone 13 by 45 per cents when traffic conditions convalesce. This significant reduction in duration is caused by 2 factors: due to improved traffic conditions the pedestrians are free to choose their paths, and most of them choose the shortest one; frequency of stop and go phenomenon is reduced in the case of lower congestion.

4.3.2 The pedestrian fundamental flow characteristics

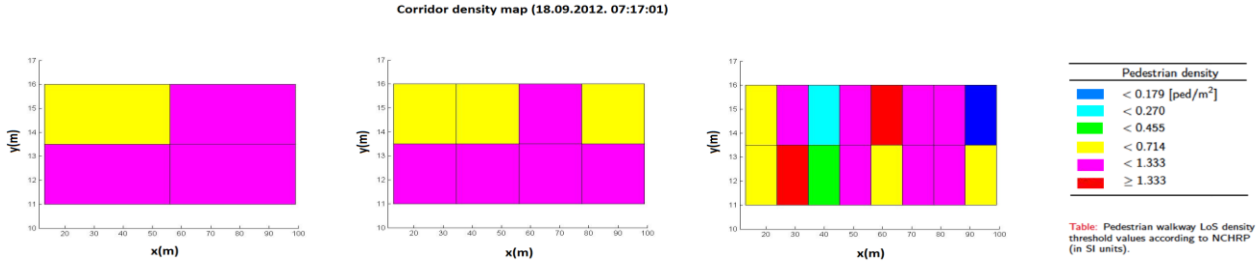
A traditional way to measure pedestrian dynamics is through a fundamental diagram which provides the relation between the flow characteristics such as pedestrian velocity, density and flow. Nevertheless, large differences are present regarding this fundamental relation in the specifications of various experimental studies, guidelines and handbooks, as shown in Section 2. It suggests that pedestrian dynamics is still not well understood. Therefore, it is necessary to develop better data analysis methods based on precise empirical data, such as the trajectories of individuals. Given the fact that the space representation is certainly the essential aspect that affects the pedestrian dynamics analysis, in this section we investigate the impact of underlying space decomposition on pedestrian density measure. The obtained empirical density-velocity relation and the methodology for the free flow speed extraction are also presented.

4.3.2.1 Density maps

The physical space, within which the pedestrians perform their movement and interactions with each other and with the surrounding environment, could be represented in different ways. In this study we are focused on discretization of the space based on the grid and Voronoi diagram structures.

The grid based method transforms the space into cell regions, where each cell is seen as entirely homogenous. In this case, one should think about the aspects related to the cell size and a partitioning nature (static or dynamic). In order to analyze the effects of space aggregation on the instantaneous density observable we have chosen three different cell sizes: $2.5\text{m} \times 43\text{m}, 2.5\text{m} \times 21.5\text{m}, 2.5\text{m} \times 10.75\text{m}$. The time instant 07:17:01 is selected because of the fact that the highest traffic rate is observed at PIW from 07:15 to 07:20, regarded as an indicator of potential congestion (Figure 7). The resulting density maps are shown in Figure 16.

Figure 16 Cell based density maps

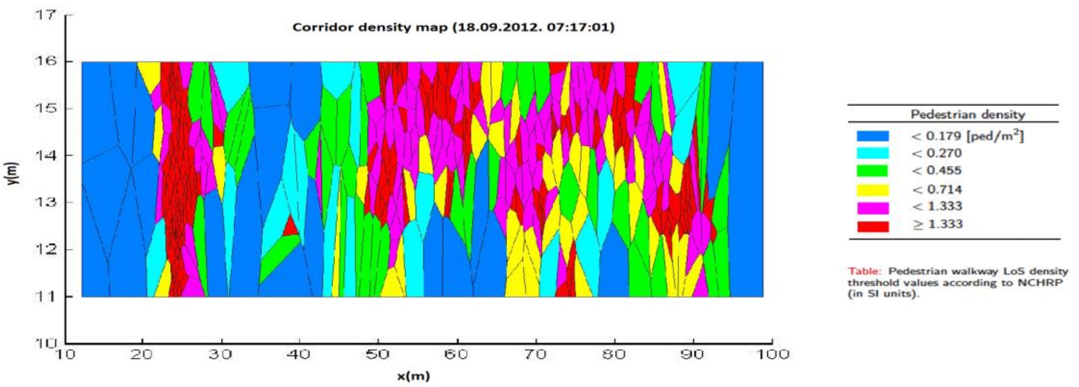


(a) (b) (c)

