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Crowdflow around a railway platform exit

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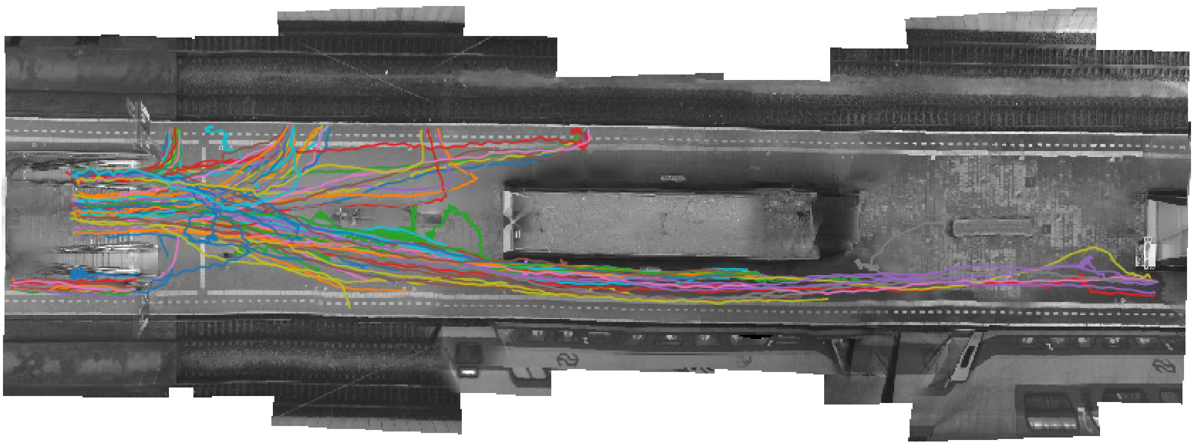

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Eindhoven, January 30, 2023

Abstract

In this research the issue of crowding at railway platform exits is investigated, specifically at one platform of Eindhoven Centraal train station. Trajectory and location data of pedestrians travelling on the platform is analyzed in order to find main causes of queuing and find ways to prevent it. The results reveal that distributing crowds better between stairs and escalators, in an early stage, can alleviate the issue of queues forming around the exit. In general, people tend to prefer taking escalators over stairs. Placement of stairs and escalators influence the distribution drastically, as people seem to prefer the route that is perceived as either shorter or faster. Based on these findings, the study recommends placing stairs in a more convenient location relative to the escalators in order to direct more people to the stairs in an early stage, preventing queues around the exit.

Contents

1 | Introduction

Increasing urbanization and global goals to reduce CO_2 emissions mean that public transport is becoming increasingly important. It is essential to ensure the public transport system is safe, efficient and future-proof. It is expected that the demand for public transport will increase by 30 to 40% in the next ten years. To prepare for this rise in utilisation of existing and new railway stations, the bottlenecks in the public transport system have to be assessed and solved.
In this study, the efficiency and congestion of pedestrians on a railway platform at Eindhoven Centraal train station are analyzed. What causes crowding around the exit of railway platforms and how do we minimize it?
ProRail has installed tracking sensors on some of their train platforms to gain insights in bottlenecks and crowd dynamics. This data has already been used to research the boarding process of trains [1], and investigate the crowd distribution over the platform. Next to that, in other countries extensive studies have already been done on pedestrian crowdflows on flat surfaces [2], and also on railway platforms [3]. What makes the railway platform at Eindhoven Centraal station unique is the fact that the exit process involves either taking stairs or escalators. The change in level causes people to be cautious and decrease their speed, influencing the crowd behind them. Also, the stairs and escalators are located next to each other and are the only option to leave and enter the platform; this can give valuable insights in decision-making of individuals in the unique environment of a railway platform.
Platform exits have limited capacity, and on crowded moments this can lead to queues which cause delays, irritation and even unsafe situations [4]. In underground or large train stations, level changes are prevalent and essential to utilize the limited space as well as possible. It is important that situations like the one in Eindhoven are better understood, in order to design future-proof stations, keeping the public transport system safe and efficient.
In this study the situation at one of the railway platforms at Eindhoven Centraal train station is analyzed. First, in Section 2, the data provided by ProRail is explained and its possibilities and limitations are explored. From Section 3 on, the research and its results are discussed. In Section 3.3 until 3.6 the trajectory data provided by ProRail is used to construct a fundamental diagram of the situation around the exit of the platform in order to get an insight in the dynamics of the situation. In Section 3.7 until Section 3.7.3, different factors that influence the decision between exiting the platform via stairs or escalators are studied in order to gain understanding about this decision-making. Section 4.2 talks about nudging techniques that can influence choices between escalators and stairs. Finally, in Section 4 it is summarized how these results can be implemented in future railway station design or redesign.

2 | Data

This research is based on data provided by ProRail. The database contains anonymous location data collected by sensors hanging over a train platform at the Eindhoven Centraal train station, and has been collected over several years. These sensors are able to identify individual people and keep track of them over the platform between frames on different times. Combining the location and time data together with the ability to identify and track individuals, trajectories of individual pedestrians can be constructed. The programming language used in this study is Python, as that is the language that is taught to all students at TU/e. It also has a number of useful libraries for data analysis such as pandas and NumPy, and plots can be generated easily using the Matplotlib library. Python is also simple and efficient, which is necessary when working with large data sets.

2.1 | Specifications

An example of a subset of the raw ProRail data can be seen in Table 2.1. The 'date_time_utc' column is the time in milliseconds, starting at a very high value. It is therefore hard to find the exact time in this column, but when filtering using python this is not a problem. The exact time can be easily found in the 'datetime' column.

Table 2.1: Sample of the raw ProRail data

	date_time_utc	tracked_object	x_pos	y_pos	datetime
1	1.66314e+12	2025575	-1476	13529	2022-09-14 08:00:00
2	1.66314e+12	2025575	-1407	13653	2022-09-14 08:00:00
3	1.66314e+12	2025575	-1363	13724	2022-09-14 08:00:00.100000
4	1.66314e+12	2025575	-1337	13804	2022-09-14 08:00:00.100000
5	1.66314e+12	2025575	-1315	13918	2022-09-14 08:00:00.200000

Each pedestrian is categorised anonymously as a unique number, specified as 'tracked object'. His or her position is then followed throughout their journey over the platform. For every timestamp, their respective x- and y-positions are saved. The location tracking and identification happens live and inside of the sensors with a sample frequency of 10Hz. This means for each time stamp, x- and y-positions are saved of all tracked objects on the platform at that time. With this data the distribution of people over the platform can be visualized and interpreted, allowing calculation of density and distribution on the platform at different times and locations, which is important for recognizing queues and general crowdedness.
By combining x- and y-positions for specific tracked objects and their corresponding timestamps, trajectories can be constructed. This is done by stitching data points of single pedestrians together [5]. A plot of some of these trajectories can be seen in 2.1.

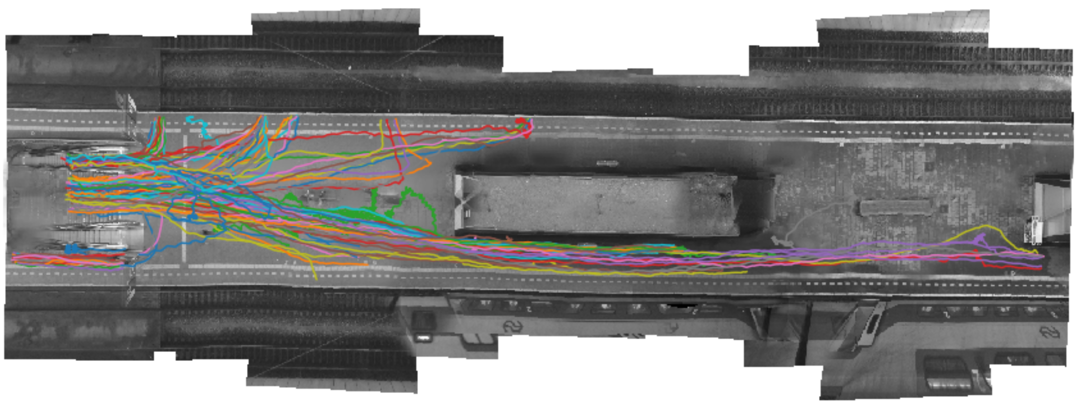


Figure 2.1: Some arbitrary trajectories

Initial location and final location can be specified using the positions of a specific tracked object in combination with the first and last timestamp. This is useful for identifying where people enter the platform and how they leave. Velocity can be calculated from location data and the sample frequency.

