Free Speed Distributions for Pedestrian Traffic

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Abstract. Free speeds are defined as the speeds pedestrians like to walk with when they are not influenced by other nearby pedestrians. Free speeds differ among pedestrians being influenced by personal characteristics, characteristics of the infrastructure and external conditions.
Free speeds and their distribution play an important role in many traffic flow models, but are also relevant in other applications, such as the design of pedestrian facilities and public transport timetables.
The fact that lots of observations on pedestrian speeds are described in literature stresses its importance. However, pedestrian free speeds cannot directly be observed, since the observer does not know whether the pedestrian is actually walking with his free speed. Free speeds based on observations therefore are usually underestimated. Available free speed estimation methods developed for car traffic appear to be not suited for pedestrian traffic. This paper presents a new method to estimate free speed distributions for pedestrian flows. It is a dedicated adaptation of a method used for car traffic.
This paper does not only describe this estimation method, but also shows an application on pedestrian data from large-scale laboratory walking experiments, simulating different traffic conditions, such as unidirectional flows, opposite flows, and crossing flows.
The approach appeared successful and may be applied for all types of pedestrian flows.

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Abstract	211
Main text	5289
Figures (5 x 250)	1250
Tables (3 x 250)	750
Total	**7500**

INTRODUCTION

Free speed or desired speed is the speed a pedestrian walks with when it is not hindered by other pedestrians. The free speed differs among pedestrians, among types of walking infrastructure, and among external conditions. This is due to the characteristics of pedestrians (age, gender, physical abilities), characteristics of walking infrastructure (grade, length, width, type of pedestrian facility), and weather and other external conditions. Since the exact relation between these characteristics is not known, free speeds usually are described as a stochastic variable with a distribution.

Free speed and its distributions play an important role in many traffic flow models, macroscopic, mesoscopic and microscopic ones. In illustration: the free speed distribution is an important input for gas-kinetic models (*1*,*2*), while many microscopic simulation models draw free speeds of individual pedestrians from free speed distributions (*3*,*4*).

Insights into free speeds are also important from the viewpoint of design of facilities and public transport timetables. Walking times between origins and destinations in a facility can be derived, giving insight into the efficiency of a facility with respect to minimizing walking efforts. For the design of public transport timetables transfer times can be predicted. These transfer times are an indication whether or not travelers may get a connection between two trains.

The aim of this paper is to derive free speed distributions for pedestrian traffic. The data on which the distributions are estimated come from large-scale laboratory walking experiments, in which different traffic conditions have been simulated. An approach to derive free speed distributions for car traffic is described in (*5*) and (*6*). This approach has been applied for pedestrian traffic in (*7*). However, in (*7*) it is stated that the headway criterion used to determine the constrainedness of a traffic participant is not suited for pedestrian traffic with opposite and crossing flows. The main contribution in this paper is the generalization of the estimation approach to all kinds of conditions by modification of the criterion for constrainedness into a fuzzy measure loosely based on a time-to-collision for pedestrians.

The paper starts with an overview of pedestrian speeds found in literature. Then, the approach developed in (*5*) and (*6*) to estimate free speed distributions for car traffic is described in short. This is followed by the explanation of its modifications to pedestrian traffic and in particular the definition of the criterion to determine whether or not a pedestrian is constrained. Next, a description is given of the data, which are used to apply the improved free speed estimation approach. The estimated free speed distributions are shown in the ensuing section and compared to the speeds found in literature. We end with conclusions and recommendations for future research.

OBSERVED SPEEDS IN LITERATURE DURING LOW FLOWS

Much literature has been found on pedestrian walking behavior, stressing the importance of real-time observations of pedestrian traffic characteristics, such as speed, flow, and density. An overview of speeds observed in literature is shown in table 1. The average speed and corresponding variance (if available) are shown, as well as the country where the study has been performed.

The speeds of individuals appear to follow a normal distribution, with an estimated mean of 1.34 m/s and a standard deviation of 0.37 m/s (see table 1). The standard deviation has been calculated as a mean of the speeds using the co-efficient of variance. Weidmann (*8*) performed a literature study on pedestrian speeds in 1993. He found a mean speed of 1.34 m/s, with speeds varying between 0.97 m/s and 1.65 m/s, which are comparable to the values of respectively 1.08 m/s and 1.6 m/s in table 1. Under specific circumstances, the normal distribution can have a positive skewness. The median speed, considered to be more representative than the average speed since it omits outliers, is found to be 1.2 m/s (*9*). The average speed in European studies appears to be 1.41 m/s, 1.35 m/s in studies in the United States, 1.44 m/s in an Australian study and in Asian studies 1.24 m/s.