As can be noticed, the spatial analysis has certain limitations associated with the discretisation of the space, since each size and boundary change affects the proportion of the number of pedestrians related to a specific space unit. The results gathered from a study of spatial data are not independent of the scale and boundaries, which is known as MAUP effect (Modifiable Areal Unit Problem) [13]. The MAUP occurs when the spatial partitioning system used for analyzing spatial data is ‘modifiable’ or arbitrary. Because of the arbitrary nature of the obtained space units (cells in this case), the results of the analysis based on these units may be arbitrary, hence not reflecting the real state of the underlying process. Effects of the MAUP have an impact on the mathematical and statistical properties of analysis and therefore a direct impact on the accuracy and reliability of the indicators obtained based on the specific space representation.

MAUP effects can be alleviated by decomposition of the space at an individual pedestrian level. For this purpose Voronoi based structures can be engaged [11]. For the given point set (pedestrians’ locations) in the Euclidean plane the ordinary Voronoi diagram represents a tessellation of the plane into a set of the regions associated with the members of a given point set. The spatial tessellation is performed in such a way that all space locations are associated with the closest member of the point set in respect of the Euclidean distance. The Voronoi diagram thus provides the space decomposition in a natural way and gives valuable tools for the analysis of spatial data.

Figure 17 Voronoi based density map



Based on the results shown in Figure 16 and Figure 17 for the same time instant and the same area of interest, it is observable that aggregation of space has an important effect on the pedestrian dynamics analysis. In the case when the disaggregated data exists, the aggregation leads to the concealment of essential information, comparing to the case when the measurement is achieved at the individual level. This conclusion suggests that, in order to obtain the maximum possible precision of the results, it is necessary to perform the analysis at a disaggregate level.

The researchers from the transportation field have already used the Voronoi based form of space representation in order to enable a more precise measurement of the pedestrian density and velocity ([4], [5] and [7]). Nevertheless, the ordinary Voronoi diagram is not the best space representation for capturing the observed real world phenomena. From everyday experience, it is well known that pedestrian movement requires a sufficient area. This area is related to a human perception field due to the fact that people attach more importance to what is in front of them than to what is behind them and what they are not aware of. Moreover, the fact that people avoid obstacles while walking is another aspect that has to be considered. Based on these facts we have developed an improved methodology for the pedestrian dynamics representation, which is our future research direction. This methodology extends the Voronoi diagram based representation of pedestrian dynamics so as to explicitly include the human perception of personal space. Thus, we have chosen to utilize the idea of the generalized, additively weighted Voronoi diagram in which the weights are specified in such a way as to reflect the phenomena observed. The generator set is represented by pedestrians' locations at a specific time. The individual's visible region of interest is incorporated using the Field of View (FoV) and the obstacle avoidance strategy. A vector representing the pedestrian direction is associated with each member of the generator set in order to be used for the FoV based calculation of the weights in space. In order to obtain personal regions that are consisted of traversable points only, we will use the concept from computational geometry and robot motion planning known as visibility graph [12].

When it comes to ordinary Voronoi space decomposition, additional issues that arise are those associated with small pedestrian allocated polygons in very dense areas, and large pedestrian allocated polygons at the rims of the groups. In order to resolve the first issue it is necessary to define events when more polygons, which are critical in terms of the area, merge together and become considered as one polygon. The second issue involves the pedestrians at the rims of the groups to whom all the remaining available space is assigned, regardless the direction of movement. The way to handle this issue is to incorporate the direction of movement in the personal space computation, as previously explained, as well as to limit the size of personal polygons for those directions that are not of the interest for pedestrians.

Our future research direction is to examine the success rate of the proposed methodology on the real data.

4.3.2.2 Free flow speed distribution

Free flow speeds are defined as the speeds pedestrians like to walk with when they are not are limited in forward movement by people to the front and side. Free flow speeds differ among pedestrians based on personal characteristics, characteristics of the trip and the infrastructure, environmental and external conditions [2].

