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Macroscopic Fundamental Diagram for Train Platforms

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Abstract The macroscopic fundamental diagram (MFD) relates the flow, density and speed of an entire network. So far, the MFD has been mostly applied to cases where pedestrians and vehicles were aiming to reach their destinations as fast as possible. However, pedestrian facilities involve different behaviours. Especially in train stations, travellers spend more time waiting than walking. Moreover, complex passenger flows (i.e. flows in different directions moving to stairs and escalators distributed over the platform) may occur on the platform, due to passengers. In this paper we show that passenger flows on platforms can be described by an MFD.

1 Introduction

For vehicular traffic, the concept of the MFD (at the time not by that name) has been introduced by Daganzo [4]. For locations with a single bottleneck, the exit rate equals the capacity of the bottleneck and queuing processes can be described with queuing theory. However, for other situations, there are internal bottlenecks, caused by the traffic load. This can be the case for pedestrian networks as well. Essential in this phenomenon is that different pedestrians have different (intermediate) destinations. Without different destinations, all pedestrians will queue for the bottleneck. However, if some pedestrians want to go into one direction, and others into another direction, one flow may block the other.

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The outflow of traffic out of a network, called *performance*, is—under the assumption of a constant trip length—proportional to the internal flow of a network, called *production*. A reduction of speed of pedestrians due to queuing in the system will lead to a lower outflow. Moreover, this lower outflow will lead to higher number of pedestrians in the system, which increases queuing, which reduces outflow. This effect hence strengthens itself.

Apart from the total number of pedestrians in a network, their distribution also plays an important role. Suppose that the pedestrians are equally spread over the network and all have just sufficient space to walk towards their destination at their desired speed. An alternative distribution would be that the same number of pedestrians would be clustered, i.e. some are in a more dense area and some are in a less dense area. Then, the ones in a less dense area still walk at their free speed, but the ones in a more dense area have to slow down. Consequently, the average speed reduces, and with that the production. The same reasoning as for the total networks also holds for parts of the network. Once congestion occurs, outflow of that part decreases, hence increasing congestion. This effect is also called "nucleation of congestion", see [12].

This principle holds in particular for platforms in train stations. Pedestrians waiting on the platform to board the train will hinder alighting pedestrians moving towards the platform exits (i.e. stairs or escalators). Although the existence of an MFD for pedestrians has been shown in other papers [3, 5, 10, 11], in this paper we will check the relation between density and flows, and explore the effect of spatial inhomogeneity of density. We thus will find whether an MFD is capable of reproducing the pedestrian dynamics on the platform. This way, the MFD might be used in the design and assessment of the performance of a platform.

This paper starts with a description of the experimental design and the data used to derive the MDF (Sect. 2), followed by an overview of the methodology (Sect. 3). In Sect. 4 the results are shown. The paper ends with conclusions and discussion in Sect. 5.

2 Experimental Design

The first choice to be made in the experimental design is whether to use simulation data or empirical data. The advantage of simulation data is that the conditions to be simulated can be fully controlled. That implies that the full range of densities can be covered, as well as different flow shares. Therefore, we have chosen to derive our MFDs from simulation data. To simulate, we have applied our microscopic pedestrian simulation model Nomad [1, 8], which has been extensively calibrated [2] and previously applied in transfer stations [9].

The investigated situation covers only the part of the platform where passengers enter and exit (see Fig. 1). The situation is as follows: a train has stopped alongside the platform, passengers alight from four doors (bottom part of the figure) and move to two stairs on the platform (top part of the figure). In order to create hindrance,

Fig. 1 Screenshot of the Nomad simulation. Different colours indicate different origins (train door) and destinations (stairs)

Table 1 Overview of the scenarios

[pes/s]	Low	Medium	High
Doors left	0.2	1.2	1.2
Doors right	0.2	1.2	1.0

passengers alighting at the left two doors move to the right exit, while passengers alighting at the two doors on the right-hand side walk towards the exit on the left. The demand is triangular, increasing during 90 s, and then reduced to 0. We distinguish three demand scenarios, see Table 1.

3 Methodology

The individual spacing for a pedestrian i (s_i) can be found by the personal space this person has. Literature shows many alternatives to calculate this individual spacing, see [6] for an overview. Here, we have chosen to use a combination of the Voronoi space [13], and an upper boundary of a circular personal space with a range of 1.5 m [7]. Figure 2 shows three examples of the resulting individual spacing.