As indicated before, the speeds shown in table 1 are observed mostly in real-life conditions. Since this paper focuses on free speeds, it would be interesting to know the free speeds in the listed literature. However, it is not possible to directly measure free speeds, since an observer does not know whether or not a pedestrian walks with his or her free speed. The speeds in table 1 are determined using low flow conditions or extrapolating the found speed-flow relations to the zero flow area. This will lead to biased free speeds, underestimating the real free speeds, as is shown in the next section. Free speeds are therefore always higher than speeds observed in low densities. To solve this problem of underestimation, a free speed estimation approach has been developed for car traffic (*5*). Unfortunately, this approach appears not to be valid for pedestrian traffic (*7*). This paper therefore presents an improved approach to estimate free speed distributions for pedestrian traffic.

TABLE 1 Speeds Observed in Literature (*10*)

Source	Mean speed (m/s)	Standard deviation (m/s)	Location
CROW (*11*)	1.4		Netherlands
Daamen (*10*)	1.41	0.215	Netherlands
Daly et al. (*12*)	1.47		United Kingdom
FHWA (*13*)	1.2		United States
Fruin (*9*)	1.4	0.15	United States
Hankin and Wright (*14*)	1.6		United Kingdom
Henderson (*15*)	1.44	0.23	Australia
Hoel (*16*)	1.50	0.20	United States
Institute of Transportation Engineers (*17*)	1.2		United States
Knoflacher (*18*)	1.45		Austria
Koushki (*19*)	1.08		Saudi-Arabia
Lam et al. (*20*)	1.19	0.26	Hong Kong
Morrall et al. (*21*)	1.25		Sri Lanka
	1.4		Canada
Navin and Wheeler (*22*)	1.32		United States
O'Flaherty and Parkinson (*23*)	1.32	1.0	United Kingdom
Older (*24*)	1.30	0.3	United Kingdom
Pauls (*25*)	1.25		United States
Roddin (*26*)	1.6		United States
Sarkar and Janardhan (*27*)	1.46	0.63	India
Sleight (*28*)	1.37		United States
Tanariboon et al. (*29*)	1.23		Singapore
Tanariboon and Guyano (*30*)	1.22		Thailand
Tregenza (*31*)	1.31	0.30	United Kingdom
Virkler and Elayadath (*32*)	1.22		United States
Young (*33*)	1.38	0.27	United States
Estimated overall average	1.34	0.37	

FREE SPEED ESTIMATION METHODS

Estimation of free speeds and free speed distributions is not as straightforward as it looks like. Pedestrians are either walking at their free speed or following another pedestrian. This suggests that only those pedestrians walking freely are considered to derive the free speed distribution. However, pedestrians having a relatively high free speed have a higher probability of being constrained than pedestrians with a relatively low free speed (*34*). This will lead to underestimation of the free speeds.

Until now, hardly any attention has been paid in literature to the estimation of free speeds for pedestrian traffic. Since more literature exists on this subject in car traffic, we start with an overview of free speed estimation approaches for car traffic (*34*):

1. Estimation of the free speed by considering the speed at low volumes (*35*). A weakness of this model is that the composition of the flow in these non-peak periods may be different from that in peak periods. The free speed distribution will therefore be different. Even at low volumes, cars might be hindered leading to underestimation of the free speed.
2. Extrapolation towards low intensities. The method allows using the relevant population, but is known to be liable to errors (*34*).
3. Application of simulation models. This method involves the use of microscopic simulation models to establish relations between observable variables and the free speed distribution (*36*).
4. Method based on Erlander's model. Erlander (*37*) developed an integral equation for traffic operations on two-lane roads with the free speed distribution as one of its components.

Since all methods mentioned above have severe disadvantages, Hoogendoorn (*5*) recently developed a new estimation approach referred to as the modified Kaplan-Meier approach (*38*). This approach is based on the concept of censored observations (*39*) using a non-parametric method to estimate the parameters of the free speed distribution. This method for car traffic has been applied for pedestrian traffic in (*7*), which lead to inconsistent results, especially for the free speeds estimated in opposite and crossing flows. Reason for this is the difference between cars and pedestrians in degrees of freedom to choose a moving direction. The decision whether or not a car is constrained (censored observation) is based on a headway criterion. This headway is calculated at a specific cross-section of the road. In uni-directional flows, this cross-section is taken perpendicular to the road axis at a specific location. All traffic participants will thus pass this cross-section and, based on the order of passing, the time between two consecutive participants may be measured (= headway). For multilane roads, the headway criterion already causes problems, since small headways are often due to overtaking participants, which are not constrained at all (*6*). Headways are always determined for traffic participants moving in the same direction. However, pedestrians have a much larger degree of freedom in choosing their walking direction. Pedestrians are therefore not only hindered by pedestrians walking in a similar direction, but they are also influenced by pedestrians coming from the sides. These latter movements will even result in more severe hindrances. The conclusion is that the headway criterion is not suitable to determine whether a pedestrian is constrained or not.

