Calibration of Pedestrian Simulation Model for Emergency Doors by Pedestrian Type

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Emergency doors may be bottlenecks in the evacuation of a building. When a pedestrian simulation model is used to assess designs of buildings, the model should accurately predict the behavior of pedestrians around emergency doors and thus the doors' capacity. Data from laboratory experiments were used to calibrate the pedestrian simulation model Nomad. In these experiments, large heterogeneous groups of people passed through a door under evacuation conditions. The collected trajectory data were used as input for an automated calibration procedure, which yielded parameter estimates for individual pedestrians. This automated calibration procedure has been extended through inclusion of data from multiple pedestrians into a single estimate. This change overcomes convergence problems because the log likelihood is insensitive to changes in some of the parameters and because of the problems of unrealistic parameter estimates. The resulting parameter distributions provided insight into pedestrian behavior. Dedicated parameter sets for the elderly, adults, and children were estimated. The parameter sets and thus behaviors of the types of pedestrians were compared and showed that different behavior was indeed observed.

Emergency doors may be bottlenecks in the evacuation of a building. Design guidelines specify door width, which depends on the number of persons that rely on a specific door (*1, 2*). Dutch guidelines, indicating a capacity of 135 persons per minute per meter of door width, are based on old experimental research with healthy students (*3*), and both the fire department and recent literature studies (*4, 5*) indicate that the capacities given in the Dutch design guidelines are high.

In 2002, the Transport and Planning Department of the Delft University of Technology, the Netherlands, performed laboratory experiments with a narrow bottleneck. This resulted in a capacity of 1.77 persons per meter per second (P/m/s) (*6*). However, the narrow bottleneck consisted of a corridor 5 m long, whereas a doorway usually has a depth of 10 to 40 cm. This most likely leads to a higher capacity for doorways, because pedestrians may accept shorter headways for a short period of time.

Kretz et al. performed bottleneck experiments as well (*7*). In their experiments, the bottleneck was a thick wall of 40 cm with an opening through which pedestrians had to pass. Various widths for the opening were considered (40, 50, 60, 70, 80, 90, 100, 120, 140, and 160 cm). The participants were healthy students, and the experimental conditions were normal. A linear decrease of the capacity was shown with increasing bottleneck width as long as only one person at a time could pass (from 2.2 P/m/s for 40-cm width to 1.78 P/m/s for 70-cm width). A constant value of the capacity of around 1.8 P/m/s was shown for larger bottleneck widths (70, 80, 100, and 120 cm).

Experimental research by Müller and (*8*) and Nagai et al. (*9*) indicated much higher capacities for bottleneck widths of between 80 and 160 cm, namely, between 2.29 P/m/s and 3.23 P/m/s. The very high densities at the start of the experiments can explain these high values. Also, the configuration of the bottleneck is slightly different, which affects the measured capacities (*10*). These values correspond to the threshold indicated in the design guidelines.

In other research, observations were made on corridors and in areas with many pedestrians present, such as stations, inner cities, and stadiums (*11, 12*). The capacities found varied between 1.03 P/m/s and 1.67 P/m/s, which are much lower than the design guidelines. However, these capacities were found in normal conditions.

Information about the microscopic and macroscopic phenomena at bottlenecks is necessary for determining which capacities are realistic and for assessing and improving ways in which bottlenecks are used during evacuation conditions. Therefore, experimental research was performed that collected detailed data about pedestrian behavior in and around doors during emergency conditions (*13*).

In Europe and in the United States, a change has been made in recent decades from prescriptive guidelines to performance-based guidelines. In the latter case, engineering (a quantitative application of scientific laws) is used for design. According to Pilzer, "the basis of all building activity should be the performance of the building in use rather than the prescription of how the building is to be constructed" (*14*). One of the issues in this respect is the availability of tools for predicting and assessing building performance for pedestrian flows in the building. Pedestrian simulation tools have been shown to be suitable for such predictions and assessments. However, the tool must be accurately calibrated and validated, not only for normal conditions but also for evacuation conditions. This paper gives parameter estimates for the pedestrian simulation tool Nomad for behavior of pedestrians near emergency doors.