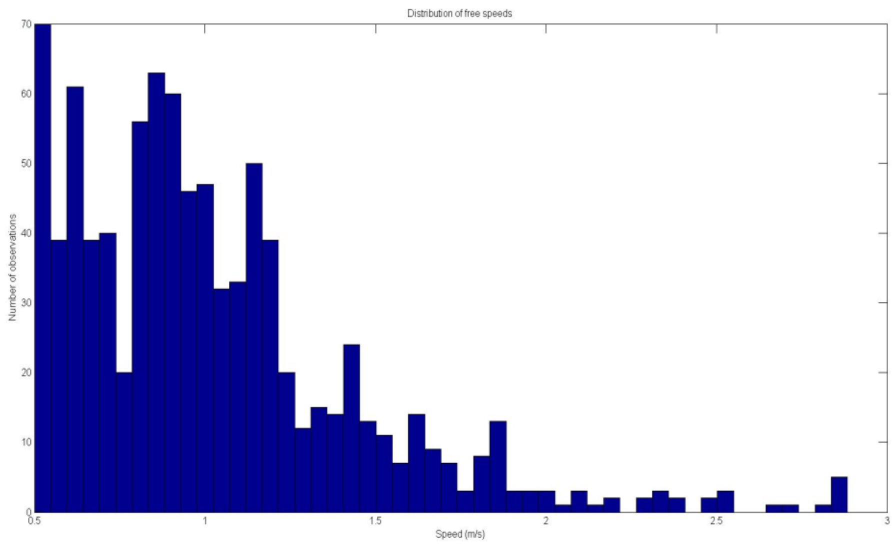
One of the advantages of the space representation via Voronoi structures is the possibility of extracting pedestrian free flow speeds. Here we consider that a pedestrian is able to walk at a desired free flow speed provided that at a specific time instance, his/her personal space measures density less than $0.05\ {}^{ped}/_{m^2}$.

Instant velocity is extracted directly from individual trajectories, and is defined as:

$$v_i(t) = \frac{x(t+\Delta t)-x(t-\Delta t)}{2\cdot\Delta t},$$

where Δt is chosen to be $0.5s$, in accordance with the fact that the pedestrians' positions are recorded every $0.5s$ (2 frames per second).

Figure 18 Voronoi based free flow speed distribution (the peak day, 09:00 – 10:00)



The resulting histogram in Figure 18 suggests the possible existence of a mixture of two exponential distributions, which will be further investigated. Based on the results, several sets of values grouped around different speeds are present. This result may be related to the fact that depending on personal characteristics, health, age, familiarity with the environment, the pedestrians have different levels of a desired free flow speed. Those pedestrians whose speed rate exceeds the 2m/s are most likely to be in a hurry to catch the train – a case typically found at facilities such as train stations.

A noticeable anomaly, which is not in accordance with the definition of the free flow speed, is a large percentage of the speed values close to zero. The reason for this observation could be related to the fact that a significant number of people have been observed in a standing position during the time interval of interest. Therefore, the corridor cannot be viewed in its entirety as an area of interest; it is necessary to exclude those sites that are attractors for pedestrians when the free flow speed analysis has to be performed. On the other hand, we cannot be sure about the degree of reliability of the collected data since this scope is not validated. However, another validated set of data for two weeks in February 2013 exists. In the very near future we will carry out the same analysis on a new set of data before making any final conclusions.

4.3.2.3 Fundamental diagram (density – speed relation)

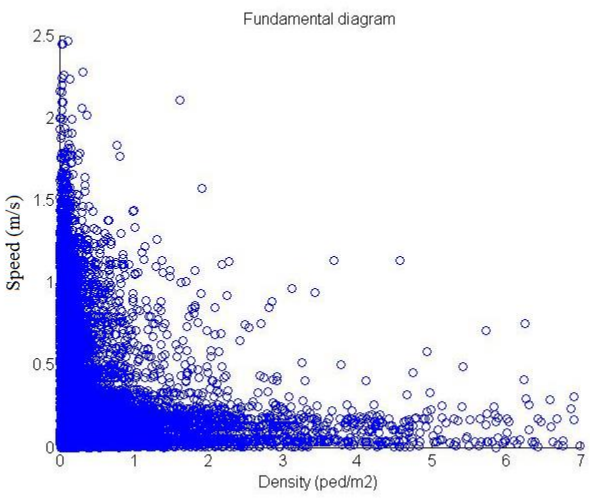
The fundamental diagram describes the empirical relation between density (k) and flow (q), but due to the *hydrodynamic relation*

$$q = k \cdot v$$

it also refers to $v(k), v(q)$.