2.2 | Limitations and cleaning

When researching decision-making of people, many things can be taken into consideration. Given that the provided data is anonymous and only consists of locations and times, many interesting things can not be taken into account. Factors such as mental or physical state, luggage and personal preference can not be derived from location data alone, while they do have a large impact on decision-making.
The data provided is also not perfect: people are assigned a tracked object number algorithmically, which can induce errors. Obstacles such as information boards can cause sensors to lose track of tracked objects for a few seconds, and when they are detected again they are assigned a new tracked object ID. Also, near the bottom of the stairs and escalators, sensors lose track of people or confuse them with others because the people are slowly moving out of the depth range of the sensors. One person travelling over the platform can be assigned multiple object ID's, losing valuable information. Next to obstructions of the sensor, factors such as height and moving speed also have influence on this. With correct cleaning most of these inaccuracies can be eliminated, and a lot of information can be derived from the data that is provided. This data is the starting point of this research.

2.3 | Selection

Location data of multiple years, day in day out, has been collected by the ProRail sensors. Busy days can have over 40 million individual data points, leading to dataframes that contain more than 3 Gigabytes of information, containing only the four basic columns. For some of this research, in particular the Voronoi diagrams generated in Section 3.5, computationally expensive calculations have to be executed. Doing this takes a relatively long time, and it is unfeasible to calculate the density for every tracked object at every timestamp of every day of data.
However, this is also not necessary. The train platform environment is a relatively constant one, with every train arriving at the same location, or very near. The doors are located on the same spots, and the station layout is also fixed. This means that a lot of information can already be taken from data of only one day, a day where most common and problematic situations have occurred. On a regular Monday for example, a lot of people are standing on the platform for their train to work during rush hour. At the same time, many people arrive for work with the same train, all wanting to leave the platform. During the middle of the day it is relatively calm, and in the afternoon it gets progressively busier again from people who are leaving work or arriving home. Each day, although crowdedness can vary a bit, the same situations occur. Therefore data of one day can already be enough to get a good understanding of the pedestrian dynamics on the platform.
Another way to decrease the amount of computation, while keeping accuracy, is by decreasing the sample frequency. The sample frequency of 10Hz is necessary to identify people correctly over different frames, but the situation on the station does not change drastically every tenth of a second. Since the individuals are already tracked and have a tracked_object ID, it is not always necessary to calculate every exact location for every sample. After calculating initial location, final location and average speed for example, you can prune the dataframe so it only consists of every 50^{th} timestamp. This gives you a sample frequency of 0.2 Hz, or once every 5 seconds. For calculating local density and finding a relation between density and velocity, this decreases computation time drastically while not losing much accuracy.
The calculations made in the decision-making sections (3.7 - 3.7.3) of the research are a lot less computationally expensive. Therefore it is a lot easier to take data of multiple days or weeks into account for generating those graphs, and these data reduction measures are less important.

3 | Research

A train station, and specifically a railway platform, is a unique environment which is hard to compare to other environments. Especially for the situation where a lot of people are leaving the platform at the same time, it is difficult to find comparable circumstances. Pedestrians enter the platform from different locations, namely all different train doors that open at the same time. Flows of pedestrians arise, and every flow has to leave the platform at the same location. However, every individual has different conditions that influence their trajectory over the platform. For example, some people are in a hurry, have large luggage items, and small groups of people arrive which want to stay together [6]. Every single one of these people has different physical and mental states, and have personal preferences for their exit routine: some move quickly to avoid crowding, others follow the stream of people. Some have a preference for the escalator, or are forced to take it, while others might want to take the stairs. Cultural difference can also have influence on this decision [7]. All these factors make every train station different, but a lot of knowledge can be extracted from a unique railway platform that can be applied at or compared to other platforms.

3.1 | Platform layout

At the Eindhoven Centraal train station, each platform is located between two train tracks (see Figure 2.1. On both of these tracks trains can arrive, and sometimes that happens at the same time. People who arrive at their destination leave the train and head for the exit of the platform. In Figure 3.1 part of the platform that can be seen in Figure 2.1 has been cut out. This is the area that this study will focus on.

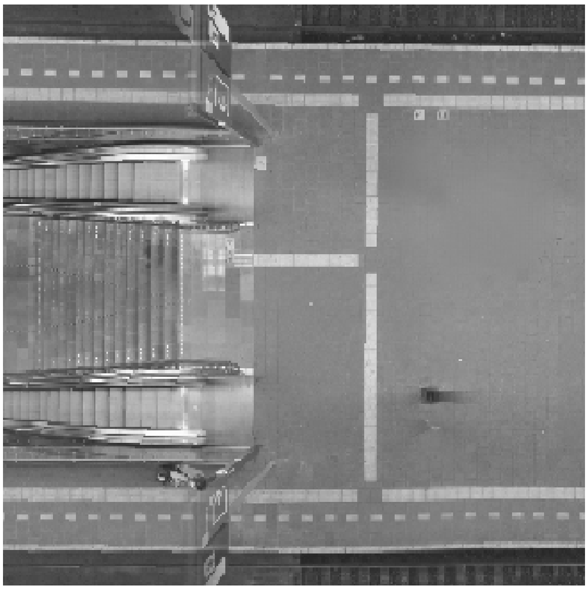


Figure 3.1: Part of platform researched in this study

It shows the exit situation of one of the platforms at Eindhoven Centraal station. What is unique in Eindhoven is that the stairs and escalators are located right next to each other. The stairs are flanked by two escalators, each going a different direction. This means exit and entrance flows interfere, but also that every pedestrian needs to choose between two exit possibilities: either take the stairs or the escalators. They are very close to each other, and crowding around either of the two also has influence on the flow to the other option. This creates a unique situation, causing delays and crowds which are manageable at this point in time but will get worse once the use of public transport increases in the near future.

3.2 | Flow management

Preventing queues is the most important factor to increase flow and decrease safety concerns [8]. Once a queue has formed, flow will decrease drastically. Queues take a relatively long time to clear, and as long as new people keep joining the crowd at a higher rate than the flow, the queues will get even longer. Once a queue has formed, the only way to clear it is by waiting until the input flow decreases and becomes

smaller than the flow of the queue, which is significantly lower than in situations where people are still able to freely move around. Preventing queues is therefore the best option in order to ensure efficient flow over the platform.
Queues or crowding can also create safety concerns as people are close to each other and have less space to manoeuvre in case of emergency. This can lead to irritation among pedestrians, and can even cause pushing and trampling in extreme cases [4].

3.3 | Fundamental diagram

In order to get an understanding of the pedestrian flow at a specific location, one of the first steps to take is to make a fundamental diagram of the situation. Fundamental diagrams are a way to represent the relationship between the density of people in a crowd and the flow rate (or velocity) of that crowd.
The fundamental diagram is a commonly used tool in the field of pedestrian dynamics [9]. It is used to understand how the density and velocity of people in a crowd are related, and how these factors can impact crowd behavior and safety.
The fundamental diagram of a situation is typically represented as a graph, with density on the x-axis and velocity or flow rate on the y-axis. The shape of the curve can vary depending on the specific setting and the characteristics of the crowd, but in general, it will have a characteristic shape, almost like a concave parabola, see 3.2 [10]).