The main contribution of this work is the modification of the criterion for constrainedness in order to make the free speed estimation approach from (*5*) suitable for opposite and crossing pedestrian flows. The new approach is based on the distance to other pedestrians on the observation area as well as the moment when this distance occurs, taking into account the walking direction of both pedestrians. The probabilities are subsequently used in the modified Kaplan-Meier approach to estimate free speed distributions.

Description of the estimation method

Let us consider individual pedestrian data collected at a cross-section. For each pedestrian p that has passed the cross-section x, we have determined its (individual) speed v_p and its time headway t_p. The aim of the approach is to determine the cumulative density function $F(v^0)$ of free speeds $\underline{v}^0$ using the available speed and time headway data.

Speed observations for pedestrian p are labeled according to their constrainedness using a conditional probability θ_p varying between 0 (free flowing pedestrian) and 1 (constrained pedestrian).

Each pedestrian p is assumed to have its own specific free speed value, in line with the free speed distribution of the pedestrian population. However, we can only measure a free speed if the pedestrian is walking freely (θ_p = 0). Nonetheless, censored observations can and must be used, since they provide information as well, namely that the free speed value will be higher than the observed speed value.

The estimation approach in (*5*) is based on maximum likelihood estimators of the free speed distribution $F(v)$ for a sample of speed observations v_p. It is assumed that free speed observations are identically and independently distributed with the probability density function $f(v)$ and survival function $S(v) = 1-F(v) = Pr(\underline{v}^0 \geq v)$. Since there is no evidence supporting the choice of a particular functional form of the free speed survival function, a non-parametric estimate for the survival function is used. Application of the method in (*5*) and (*6*) shows that this non-parametric estimate of the survival function $S_\infty(v^0)$ can be determined using the following equation:

$$S_\infty\left(v^0\right) = \prod_{j=1}^{m\left(v^0\right)} \left(\frac{n-j-1}{n-j-\theta_j} \right) \tag{1}$$

where $m(v^0)$ denotes the number of observations v_j that are smaller than or equal to v^0, and n denotes the number of observations (note that $m(\infty)=n$). θ_j indicates the probability of pedestrian j being constrained.

We refer to (*5*) and (*6*) for a complete derivation of equation 1, for more technical details and for the verification of the estimator using synthetic data. This verification shows that the approach yields an unbiased estimator of the mean free speed and is able to determine the free speed distribution from traffic data (individual speeds and headway measurements) under a variety of conditions.

A NEW CRITERION FOR SEPARATING FREE FLOWING AND CONSTRAINED PEDESTRIANS

In equation 1, θ_p denotes the probability that pedestrian p is constrained. The previous section showed that the headway criterion is not suited to identify this probability for pedestrians. In this section, we will derive a new criterion using fuzzy logic.

The probability that a pedestrian p is constrained is directly related with the presence of other pedestrians q_i near pedestrian p. Not only the distance between the pedestrians is important to determine the hindrance, but also the time aspect: someone getting very close over a few seconds will give less hinder than someone currently at the same close distance. In car traffic, two notions are known in this respect, namely time-to-collision (TTC) and post encroachment time (PET). The TTC indicates how long it will take until two cars will collide, given that both cars will maintain their current driving speed. The PET is defined as the period of time from the moment when the first road user is leaving a conflict area until the second road user reaches it (*40*). Here, we will look at the distance between two pedestrians and how this distance varies over time, assuming that both pedestrians maintain their current walking speed and angle of movement.

Figure 1a shows a hypothetical situation, with four pedestrians present in the observation area (the arrows indicate their current walking speed). The aim is to determine θ_p, depending on the pedestrians q_1, q_2 and q_3. Since pedestrians are anisotropic (they will mainly react to pedestrians in front of them), only pedestrians q_1 and q_2 will be considered in the approach. Extrapolating current speeds of the pedestrians, the distance between the centers of the pedestrians is calculated over time (see figure 1b).