Most simulation studies on evacuation address evacuation behavior of adults, who are expected to bring themselves to safety in an evacuation. However, children (to age 14) account for 26% of the Western world's population and the elderly (65 and older) for 8% (*15*). Numerical models are used to predict evacuations with heterogeneous populations that include children while applying a normative description of the population without proper validation (*16*). This does not conform to the growing demand for equal egress (*17*). However,

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little is known about the behavior of these age groups. Buchmüller and Weidmann discussed the relationships between walking speed and age and between gender and walking purpose and found significant differences (*12*). Daamen and Hoogendoorn showed that the behavior of different age groups affects macroscopic traffic flow characteristics, such as capacity (*13*). By applying multivariate regression, they showed the following relationship between the capacity of emergency doors and flow composition:

$$C = 2.67 + 1.06 \cdot P_C - 0.21 \cdot P_E \tag{1}$$

where P_C and P_E, respectively, denote the share of children and the elderly in a pedestrian flow consisting of adults. The impact of composition on capacity is considerable. The data in their research stem from experiments used to obtain the results presented in this paper. This paper therefore presents dedicated parameter estimates for children, adults, and the elderly and discusses the differences.

First, an overview is given of the performed evacuation experiments, including the experimental setup, and the Nomad simulation model is introduced. Then, hypotheses on the behavior of the three groups (children, adults, and the elderly) are introduced. The calibration procedure is described, and then the calibration results and interpretation of the results are presented.

EVACUATION EXPERIMENTS

The evacuation experiments were conducted on January 8, 2009, in a large hallway. A wall was located perpendicular to the side wall of this hallway. A doorway opening was created in the wall, which was easy to adjust in width. An emergency exit sign was placed above the doorway to imitate a real-life situation (Figure 1*a*). A traffic signal turned green when the participants could start walking (Figure 1*a*). Before every experiment, the group of participants lined up 5 m upstream of the wall behind a line on the floor (Figure 1*b*). An extensive description of the experimental setup is available elsewhere (*13*).

The experimental variables were the composition of the population using the door, the doorway width, and the conditions under which the door was used. Seven population compositions were used, corresponding to characteristic buildings or situations: school, station during peak hours, retirement home, work meeting, shopping center, a disabled population, and an average population. For ethical reasons, the disabled part of the population consisted of three blindfolded persons and three persons in wheelchairs. In total, 75 children who were 11 years old (blue caps), 90 adults (red caps), and 50 elderly persons (yellow caps) participated in the experiments. This leads to populations of between 90 and 150 persons, which were large enough to cause congestion upstream of the door so capacities could be observed.

The conditions under which an emergency door is used may vary considerably. In the experiments, both the stress level of the participants and the light intensity were varied. Little is known about how to introduce stress in an experiment. Two methods have been considered favorable: encouraging participants to hurry by rewarding them according to their performance and exposing participants to noise. The latter option was chosen for this experiment, and a slow-whoop signal was sounded. The stress level of the participants was raised by combining the slow-whoop signal with a stroboscopic light. Participants thus were exposed to three stress levels: none, induced by a slow-whoop signal, and induced by a combination of a slow-whoop signal and a stroboscopic light. The light intensity was reduced by reducing illumination to a low level. Two alternative light situations were considered: full lighting (200 lux) and dimmed (1 lux, corresponding to emergency lighting).

In the experiments, the width of the opening varied between 50 cm (the minimal free passageway of an escape route in the Dutch design guidelines for existing buildings) and 275 cm. In addition to an opening 85 cm wide (minimal free passageway of an escape route in the design guidelines for new estates), openings were a multiple of 55 cm. An opening of 100 cm was tested for its correspondence with normative capacity expressed as the number of persons passing an opening 1 m wide in 1 min.

The final experimental variable related to whether the outflow of pedestrians after passing the doorway was free. In the real world, doors cannot always open 180° degrees but may be restricted. In the experiments, a fixed door opening of 90° was used. The total doorway width was not affected.

All combinations of experimental variables should be investigated, but because this was not feasible (the experiments were to last no

(a) (b)

FIGURE 1 Overview of experiments.

TABLE 1 Overview of Performed Laboratory Experiments

Experiment	Opening Width (cm)	Population	Sight (lux)	Open Door	Start Time (hh:mm)
1	100	Average	200	No	9:58
2	220	Average	200	No	10:17
3	85	Retirement home	200	No	10:43
4	85	Average	200	No	10:58
5	165	Average	1	No	11:25
6	275	Average	200	No	11:52
7	85	Work meeting	200	No	12:49
8	85	Disabled	200	No	12:23
9	85	School	200	No	13:48
10	85	Average	1	No	14:08
11	50	Average	200	No	14:24
12	110	Average	200	No	14:39
13	85	Shopping center	200	No	15:19
14	85	Average	200	Yes	15:40
15	165	Average	200	No	16:03
16	85	Station	200	No	16:24

longer than a day), for each experiment one variable was changed, and for the other variables the default value was maintained. By interpolation of the results of the various experiments, pronouncements could be made on the experiments not performed. The stress levels were varied for all experiments.