This individual spacing can be transformed into a local density k_i:

$$k_i = 1/s_i \tag{1}$$

Locally, the average density is now the average of the local densities:

$$k_{\text{lc}} = 1/N \sum_{i=1}^{N} k_i \tag{2}$$

A global definition for the density would be the number of pedestrians per space occupied by these pedestrians. This would be proportional to the accumulation in

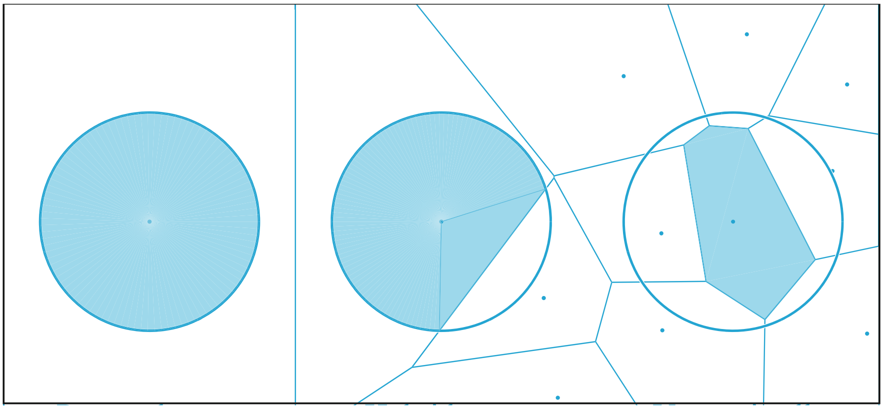

Fig. 2 Example to calculate the individual spacing for a pedestrian using the Voronoi diagram and a personal space. The most left circle shows a pedestrian whose circular personal space is within the Voronoi personal space, so the circle is taken as individual spacing. The most right situation shows a pedestrian whose Voronoi personal space is within the circular personal space, so the Voronoi space is taken as individual spacing. For the pedestrian in the middle, the circular personal space overlaps the Voronoi personal space, so the individual spacing is the intersection of both personal spaces

terms of the MFD. In equations, we derive

$$k_{\text{gb}} = \frac{\text{Number of pedestrians}}{\text{Occupied space}} = \frac{\sum_{i=1}^{N} 1}{\sum_{i=1}^{N} s_i} = N \frac{1}{\sum_{i=1}^{N} s_i} = 1 \Bigg/ \left(\frac{1}{N} \sum_{i=1}^{N} s_i \right) \tag{3}$$

This shows that the global average density is the inverse of the mean spacing per pedestrian.

Note that this is equivalent to the *weighted* mean density, with weights w equal to the size of the area of one pedestrian.

$$k_{\text{gb}} = \frac{\sum w_i k_i}{\sum w_i} = \frac{\sum s_i k_i}{\sum s_i} \tag{4}$$

This derivation illustrates that the global density is the average density in which each part of *space* gets an equal value, rather than each pedestrian.

The (instantaneous) inhomogeneity of the pedestrians is defined by the standard deviation of the local densities:

$$\gamma_{\text{lc}} = \sqrt{1/N \sum_{i=1}^{N} (k_i - k_{\text{lc}})^2} \tag{5}$$

Table 2 Different measures to describe the MFD

Perspective	Local (from user)	Global (system)
Density	$k_{\mathrm{lc}} = \frac{1}{N} \sum_{i=1}^{N} k_i$	$k_{\mathrm{gb}} = N \frac{1}{\sum_{i=1}^{N} s_i}$
Inhomogeneity	$\gamma_{\mathrm{lc}} = \sqrt{1/N \sum_{i=1}^{N} (k_i - k_{\mathrm{lc}})^2}$	$\gamma_{\mathrm{gb}} = \sqrt{\frac{1}{\sum_{i=1}^{N} s_i} \sum_{i=1}^{N} s_i \left(k_i - k_{\mathrm{gb}}\right)^2}$

Equivalent to density, we can also define a measure of inhomogeneity weighted for the area

$$\gamma_{\mathrm{gb}} = \sqrt{\frac{1}{\sum_{i=1}^{N} s_i} \sum_{i=1}^{N} s_i \left(k_i - k_{\mathrm{gb}}\right)^2} \tag{6}$$

Table 2 shows an overview of the measures defined above.

For the analysis, we check for the relationships between the quantities mentioned above. We are interested how the global and local densities relate. To check whether an MFD approach is feasible, we check the relationship between local density and speed, and between local density and internal flow. Finally, check whether there is a relation between density and inhomogeneity.

4 Results

Figures 3, 4, 5, and 6 show the results. For readability, we only included medium (in grey) and high (in blue) demand in the figures. Moreover, we have removed the small local densities which correspond to the circular personal spaces (indicated by the dotted line in the left-hand side of the figure). In all figures, we clearly see the scenarios, covering different density ranges and different severity of the gridlock.

Figure 3 shows the relation between global density and local density. We see that these densities differ more when densities increase, where the local density is higher than the global density. This is according to our expectations. In the following, we will therefore focus on the local density.

Secondly, we look at the relation between speed and local density in Fig. 4. We see the well-known shape of the fundamental diagram. However, for the medium demand, we see a second, "horizontal line". This horizontal "line" is the result of gridlock situations due to the internal bottleneck caused by the crossing flows: due to lower demands, pedestrians keep moving slowly and one by one the pedestrians exit the platform.