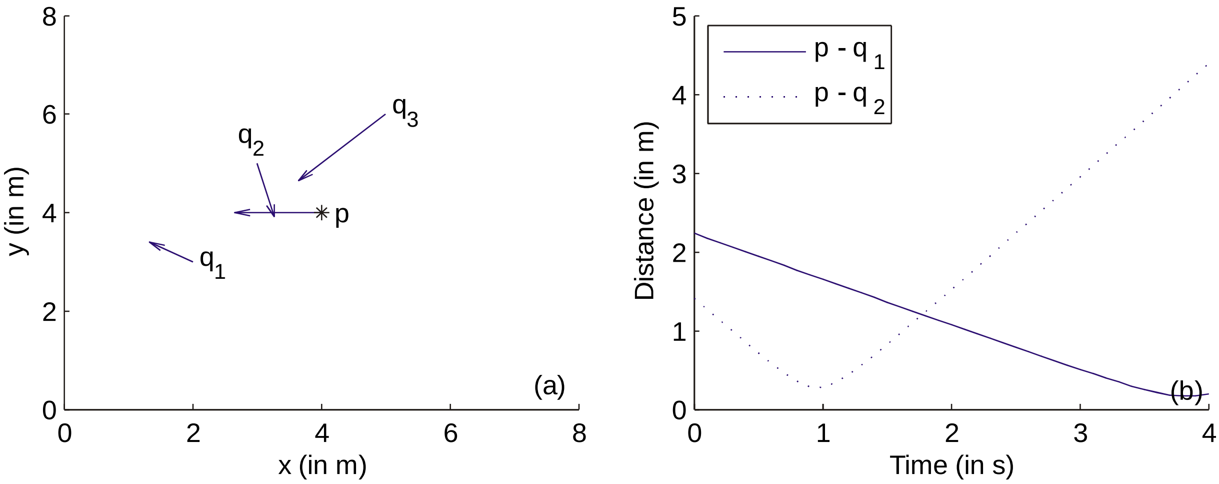

FIGURE 1 Conflict area of pedestrian *p* (a) and distance between pedestrian *p* and pedestrians q_1 and q_2 in the observation area (b).

In effect, figure 1b shows two criteria for the constrainedness of a pedestrian, namely distance between pedestrians and the moment that a specific distance occurs. The fuzzy approach is very suited to describe θ_p as a degree-of-constrainedness of a pedestrian, varying between 0 (free flowing pedestrian) and 1 (constrained pedestrian). For a mathematical underpinning of the use of fuzzy logic in this type of problem we refer to (*6*). This approach is also able to handle a combination of criteria, as is the case here: the probability that a pedestrian is constrained is higher when the distance to another pedestrian is smaller ('proximity') and the moment this occurs is closer ('urgency'). The specific relations for the membership (probability) functions for proximity $\theta^P(d)$ and urgency $\theta^U(h)$ are shown in figure 2.

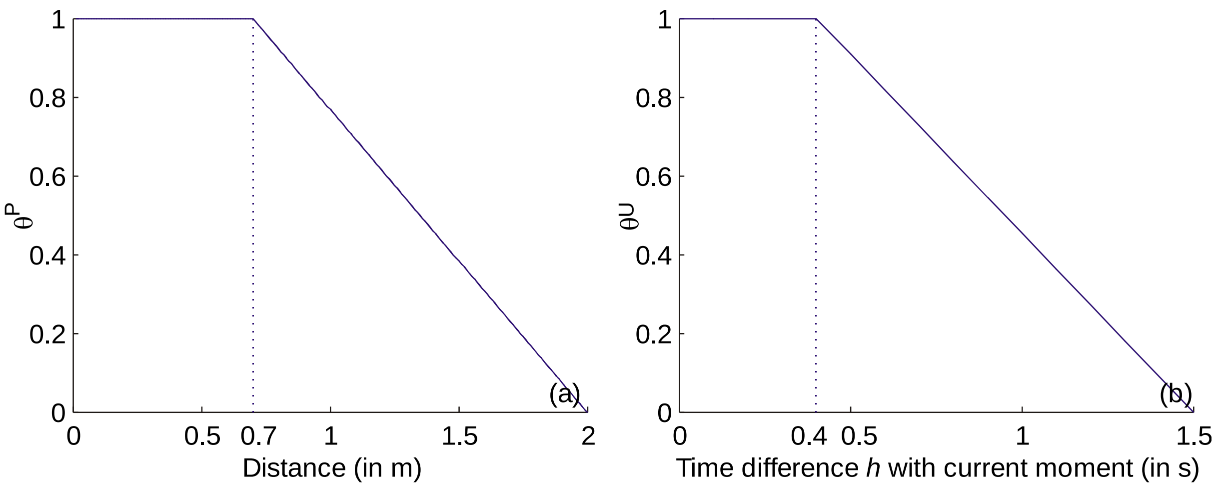

Figure 2 Membership functions for proximity (a) and urgency (b).