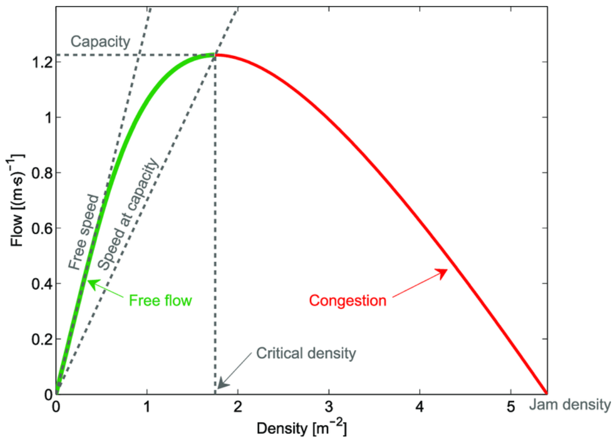


Figure 3.2: Typical shape of Fundamental Diagram

First, flow rate increases linearly when density increases. At a certain point, around a density of 1 m^{-2}, the slope of the line starts decreasing. This indicates that pedestrians start to anticipate on people around them. This causes a chain reaction where people see other people slowing down for people in front, and subsequently also slowing down. This phenomenon reduces the average speed of a person and therefore, although density is still increasing, flux is not increasing linearly anymore.
The higher the density, the more this will occur. Then, after a critical point, the flow rate will decrease as density increases. This is because at higher densities, there is so much interaction between people that it causes congestion, which leads to much slower movement and queues.
Free speed denotes the speed at which people move when there is no one else around. The critical density is the point at which congestion starts to have such a large impact that the flow will actually decrease with increasing density. The jam density indicates the point at which the entire flow is jammed; this normally does not happen at platform exits as there are never any obstacles preventing the entire flow from moving.
A fundamental diagram can be used to analyze a wide range of crowd-related issues, such as:

- Evaluating the efficiency of a given space
- Understanding the dynamics of crowd behavior
- Determining safe capacity limits for a given space
- Analyzing the impact of crowd control measures
- Comparing efficiency of different environments

It is important to note that the fundamental diagram is a statistical representation of crowd flow and that it is an average of crowd behavior. It is not applicable to individuals or small groups of people within this crowd, and it should not be used to predict the behavior of individuals.
Overall, the fundamental diagram can be a useful tool for understanding and analyzing pedestrian flows and for making informed decisions about crowd management and efficiency. Applying that to the situation of the Eindhoven Central Train Station, it is important to know the critical density at which the efficiency of the flow starts decreasing. Knowing this can influence modifications that may be made on the station design, or can impact station design of new train stations. With the knowledge that the current stations are almost operating at their limits it is good to know how to utilize platform space optimally, especially around the exit where crowd densities will peak when busy trains arrive.

3.4 | Filtering

When plotting an arbitrary trajectory, very sudden changes in direction are visible due to the discrete nature of the measurements and the inaccuracies of the sensors, as can be seen in Figure 3.3. We can see a pedestrian leaving the platform, who makes a side step at the top of the stairs. This is a good test trajectory as there are straight parts, as well as a sudden change in direction. These factors have an impact on the calculated velocity of this pedestrian, which will have a very high peak, while the person is moving at a relatively constant speed in reality.

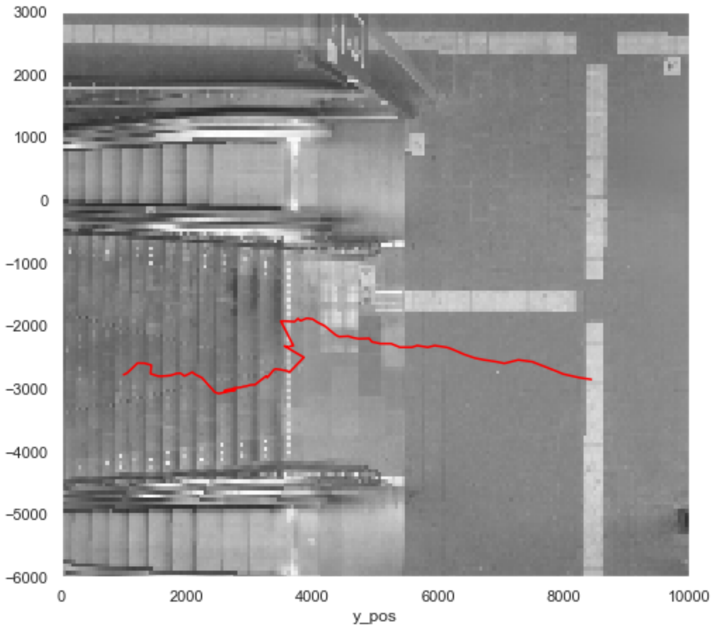


Figure 3.3: An arbitrary trajectory of a pedestrian exiting the platform

Before we can generate a fundamental diagram of the situation at Eindhoven central station, first the ProRail data needs to be filtered in order to get these kind of velocity inaccuracies out of the data. Filtering pedestrian trajectory data on a train platform can be difficult for several reasons:

- Train platforms are typically crowded and dynamic environments with many people moving in different directions, which can make it difficult to track and filter individual pedestrian trajectories.
- Pedestrian trajectories can be affected by measurement noise, such as errors in sensor readings, which can make it difficult to accurately separate the pedestrian's movements from noise.
- People on a train platform may be walking, standing, or sitting which can make it difficult to track and filter their trajectories accurately.
- It is important not to over-filter the data as sudden movements do actually occur regularly at train platforms.

A good filter to use for this specific case is the Savitzky-Golay filter. A Savitzky-Golay filter works by fitting a polynomial of a certain degree to a set of data points surrounding a target point, and then using the values of the polynomial at the target point as the smoothed value for that point. The polynomial is determined by a 'least-squares' fit to the data points, which means that the polynomial is calculated in a way that the sum of the squares of the differences between the polynomial and the data points is as small as possible.
To apply the filter, a sliding window is moved over the data, with the polynomial being fitted to the data points within that window at each position. The size of the window and the degree of the polynomial can be adjusted to control the amount of smoothing applied to the signal.
The filter can be used to smoothen a signal while preserving features such as peaks, because the polynomial is able to capture the shape of a peak even if the data points within the window do not exactly match the peak. It is also useful for removing noise from a signal, as the polynomial fit will tend to average out small variations in the data. It is important to note that the filter will introduce some lag, which means that the smoothed signal will be slightly behind the original signal. However, since this lag is introduced everywhere and the situation of a train platform is not changing very fast, this is not a problem.

3.4.1 | Test trajectory

On the test trajectory shown in 3.4, the Savitzky-Golay filter is used with a window length of 15 frames, using the data of 1.5 seconds to approximate the next point. It is fitted with a polynomial of degree three in order not to over-filter the data. As can be seen in Figure 3.4, the trajectory now looks a lot more natural than before, in figure 3.3. The details like the sidestep in front of the stairs are preserved, while generating a smoother and more realistic human trajectory.