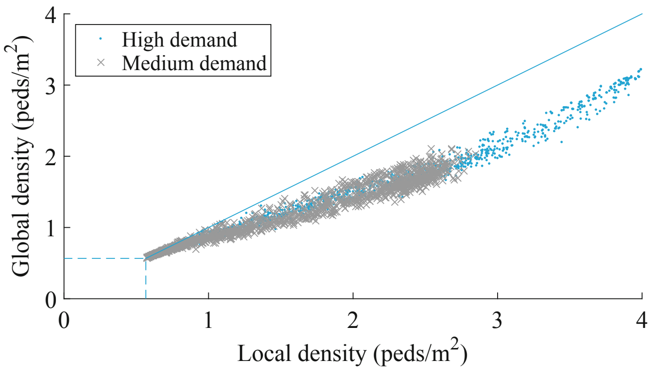

Fig. 3 Relation between the global density and the local density

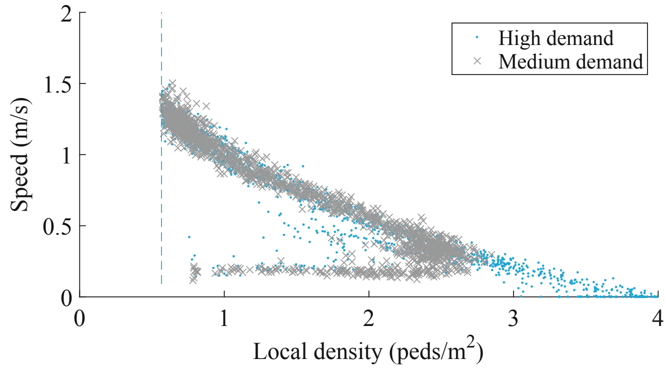

Fig. 4 Relation between speed and local density

The MFD is shown as the relation between the local density and the internal flow (calculated as speed times local density) in Fig. 5. Just like for the speed–density relation, we see the gridlock situation where the internal flow is reduced to almost zero for high local densities. For the medium demand, this gridlock does not occur. Only temporary deadlocks occur, which decrease the outflow, but the passengers do not come to a complete standstill.

Finally, we show the relation between local inhomogeneity and local density in Fig. 6. Starting from the minimum local density, we see that the local inhomogeneity gradually increases. This increase is not linear, though, as it reduces when local densities get higher. It looks like a limit exists for the local inhomogeneity, which is probably due to the limited space and the fact that parts of this space are not used by passengers, as they are heading towards the exits.

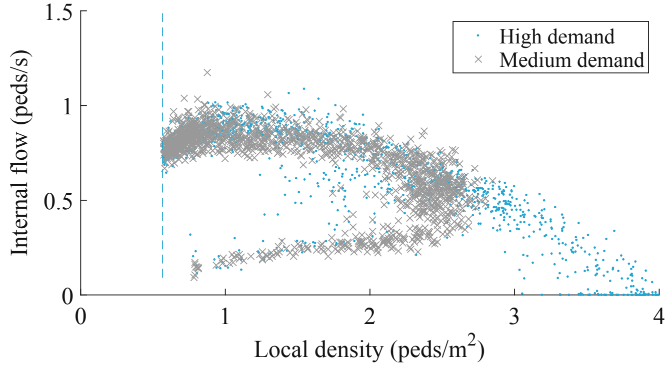

Fig. 5 Relation between internal flow and local density

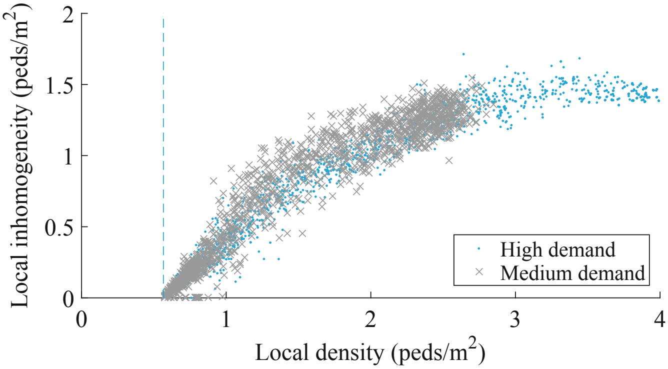

Fig. 6 Relation between inhomogeneity and local density

5 Conclusions

We have calculated the macroscopic fundamental diagram (MFD) describing passenger flows on a platform using simulation data. Local densities have been calculated based on the joint surface of Voronoi cells and circles surrounding passengers describing their personal space. A clear relation between outflow (production) and local density has been found. This shows that speed reduction on a platform is not due to the limited capacity of the exits, but due to internal bottlenecks (hindrance due to crossing flows). The pedestrian dynamics cause a reduction of the outflow. This proves the importance of using MFDs to predict passenger flow operations on platforms.

Whereas inhomogeneity in density on the platform might be of influence, we found it to link directly to local density, so it might be redundant to use two variables to describe flow, and local density could suffice as independent variable.

In future work, we will investigate the shape of the MFD using empirical data, and see how we can use the MFD in the design and assessment of passenger flows on platforms.

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