For a given distance d between two pedestrians p and q_i the membership $\theta^P_{p,q_i}(d)$ is determined as well as the membership $\theta^U_{p,q_i}(h)$ for the time period h that has expired until this distance occurs. The function $\theta^P_{p,q_i}(d)$ can be interpreted as the probability that two pedestrians having an intermediate distance d are constrained, while the function $\theta^U_{p,q_i}(h)$ can be interpreted as the urgency of a specific time moment. The probability that pedestrian p is constrained due to a specific pedestrian q_i depends on both $\theta^P_{p,q_i}(d)$ and $\theta^U_{p,q_i}(h)$. This joint probability θ_{p,q_i} can be explained as the probability that a pedestrian experiencing a specific distance d after a time period h is constrained. In fuzzy logic the product is used as an AND operator for two membership functions:

$$\theta_{p,q_i}(d,h) = \theta^P_{p,q_i}\left(d\right)\cdot\theta^U_{p,q_i}\left(h\right) \tag{2}$$

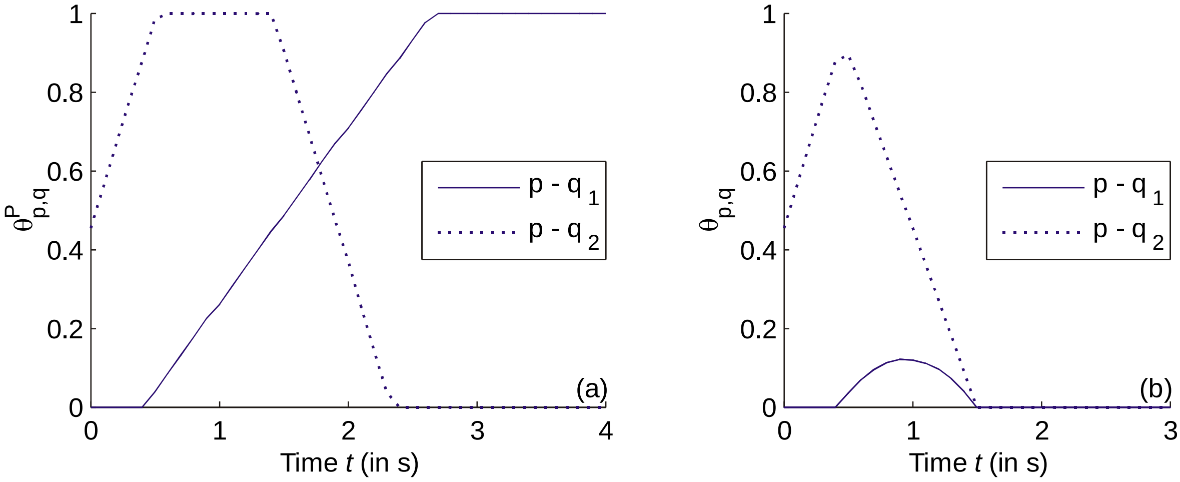

Figure 3 Probabilities of pedestrian *p* (see figure 1) being constrained by pedestrians q_1 and q_2 as a function of distance (a) and as a function of both time and distance (b).

Figure 3 shows the probabilities of pedestrian p being constrained by pedestrians q_1 and q_2 in the example shown in figure 1. In figure 3a, the distance between two pedestrians is transformed into a probability that pedestrian p is constrained due to this (short) distance. The figure also shows how this probability evolves over time. We see that the closer pedestrian q_2 comes, the higher becomes the probability of pedestrian p being constrained. After somewhat more than 2 seconds, pedestrian q_2 is so far away that pedestrian p is able to walk freely. Pedestrian q_1 is so far away in the beginning (t = 0) that pedestrian p is not constrained by pedestrian q_1. However, this pedestrian is coming closer, until it will completely constrain pedestrian p after somewhat less than 3 seconds. In figure 3b, also the time aspect is taken into account. We see that the probability of pedestrian p being constrained by pedestrian q_2 does not become 1, since this pedestrian approaches after some time, which makes it possible for pedestrian p to avoid the conflict with pedestrian q_2. For pedestrian q_1, this is also the case, leading to only very slight hindrance for pedestrian p. The high hindrance will only occur after 2.5 seconds, which leaves enough time to anticipate.

For each pair of pedestrians (in the example p - q_1 and p - q_2) the maximum θ_{p,q_i} (= maximum hindrance) needs to be calculated. It might be argued that this is the minimum distance between the pedestrians. However, if the two pedestrians have nearly the same angle of movement, this point would be at the end of the area (θ^P = max; $\theta^U = 0$, see pedestrian q_1 in figures 1 and 3), whereas at some earlier moment, pedestrian p may already be hindered ($0 < \theta^P <$ max; $\theta^U > 0$, in the example at t = 1 s.). Therefore, θ_{p,q_i} is determined over the complete predicted time period and the maximum of all these probabilities is assigned to this pair of pedestrians:

$$\theta_{p,q_i} = \max(\theta^P_{p,q_i}(d)\cdot\theta^U_{p,q_i}(h)) \tag{3}$$

In the example, $\theta_{p,q_1} = 0.15$ and $\theta_{p,q_2} = 0.90$. To determine the θ_p we need to know which pedestrian q_i is most constraining pedestrian p and assign the corresponding θ_{p,q_i} to pedestrian p. To do this, we take the maximum of θ_{p,q_i} for each pedestrian q_i on the area:

$$\theta_p = \max_{q_i}\left(\theta_{p,q_i}\right) \tag{4}$$

In the example θ_p is equal to 0.9.