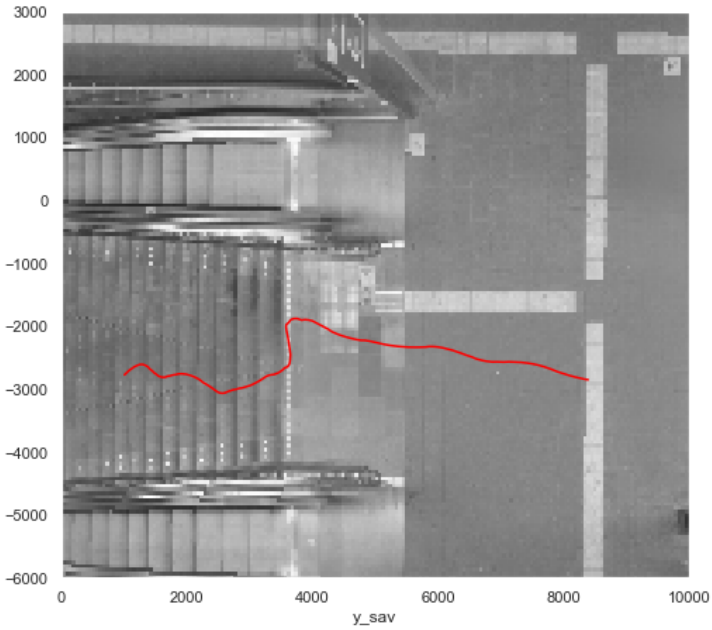


Figure 3.4: The same trajectory with a Savitzky-Golay filter

It can also be seen in the velocity profile in Figure 3.5 that the exactly calculated and filtered data still look alike, but the filtered velocity is way more constant. Sudden peaks of over 2 m/s are prevented, but relatively small differences in speed are still preserved.

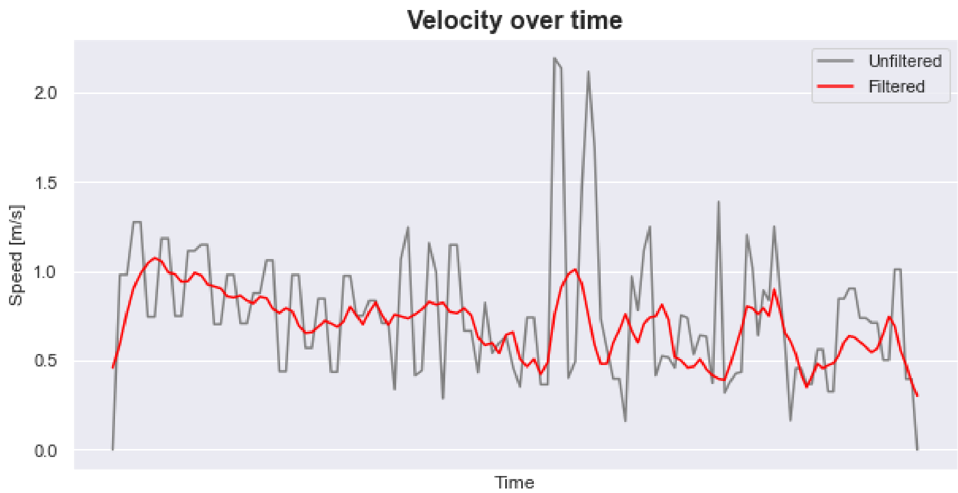
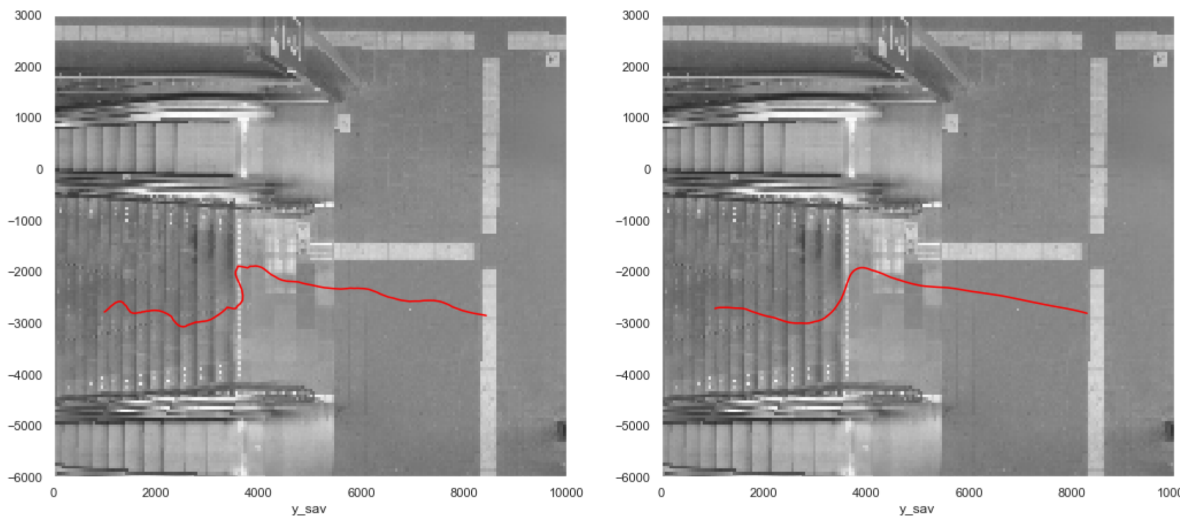


Figure 3.5: The velocity profile of the aforementioned trajectory

In Figure 3.6 some consequences of wrong filtering parameters can be seen. In Figure 3.6a the polynomial which is used in the Savitzky-Golay filtered is of order 6, which causes the sudden changes in direction and thus velocity to persist. In Figure 3.6b, a polynomial of degree three has been used, but the window length is set to 35 frames. This causes a lot of nuance to be lost, and it is not clear anymore that the person is making adjustments right before descending the stairs.



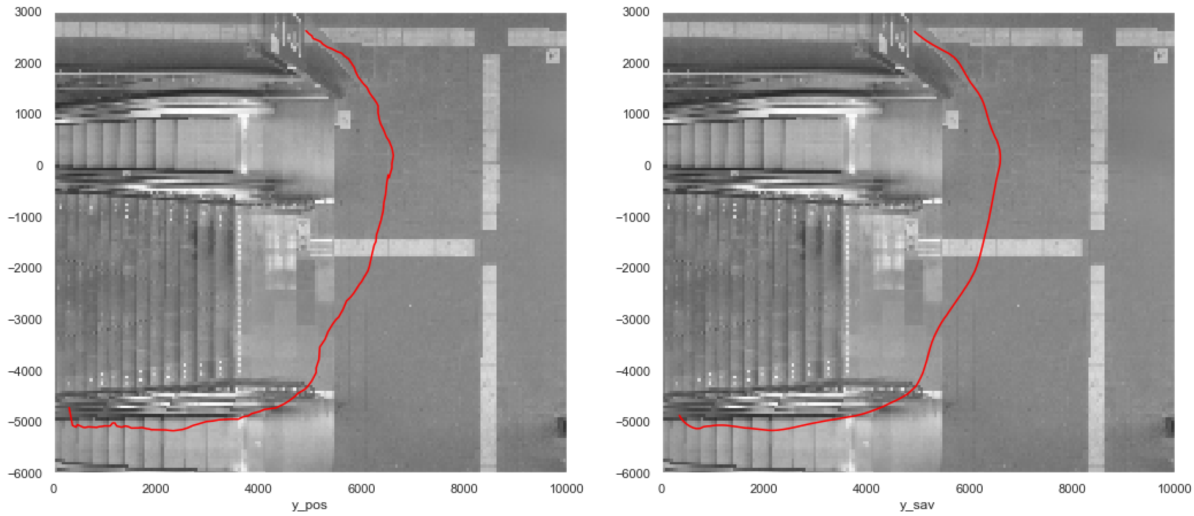
(a) High order polynomial

(b) Long window length

Figure 3.6: Filtering problems

3.4.2 | Simple trajectories

The peaks in velocity can also be seen for relatively simple trajectories, that seem like they should have a constant velocity profile (see Figure 3.7). It is important to filter these as well. The data for the fundamental diagram will be taken from a lot of measurements, because the situation and crowdedness constantly change. This means every frame gives new, usable information. Peaks in velocity caused by errors therefore give wrong representations of the velocity at a certain density which results in an inaccurate fundamental diagram.