In this section, we will focus on the relation $v(k)$, describing the relation between the density and speed, for the peak day at the PIW corridor. The obtained relation is based on trajectory data for the time period from 10:00 to 10:05, with a sample rate of 1s, based on the Voronoi space representation. The resulting diagram is presented in Figure 19.

Figure 19 Voronoi based fundamental diagram



As noticed, the results for the fundamental diagram in Figure 19 significantly differ from those found in the literature (Figure 1). The most striking deviation is related to the fact that very low speeds are observed for the low density levels. There are various reasons for the detected discrepancies. One of them is the fact that the diagram shown in Figure 18 has been constituted on the basis of empirical data, where pedestrians perform their movement without external instruction, compared to the fundamental diagrams based on data obtained from well controlled experiments. For a large number of individual trajectories we have observed some periods during which pedestrians do not perform any movement. This situation actually makes sense, if we take into account that many people arrive at the station before the train's departure and therefore spend some time simply waiting in corridors. The same can be said in reference to the familiarity with the place which is proven to vary for all pedestrians. Pedestrians are also attracted to the signs, the information boards, the shops and the billboards that exist along the corridor. Therefore, the average speed should be expected to be less in this case than in the one of experimental data.

Empirical observations show a scattering phenomenon, as the effect of a large number of factors (personal characteristics, geometric settings, environmental conditions, etc.), highly motivating the stochastic density-speed relationship model. From Figure 19 it is obvious that there is a distribution of speed at a certain density level due to the stochastic nature of pedestrian flow, which is in contrast to the ‘pair-wise’ pattern from deterministic models. In order to justify the need for the stochastic density-speed relationship, in the ensuing period a comprehensive analysis of empirical density-speed observations will be conducted and the underlying mechanisms of the scattering feature will be analysed.

As in the previous subsection, the same is true for the obtained fundamental diagram - in the very near future we will carry out the same analysis on a new, more reliable data set before we make final conclusions.

5. Conclusion and future work

This contribution presents the empirical results of microscopic and macroscopic, both qualitative and quantitative, pedestrian flow characteristics. Conclusions are performed under the assumption that the used data set of individual trajectories is insufficiently good representation of the reality, but we notice that all results will be validated in the very near future, on the new data set available for the two weeks in February this year.

Based on the descriptive analysis, we have observed that pedestrians generally tend to keep a certain distance from the walls whenever possible, and their ability to achieve movement in the form of a straight line decreases with the increase in distance to be passed. Within the mobility hub, such as train station, the pedestrians more often create the groups than lanes of people walking in the same direction. However, regarding the periods of higher congestion, we have observed a kind of distinctive collective intelligent behaviour – lanes are formed in order to achieve better efficiency of movement when traffic conditions deteriorate.

The results on the quantitative analysis for the corridor scenario suggest that the impact of congestion on pedestrian movement behaviour can be analysed through the travelled distances and the corresponding durations for the specified O-D pairs. We have shown, with the example of the density observable calculated based on the grid space representation, that the MAUP effect is significant and should be taken into account when the analysis is performed based on spatial data. In reference to that, we have concluded that by performing the analysis at the disaggregated level, with the aid of Voronoi structures, it becomes possible to get the results that would precisely reflect the real state. However, we have also identified certain issues associated with this kind of space decomposition:

- small polygons allocated to pedestrians in very dense areas,
- large polygons allocated to pedestrians at the rims of the groups,
- direction of movement is not taken into account,
- personal polygons overlap with the obstacles.

We have proposed a methodology so as to overcome these issues the success of which will be evaluated on a new, validated and more reliable set of data. In the ensuing period, the aforementioned quantitative analysis will be performed for the stairs and ramps scenarios as well.

Detailed analysis of the underlying mechanisms of the density- speed scattering feature is in direction of future research.

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