DATA COLLECTION ON PEDESTRIAN WALKING BEHAVIOR USING LABORATORY EXPERIMENTS

The Transport & Planning department of the Delft University of Technology has organized controlled walking behavior experiments. Main advantage of performing experiments is the control of the conditions – both with respect to the observed situation and the system of data collection, such as location of the camera, ambient and weather conditions. Another benefit is the flexibility to systematically vary experimental variables to see effects of these variables on the behavior of individual pedestrians and of the total pedestrian flow. Examples of these experimental variables are flow size, walking directions, and speed differences due to simulated external conditions. It may be argued that the behavior of pedestrians during the experiments will not be very different from their real-life walking behavior since walking is mostly a skill-based task, thus requiring little or none conscious consideration. For more information see (*10*).

By performing walking experiments, we can determine the stimuli, the walkers' responses, and the relations between them, which collectively determine pedestrian behavior. Apart from the methodological advantages, experiments allow observations of conditions that are not readily available or are very difficult to observe in real-life. For details see (*41*).

Ten walking experiments have been conducted in a large hallway. A digital camera was mounted at the ceiling of the hallway, at a height of 10 m, observing an area of approximately 14 meters by 12 meters. In each of these experiments approximately 75 pedestrians have been involved, not only TU Delft students, as we took special care to select a sample representative for the Dutch population. Results of five experiments are shown in this paper. These experiments concern unidirectional flows, opposite flows, crossing flows, and two experiments with a bottleneck. In the wide bottleneck experiment the bottleneck has a width of 2 meters, whereas the bottleneck has a width of 1 meter in the narrow bottleneck experiment. The width of the narrow bottleneck is such that pedestrians inside of the bottleneck are not able to pass each other. The flow in each experiment varied between hardly existent and congestion in the narrow bottleneck experiment.

The video data of the experiments contain the raw data, which in this form is not suited to perform the intended analyses. The approach to extract highly accurate trajectory data from digital video footage is discussed in (*42*). The free speed distributions presented in this paper are based on these trajectory data, where the location of each pedestrian on the observation area is known in centimeters for each tenth of a second.

Figure 4 shows the view from above on the narrow bottleneck experiment. All pedestrians wear caps and white shirts. The bottleneck of 1 m wide is situated on the left, whereas pedestrians walk from right to left.

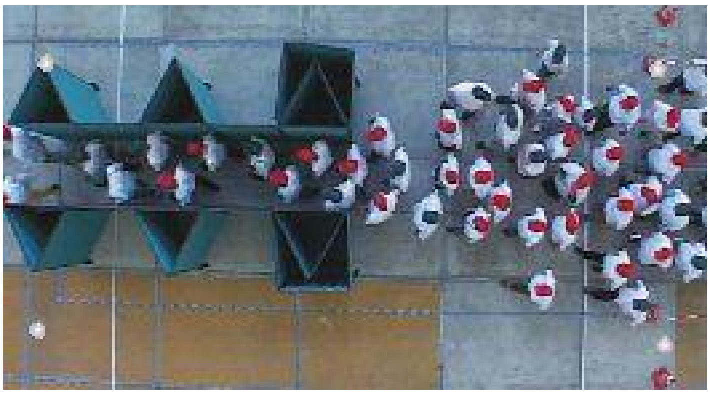

FIGURE 4 Overview of the narrow bottleneck experiment.

FREE SPEED ESTIMATION FOR DIFFERENT FLOW DIRECTIONS

Let us now present the estimation results from application of the method to five experiments in figure 5 and table 2. Figure 5 shows the empirical cumulative distribution function of the speed $F(v)$, the distribution of the free speed of the unconstrained pedestrians ($F^0(v^0)$) and the estimated free speed distribution using the modified Kaplan-Meier approach ($F_{mod.\ KM}(v)$). Table 2 contains the corresponding mean speeds, standard variation, and median speeds.

TABLE 2 Estimation Results for Five Walking Experiments

	Speeds of all pedestrians			Unconstrained speeds			Estimated free speeds		
Experiments	Mean	St. var	Median	Mean	St. var	Median	Mean	St. var	Median
One-dir	1.46	0.15	1.45	1.49	0.15	1.48	1.57	0.18	1.56
Opposite	1.33	0.16	1.33	1.37	0.15	1.37	1.55	0.21	1.54
Crossing	1.38	0.22	1.39	1.45	0.19	1.45	1.64	0.25	1.60
Wide	1.20	0.26	1.19	1.35	0.25	1.36	1.56	0.26	1.60
Narrow	0.96	0.26	0.89	1.21	0.33	1.22	1.44	0.28	1.47