(a) A simple, unfiltered trajectory **(b)** The same trajectory with a Savitzky-Golay filter

Figure 3.7: Filtered and unfiltered simple trajectory

The velocity profile for this trajectory, both filtered and unfiltered, can be seen in Figure 3.8

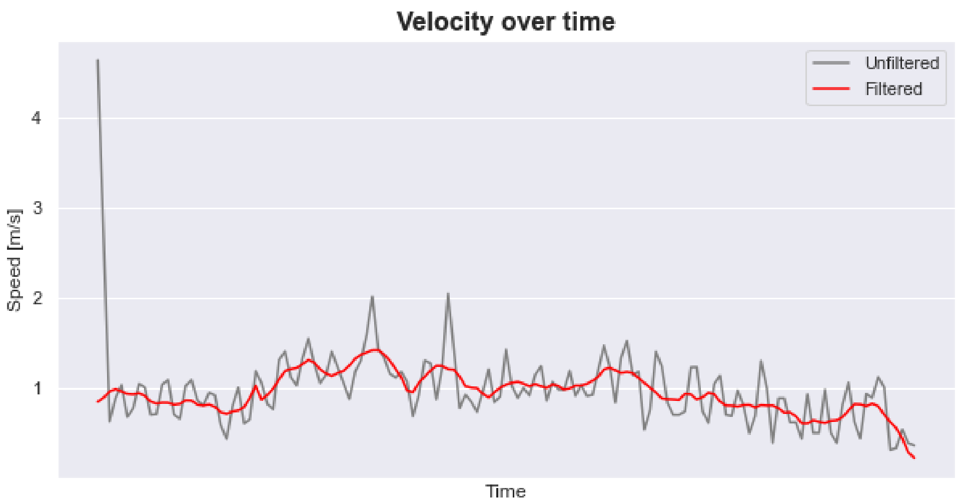


Figure 3.8: The velocity profile of the second trajectory

3.5 | Density

The other variable in a fundamental diagram is the density. Density is very easily calculated by dividing the number of people over a given area, but this does not suffice in this case. Because the crowds are very unevenly distributed over the platform, with locally very high peaks and other places barely occupied, another method is necessary to calculate the density for the fundamental diagram. A way to calculate local density numbers accurately is by using a Voronoi Diagram [11]. A Voronoi diagram is a mathematical construct that divides a plane into regions called Voronoi cells, based on the distance to a set of points. Each Voronoi cell contains all the points that are closer to a specific point than to any other point. So, for a set of 100 points, there will be 100 Voronoi cells, one for each seed point. The boundary of each cell is called the Voronoi edge, and it is made up of the set of all points that are exactly in the middle of two points. A Voronoi diagram of an arbitrary situation at the station can be seen in Figure 3.9.

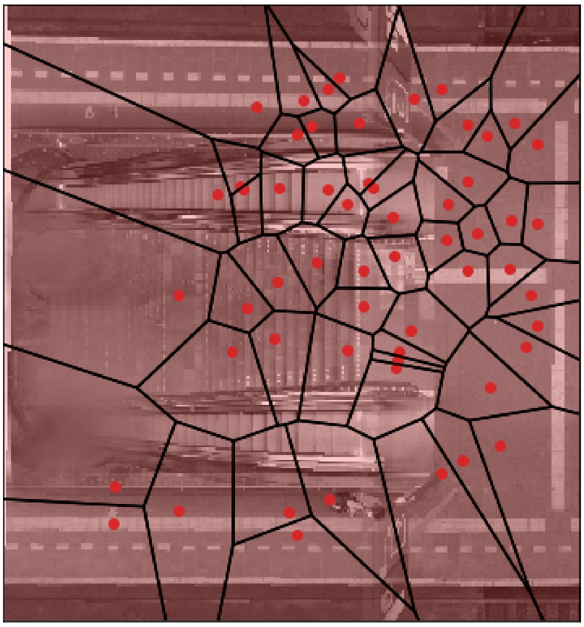


Figure 3.9: Voronoi diagram on arbitrary time

This figure will however still give the same density as would be given when the area of the whole platform would be considered. In this following Voronoi diagram, the maximum area a Voronoi cell can take up is approximately $3.14m^2$ as each cell boundary is defined by a circle with a radius of 1 meter. This is decided upon in order to get an estimate of local density, by assuming the trajectory of a pedestrian is not influenced significantly by people more than 1 meter away [12].

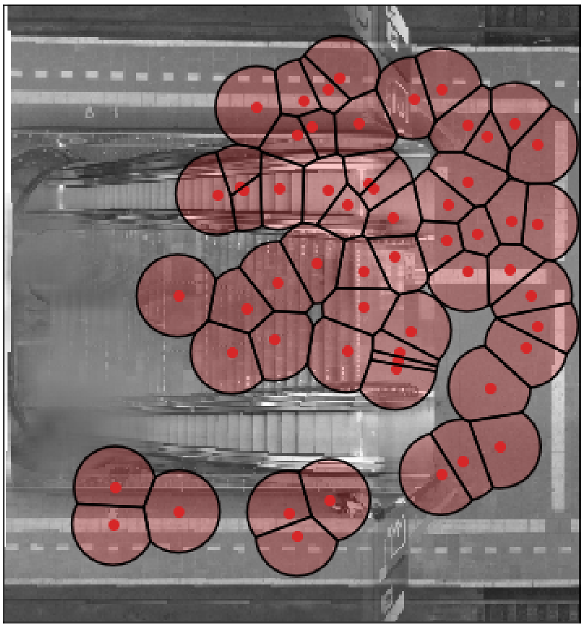


Figure 3.10: The same Voronoi diagram, but constrained

Introducing constrained Voronoi diagrams does however create an issue: the minimum density will never be 0, as the area per pedestrian will always be of a maximum size, in this case 3.14 m^2. This means that the area per pedestrian is always a minimum of $\frac{1}{3.14}$ m^2, consequently also limiting the density to $\frac{1}{3.14}$ m^{-2}. Not solving this creates an incomplete fundamental diagram.
The way this issue can be overcome is by using different methods to calculate the density. When the total number of people on the platform is low, the density is calculated 'the simple way': by dividing the amount

of people over the total area of the platform. Since it is relatively calm on the platform, the influence of pedestrians on others is relatively small and most people can travel at their free speed, so the exact relative density is not that important to get an accurate value for the flow. Then, on busier moments, where crowding and queues occur, the Voronoi density is used to get a more accurate representation of the situation at the platform and the dynamics in the crowd. Combining these methods creates a complete fundamental diagram, both for quiet and crowded situations.

3.6 | Generating a fundamental diagram

Once the velocity data has been filtered and the local density has been calculated, it is possible to generate a fundamental diagram of the specific situation at the Eindhoven Centraal platform. For each data point, density is plotted against the flow. Flow is calculated by multiplying the density with the velocity. We expect to see a figure similar to Figure 3.2, with a linear part, a peak and after that a decline in flow. Plotting all data points at once gives the result seen in Figure 3.11.

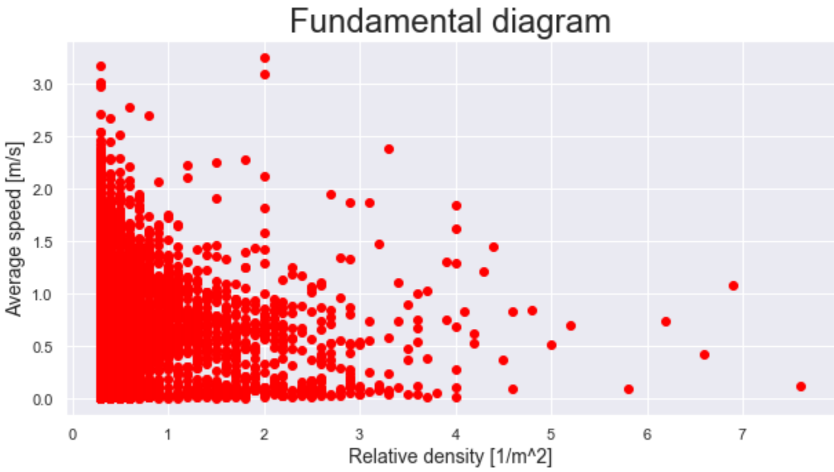


Figure 3.11: Data points for creating the fundamental diagram

What can be seen in the picture is that at low densities, the speed is spread out. People have very different moving speeds and are not influenced by one another. The higher the density, the more the velocities converge. This diagram does not give usable information. To solve this problem, the density is divided in bins with steps of 0.01, and calculating the average velocity for each bin. Figure 3.12 shows the average speed for each bin of relative densities.