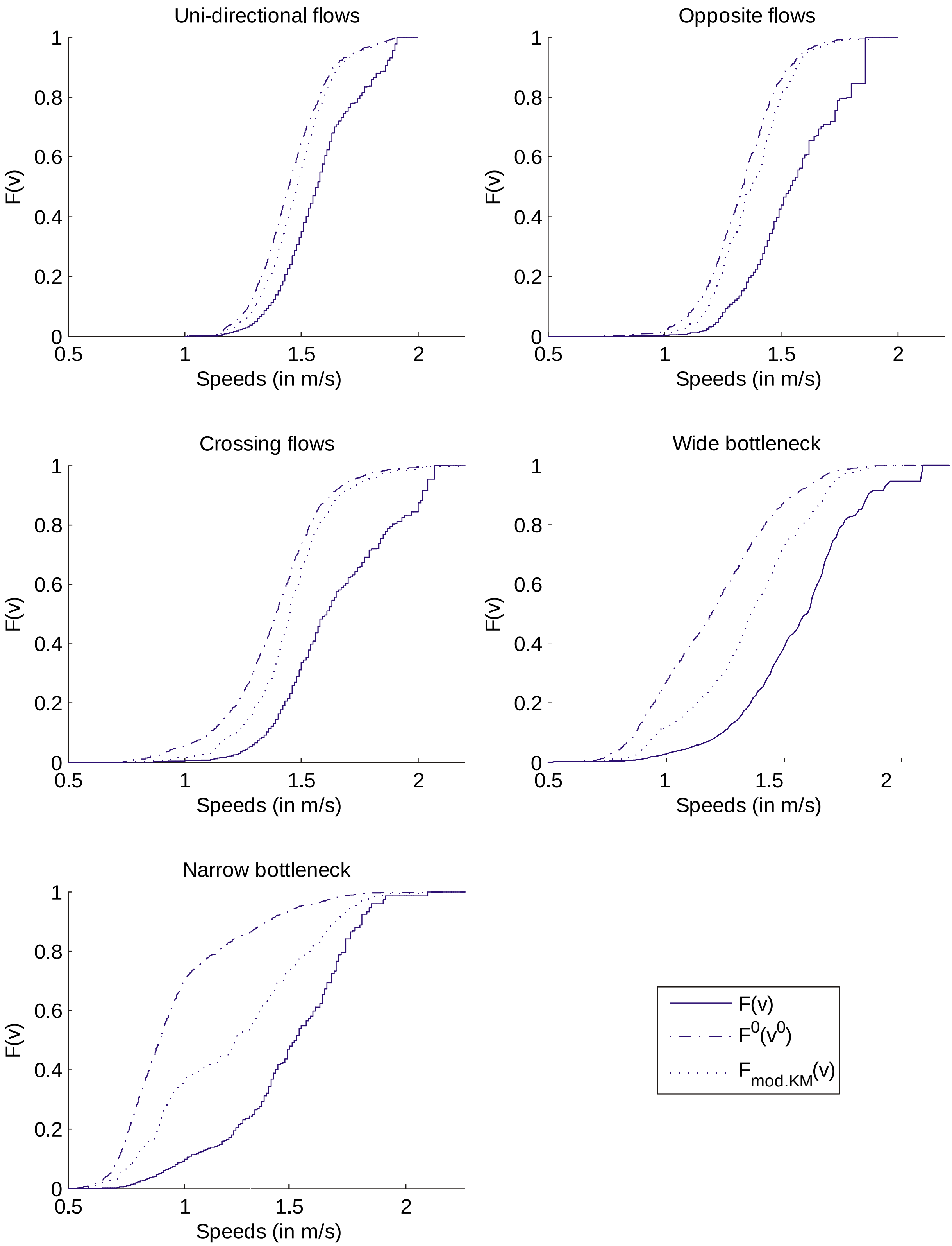

FIGURE 5 Estimation Results for Five Laboratory Experiments.

We can see that the estimated free speeds vary between the experiments, with a maximum of 1.64 m/s (crossing flows) and a minimum of 1.44 m/s (narrow bottleneck). The free speeds are higher than found in literature, which is as expected, since the literature discusses observed speeds, whereas this paper considers free speeds. Note that in (*10*) it is shown that the average speed of all experiments during low flows equals 1.41 m/s, which is comparable to values found in literature. The fact that the free speeds are higher can therefore not contributed to the experimental effect, but is due to the fact that even in low flows pedestrians can be constrained.