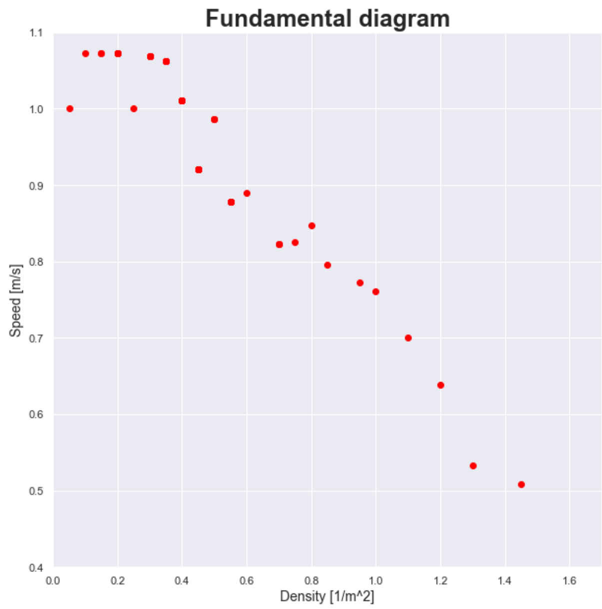


Figure 3.12: The velocities for the fundamental diagram

It is clear that the average speed decreases with increasing density as expected. Then, the velocity is multiplied with the density to obtain the flow, and consequently the final fundamental diagram. The result of this can be seen in Figure 3.13. In order to construct the diagram, data of 1 full, busy day has been considered. It is a Monday in a week when university was open and it was not a vacation day. The sample frequency has been decreased to 0.2 Hz to reduce computation time.

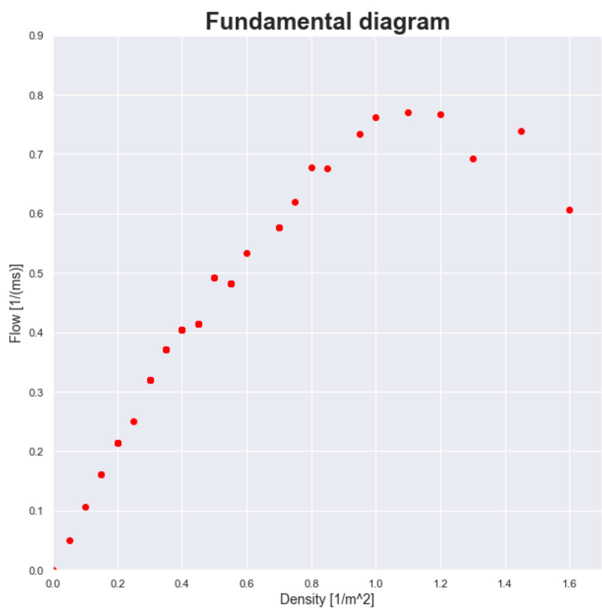


Figure 3.13: The fundamental diagram for Eindhoven Central train station

We can indeed see linear behavior up to 0.5 pedestrians per square meter. After that, the slope slightly decreases, and around 0.8 pedestrians per square meter it quickly decreases until it flattens out. The critical density can be read off the diagram and is around 1.1 pedestrians per square meter, which is similar to values found in other researches around bottlenecks [13]. After reaching critical density, although there are more people moving, the throughput decreases. It is therefore important to try and avoid densities higher than the critical density in order to ensure an efficient and safe crowd flow.
In this fundamental diagram the flow does not decrease all the way back to 0. Densities higher than 1.6 pedestrians per square meter rarely occur and are mainly caused by people walking in small groups, which

is not representative of the crowding situation around the exit. Also, unlike traffic jams, there is no point at which everyone is standing still: in regular situations the stairs and escalators are not blocked and although it might not be the most efficient, there will always be some flow.
The capacity of the exit of the platform is around 0.8 pedestrians/(ms), which is lower than is generally observed on flat surfaces [13]. This is logical as people tend to be more careful when taking their first steps down a stairs, or waiting for the right moment to board the escalator.
The found critical density and capacity can be used in further research on other train platforms with different layouts. Fundamental diagrams of different situations can be compared to find similarities and differences, and give an indication about which of the situations is better.

3.7 | Decision-making

In order to get an efficient flow around the platform exit, optimal distribution between stairs and escalators is essential [14]. People make decisions between these two options both consciously and subconsciously, with different factors playing a role. Some research has already been done on the behaviors of pedestrians in choosing between escalator and stairs at Hong Kong railway stations [14]. However, this study only considered the influence of delay on the route choices, and did not take into account other factors such as the location of getting off the train. Another study on the choices between stairs and escalators has been done on Dutch stations [15], but the dataset was relatively small and this was not focused on the bottleneck that occurs on busy moments. With the data ProRail provided, combined with more computer power relative to the older studies, new territory can be explored with the large amount of data points and tracking technology.
As has been discussed in Section 2, some decision influences can not be researched with the data that was provided. For example, physical ability, luggage and mood or character can not be deducted from trajectory data alone. However, a lot of subconscious or partly conscious decisions can be analyzed, creating pointers for more efficient station design in the future.

3.7.1 | Crowdedness

One of the factors that play a role in decision-making around stairs and escalators is crowdedness around the exit area [16]. This seems obvious but it should not be overlooked, and it is also quantifiable. Escalators have a very limited capacity and are full very quickly at busy moments. They are limited by practical things such as a maximum speed where it is still safe to board and get off. They also have a maximum width because of multiple reasons, such as energy efficiency, safety and the fact that people want to hold on the hand rail. In general, people prefer the escalator over the stairs because of the efficiency and the fact it seems faster [17]. This means that the escalators fill up relatively quickly. When the escalator gets busier and fuller, we would expect that people tend to prefer the stairs as they are wider (specifically at Eindhoven Central train station) and can therefore handle a larger flow of people.
The method used in this research to find a correlation between the crowdedness around the exit and exit choice (stairs or escalators), is based on a few assumptions:

- People make their decision on whether to take the stairs or escalators before they are actually at the exit of the platform.
- This decision is influenced by crowding in front of the exit.
- If people's decisions are influenced by crowding, they must be relatively close to the exit and have clear sight on the crowd situation.

These assumptions were made to create a clear process of classifying people's choice based on the crowdedness. It consists of two boxes, that can be seen in Figure 3.14. The green lines denote the separation between stairs and escalators.

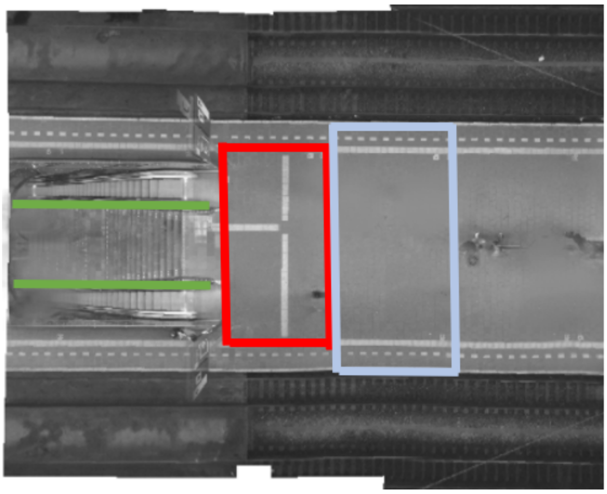


Figure 3.14: Limit boxes used for classification

The red square denotes the gauge for crowdedness: the number of people in this box indicates the crowdedness in front of the exit.
The blue box is the 'classification box'. For each point in time, the number of people in the red box is registered. At that same time, for each individual in the blue box, their future decision, stairs or escalators, is registered. This is possible because we have the final position of each individual, and we can classify whether their trajectory ends at the stairs or at the escalator. Now, for each time stamp, we have both a gauge for crowdedness in front of the exit and the knowledge whether people in the blue box will take the stairs or the escalator. For each number of people in front of the exit, the partition of people taking the stairs can then be calculated. Doing this and plotting it in a line plot yields the result that can be seen in Figure 3.15.

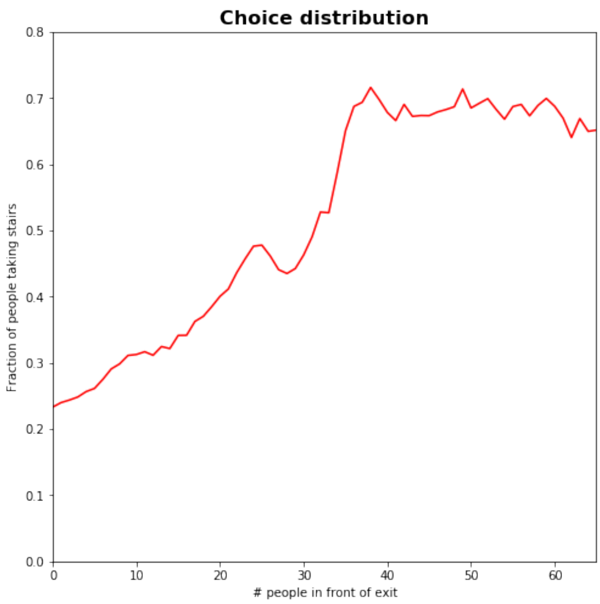


Figure 3.15: Distribution based on crowdedness

This plot includes information of four full days, using more than 20 million data points. It can be clearly seen that when the platform exit gets more crowded, people are more inclined to take the stairs. There seems to be a linear relation, with a small dip in the middle, until it flattens out at around a 70/30 distribution between stairs/escalators.
What is interesting to see is that in situations where there is almost no one around, more than 75% of people tend to take the escalator. This may be because of the ease of use, speed or the fact that other people also use the escalator, so-called herd behavior [18]. However, since the escalator is also the first

option that gets crowded, forming queues and decreasing efficiency, the stairs seem to get more appealing the busier it gets. Assuming that both stairs and escalators are working at full capacity at the far right of the plot, since the distribution does not change anymore, the capacity of the stairs is significantly higher. This is mainly due to the stairs being wider.
In the ideal situation, people would use the escalators as if it were stairs, walking down. Then the speed at which people travel would increase significantly. However, if it is busy on escalators, people tend to stand still, blocked by people in front of them. This limits the capacity of the escalators significantly. Stairs have similar problems and people tend to keep more distance to others on the stairs relative to the escalators [19], but naturally slower and faster 'lanes' will form on the stairs accommodating for different speeds at which people travel. This, combined with the fact that stairs can be a lot wider, mean that stairs generally have a higher capacity than escalators.
Figure 3.15 indicates that people tend to prefer the seemingly more comfortable option, the escalator, over of the stairs. However, stairs have a higher maximum capacity as it is not limited by a certain width or speed. In order to get the most efficient flow, it is therefore recommended to make stairs more attractive to use than the escalators to prevent queues in front of the escalators.
When designing new train platforms, the thing to take from this part of the research is to separate stairs and escalators, so the queue in front of the escalator does not influence the efficiency on the stairs. Subsequently, the lack of a queue (or a shorter one) in front of the stairs can persuade people to take the stairs earlier.

3.7.2 | Station layout

As the most important influence on the choice between stairs and escalators is convenience, the station layout plays a significant role. At Eindhoven Train station, on the platform we are studying, the stairs and the escalators are right next to each other. The distance to either of them is therefore relatively similar, one is not much further away than the other, regardless of where people exit the train. However, one is still closer to the rails than the other: if you exit the train at the top rail, the escalator is marginally closer than the stairs. On the other side, exiting the train at the bottom rails, the stairs are closer (see Figure 3.1). As we have seen in Section 3.7.1, in general, most people prefer the escalator. Will this distribution change based on the exit position of people?
The method used to find this out was relatively straightforward. For each tracked object that appears in the dataset, its initial location is taken and classified in either the top rails or the bottom rails. Then, their final location is analyzed and it is also classified as either exiting via the stairs or exiting via the escalator. Using a full day of data, over 20.000 trajectories have been analyzed and the fraction of people taking the stairs for each exit location can be seen in Figure 3.16.

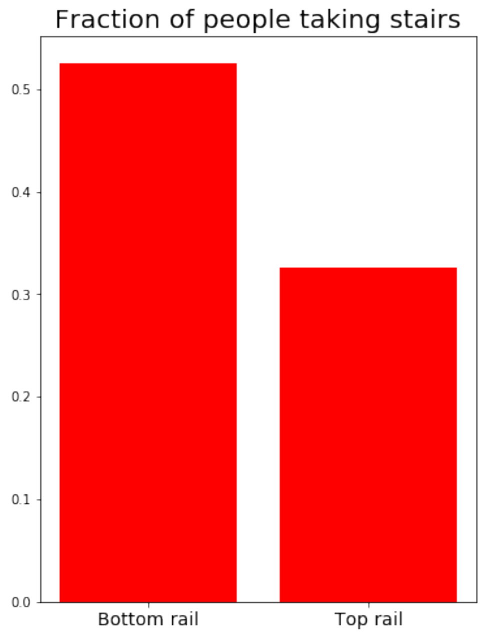


Figure 3.16: Fraction of people taking stairs

The bar chart shows a very clear distinction between people coming from a train at the top rails and the people arriving at the bottom rails. The data used consists of a full regular Monday, including both busy and quiet moments. In total around 40% of people entered the platform from the top rails, which might influence the usage of stairs negatively; if it is less crowded people tend to prefer the escalator, which is also already closer. If a queue has already formed, people might also be more inclined to join the queue than to walk around it and use the stairs. However, both of these influences that are just described will always have an influence when stairs and escalators are located next to each other.
What can be concluded from this is that people take the distance they have to travel into account when making the decision on how to exit the platform. Although in general people tend to prefer the escalator to the stairs, locating the stairs closer to the rails than the escalator drastically impacts their decision and skews it towards taking the shorter route: the stairs. This is an important outcome to take into account when designing new stations.

3.7.3 | Average speed

The final influencing factor that has been analyzed in this research is the speed at which people travel. Every person has a different travel speed, influenced by physical ability and mental state, and people in a hurry tend to move faster. In an ideal situation for an individual, when the platform is completely empty, it would be fastest to take the escalators as the speed of the escalator combined with the walking speed would lead to the fastest exit. However, if there are people standing still on the escalator, their velocity is limited by the velocity of the escalator and it may be faster to use the stairs. Also, queuing tends to happen more in front of the escalator than the stairs as the capacity of the stairs is higher.
These factors lead us to expect that people who move at a higher speed, will prefer the stairs over the escalator. Note that we want to look at 'free speed' (see Section 3.3), since when people are limited in their speed by others, their decision will be made mostly on the factor which of the two options is least crowded or seems fastest. Since people arrive with other people at the station at the same time, the chance of someone standing still on the escalator is very high. Because people who are in a hurry prioritize being fast over being energy efficient, they might prefer the stairs most of the time over the escalator.
In order to verify this hypothesis, a graph has been made that relates the average speed of pedestrians to their probability to take the stairs. For every trajectory, an average speed is calculated, and they are classified in bins. Then, for each bin of average speed, the distribution between stairs and escalators is calculated. The graph can be seen in Figure 3.17.