Table 2 shows that the mean of the estimated free speeds is similar for the experiments with the unidirectional flows, the opposite flows, and the wide bottleneck. The first and the latter experiment both have unidirectional flows, whereas the wide bottleneck only slightly causes congestion. The estimation method thus appears to filter these constrained observations and comes up with a satisfying distribution. In the experiment with opposite flows the self-organization effect causes lane formation, which leads to several unidirectional flows. Only the tangential points between the lanes cause hindrance, but the flows are not large enough to decrease pedestrian speeds significantly. The mean of the estimated free speeds in the narrow bottleneck experiment is significantly lower than that of the other experiments. This might be due to the overrepresentation of constrained observations. We have seen that this also gives problems in estimating the bottleneck capacity (*43*). The experiment with the crossing flows gives the highest estimated free speeds. This indicates that too many pedestrians are considered constrained. However, the median free speed in this experiment equals the median free speed found in the wide bottleneck, indicating that some outliers have occurred in this experiment.

Figure 5 shows the large difference between the three distribution functions. That is, only using the speeds of the unconstrained pedestrians ($F^0(v)$) clearly leads to an underestimation of free speeds. This is due to the fact that pedestrians with a high free speed have a higher probability of being constrained and therefore have a lower probability to be observed and thus included in this distribution. Furthermore, we see that the difference between the distribution functions changes over the experiments. The highest difference occurs in the narrow bottleneck experiment, since the number of constrained pedestrians is the highest. In the experiment with unidirectional flows the difference is the lowest. Here, the flows are the lowest and since all pedestrians walk in the same direction the least number of conflicts occurs. For the experiment with the opposite flows, the difference is larger than for the unidirectional flows, since more conflicts occur. However, the self-organization effect lane-formation decreases this number of conflicts again. As expected, we see that the difference is larger again for the experiment with the crossing flows, which has been the reason of developing a new criterion for the constrainedness of a pedestrian.

For the experiments with opposite flows and crossing flows a separate estimation has been performed for each walking direction (see table 3). We can see that the mean and the median of the estimated free speeds are similar for both walking directions in both experiments. Since the composition of both flows is identical, this is as expected. In the speed observations and the unconstrained speeds in the crossing flows a significant difference has been identified between the two flows. It appears that the estimation method is perfectly able to correlate these higher speeds to less constrained pedestrians, leading to reliable free speed estimations.

TABLE 3 Estimation Results per Walking Direction for Experiments with Opposite (top) and Crossing Flows (bottom)

	Speed			Unconstrained speeds			Estimated free speeds		
Experiments	Mean	St. var	Median	Mean	St. var	Median	Mean	St. var	Median
Opposite	1.33	0.16	1.33	1.37	0.15	1.37	1.55	0.21	1.54
Right – left	1.33	0.15	1.33	1.37	0.14	1.36	1.53	0.18	1.51
Left – Right	1.34	0.17	1.34	1.37	0.16	1.36	1.55	0.21	1.55
Crossing	1.38	0.22	1.39	1.45	0.19	1.45	1.64	0.25	1.60
Right – left	1.46	0.16	1.46	1.49	0.16	1.47	1.64	0.22	1.61
Top – bottom	1.29	0.23	1.30	1.37	0.18	1.38	1.64	0.29	1.58

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This paper has shown how the approach to estimate free speed distributions for car traffic can be improved in order to make it applicable for pedestrian traffic and opposite and crossing pedestrian flows in particular. The criterion determining the probability of a pedestrian being constrained has been based on a fuzzy approach, using the distance between pedestrians and the time moment this distance occurs as parameters of the membership functions.

Free speed distributions have been estimated on data derived from laboratory experiments, in which unidirectional flows, opposite flows, and crossing flows have been simulated. Distributions have been compared for all speeds (including both constrained and free flowing observations), for unconstrained speeds (only free flowing pedestrians), and finally for the free speeds calculated by applying the free speed estimation approach presented in this paper. The estimated free speeds vary between the experiments, with a maximum of 1.64 m/s (crossing flows) and a minimum of 1.44 m/s (narrow bottleneck). The free speeds are higher than found in literature, which is as expected, since the literature discusses observed speeds, whereas this paper considers free speeds. Since in (*10*) it is shown that the average speed of all experiments during low flows equals 1.41 m/s, the higher free speeds cannot be contributed to the experimental effect, but are due to the fact that even in low flows pedestrians can be constrained.

We have seen that, as expected, these distributions varied significantly in each experiment: only using the speeds of the unconstrained pedestrians (= during low densities) clearly leads to an underestimation of free speeds, due to the fact that pedestrians with a high free speed have a higher probability of being constrained. The estimated free speed distributions did not vary significantly between the experiments, thus underlining the ability of the estimation method to identify the free speed distribution independent of the experiment performed.

Despite the promising results, some additional research is still to be performed. One of the points is to investigate the sensitivity of the approach for the choice of parameters of the membership functions. Also the form of the membership functions might be varied. A first exercise showed that quadratic functions with similar parameters as presented in this paper did not improve the estimation results. In addition to the application of the approach on experimental data, it can be applied on real life data. Finally, the influences on the free speed distributions as mentioned in the introduction (such as personal characteristics, characteristics of the infrastructure and external conditions) can be studied in detail.

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