Figure 3.17: Average speed plotted against distribution

In order to create this diagram, the velocity data has been divided in steps of at least 0.1 m/s. Then, for every bin, the fraction of people taking the stairs has been calculated. At the right part of the graph, we can see that the steps between points are bigger. Each point in this figure represents at least 100 people. If there are less than 100 people for one velocity step, their data is combined with the data from the next step of 0.1 m/s in velocity. Because there are less people travelling at very high average speeds, the points are spaced further apart. Binning the data in velocity steps of 0.1 m/s ensures the graph is smooth, and setting a minimum amount of data points for each point in the graph ensures the data is representative and is not contaminated with single outliers.

It can be seen in Figure 3.17 that from 0 to roughly 1.5 m/s, the fraction of people taking the stairs first increases and then decreases. Speeds below 1 m/s are relatively insignificant for this part of the research, as we want to know whether walking speed has an impact on exit method choice. Average speeds below 1 m/s are mainly caused by queuing and crowding, and can therefore not be regarded as 'free speed'.
There seems to be a small peak in the fraction for people travelling around 0.7-1.0 m/s. This is probably caused by the fact that people tend to travel slower due to interaction with other people at more crowded moments. At the same time, because of the crowdedness, people tend to take the stairs more often, see Section 3.7.1. Then, when the platform is relatively empty, and people can move at their own preferred speed (around 1.4m/s for most people [20], see Figure 3.18), a relatively standard fraction of 30% of people will take the stairs. However, with increasing average speed, it can be seen that the fraction of people taking the stairs also drastically increases. This indicates that people who move very fast relative to others, or are in a hurry, do not want to be limited by the people standing still on the elevator and prefer the stairs as there is more space most of the time. However, there does not seem to be a clear correlation between walking speed and the chance of taking the stairs. Only when people are running, the division changes remarkably.

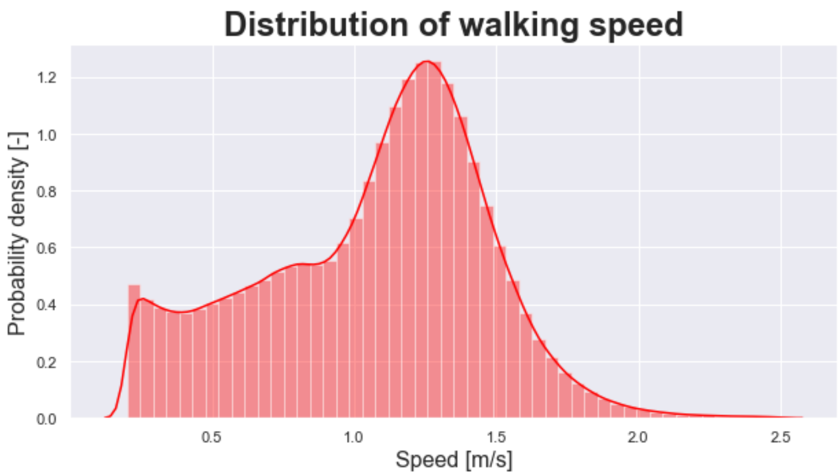


Figure 3.18: Distribution of walking speeds on the platform from a full day

Note that the fraction in Figure 3.17 will end around 70% of people taking the stairs, and not 100%. This is caused by the fact that when the elevator is empty, running down the moving escalator is faster than just running down the stairs. People who want to exit the platform as quickly as possible will therefore choose for the fastest option; running down the escalators.
It can also be seen in Figure 3.18 that the distribution only starts at 0.2m/s. For a large amount of data points, people are standing still waiting on a train. Since we are focusing on the walking speed, we can disregard people that are standing still or almost not moving. Omitting values below 0.2m/s gives a much clearer overview of the distribution of walking speeds.

4 | Conclusion and recommendation

What causes crowding around the exit of railway platforms and how do we minimize it? That is the question this research tries to answer. The answers given to this question can be used to give recommendations for railway station (re)design.
Considering all of the factors researched in this study, some recommendations can be made for the design of future-proof public transport stations. Although this study has focused on a very specific exit situation at a railway platform, the findings are not exclusive to railway platforms with this exact layout and can be applied in different situations as well. Public transport platforms are a unique environment however and it is not certain that these findings can be applied in non-public transport related environments.
The values found in the fundamental diagram serve as a baseline for other railway platforms where similar research can be done. ProRail has installed the same sensors as the ones in Eindhoven on other railway stations as well, namely in Amsterdam and Utrecht. These stations have very different layouts to the one in Eindhoven and following the same procedure to make a fundamental diagram of those situations can give valuable insights in what would be a more optimal platform layout. Finding a similar layout but in a different country may also give interesting insights in cultural differences and their influence on pedestrian flow.

4.1 | Station layout

Looking at the decision-making parts of this research can already give some pointers in what layout would probably result in a more efficient pedestrian flow. The biggest decisive factor when choosing how to exit the platform on busy moments seems to be the crowdedness: whichever option is less crowded, seems to attract people. This is logical since most people do not like standing around waiting, and especially not close to others.
When it is not busy, people seem to have a bias towards the escalators. This means that queuing occurs more often in front of the escalators than in front of the stairs when it gets busy. However, having stairs and escalators located very close to each other, like at the platform analyzed in this study, means that crowd in front of either of the two also influences people wanting to take the other option. For example, consider the situation of someone leaving a train from the top rail, at the left of the station (see Figure 3.1), and there is a queue in front of the escalator. In that case, there is probably a crowd already formed which is hard to go around in order to get to the stairs. These people are therefore almost forced into taking the escalator, or are at least forced to wait until the queue has cleared a bit before getting to the stairs.
This situation is a common occurrence at the Eindhoven platform during rush hour, a way to prevent this would be to split the escalators and the stairs. This way, people who want to take the escalators and are okay with waiting for it, are able to do so while disturbing the flow to the stairs a lot less. At the Utrecht train station stairs and escalators are located far apart, it would be interesting to take a look at the decision process there and see if the different flows have less interference.
Another important factor influencing the decision between leaving the platform via stairs or escalators is the shortest path: people tend to have a preference for the option that is closer to them. This is also logical, especially in the case that the escalator is closer. Another way to separate flows to escalators and stairs would be to locate the stairs in a more convenient location relative to the escalators. The existing bias to escalators will still lead a lot of people to them, but the distribution between the two is now more equal since the stairs are closer. Since stairs can also be a lot wider than escalators, meaning they can have a higher capacity, this could alleviate queuing problems.
The average walking speed of people does not seem to have a large influence on the distribution between the two exit options, and therefore it is not necessary to make any changes to station design where distinction is made between people based on their travel speeds.

4.2 | Nudging

It is possible to alleviate crowding issues without changing the station layout which may not always be possible or which can take a long time. There are methods to nudge people in certain directions when making the choice between escalators and stairs, such as placing railings [21] or including a flat section in a long stairway [22]. Also, experiments have been done where message prompts are installed around the stairwell in order to nudge people into taking the stairs [23], or people are trying to be nudged by light [24]. It is very interesting to see what influence these methods have in railway station environments, as

the pedestrian dynamics in on public transport stations are different to most of the situations in these researches.
There are a many nudging methods which can help direct people towards a certain exit point on the platform. Possible ways to this are by placing rails, using message prompts or by making use of light. It is interesting to see whether these nudging techniques are effective at public transport stations.

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