Each experiment was performed multiple times to guarantee the reliability of the observations. A total congestion time of 3 min should be achieved to determine the number of repetitions. Because the time of congestion for wide doors is shorter than that for narrow doors, more repetitions are performed for the wide doors. An overview of the experiments is shown in Table 1.

The experiments were observed with a digital video camera and an infrared camera. The infrared camera observed LEDs attached to the tops of the caps worn by the participants. This technique guaranteed good observations in dim light. A digital camera, attached to the ceiling next to the infrared camera, was used for the other experiments. Using the methodology described by Hoogendoorn et al. was used to derive trajectories from the video footage (*18*). These trajectories formed the basis of the empirical findings presented in the next sections.

NOMAD: MICROSCOPIC PEDESTRIAN SIMULATION MODEL

The microscopic pedestrian simulation model Nomad was developed at the Department of Transport and Planning at the Delft University of Technology (*19, 20*). Nomad is an agent-based model that covers the tactical and operational levels of human behavior, including route choice behavior, activity (area) choice behavior, walking behavior, waiting behavior, and behavior in special infrastructure elements, such as revolving doors and turnstiles. The walking behavior model predicts the acceleration of a pedestrian $\vec{a}_p(t)$ as a function of the free velocity $\vec{v}_p^0$, the current speed $\vec{v}_p(t)$, the position $\vec{r}_p(t)$, and distance $d_{pq}(t)$ between pedestrians p and q as follows:

$$\vec{a}_p(t) = \vec{f}_p\left(\vec{v}_p(t), \vec{r}_p - \vec{r}_q, \dots\right)$$
$$= \frac{\vec{v}_p^0 - \vec{v}_p(t)}{T_p} - A_p \sum_{q \in Q_p} \vec{u}_{pq}(t) e^{\frac{-d_{pq}(t)}{R_p}} 1_{\vec{u}_{pq}(t)\cdot\vec{v}_p(t)>0} \tag{2}$$

where Q_p denotes the set of pedestrians that influence pedestrian p and where

$$d_{pq}(t) = \left\|\vec{r}_q(t) - \vec{r}_p(t)\right\| \tag{3}$$

and

$$\vec{u}_{pq}(t) = \frac{\vec{r}_q(t) - \vec{r}_p(t)}{d_{pq}(t)} \tag{4}$$

The model has four pedestrian-specific parameters to be estimated: the free speed $V_p^0 = \|\vec{v}_p^0\|$, the acceleration time T_p, the interaction constant A_p, and the interaction distance R_p. The indicator function $1_{\vec{u}_{pq}(t)\cdot\vec{v}_p(t)>0}$ is 1 if pedestrian q is in front of p and 0 otherwise. This implies full anisotropy in the sense that a pedestrian does not take notice of any pedestrians behind him or her. The desired walking direction $e_p^0 = \vec{v}_p^0/V_p^0$ is derived from the data by taking a rough smoothing of the speeds.

MEASUREMENT AND ESTIMATION SETUP

The remainder of the paper investigates and compares the walking behavior of three populations: children, adults, and the elderly. A model-based approach is proposed, in which the described trajectory data are used to estimate the parameters of the microscopic simulation model Nomad.

Differences in four behavioral parameters are investigated: free speed, time to accelerate toward free speed and planned direction, interaction strength, and interaction distance. These parameters are discussed in detail in the next section. The analysis is structured according to the following behavioral hypotheses, which reflect the expected differences between the considered groups:

Hypothesis 1. Under emergency conditions, children have a higher free speed $\vec{v}_p^0$ than adults, whose free speed in turn is higher than the free speed of the elderly.

Hypothesis 2. The time to accelerate to free speed and planned direction T_p will be shortest for children and longest for adults. This mainly depends on assumptions about physical abilities: children are usually more able (and willing) to vary their walking speed than are adults and the elderly.

Hypothesis 3. The interaction constant A_p will be strongest for the children and weakest for the elderly. The assumption is that the children will react toward the pedestrians around them, whereas the elderly will maintain their own paths.

Hypothesis 4. The interaction distance R_p will be smallest for the children and highest for the elderly. It is assumed that the elderly anticipate earlier the movements of the people around them.

Assessment of the estimated parameters is followed by a comparison of the parameters estimated during normal conditions.

CALIBRATION METHODOLOGY

This section discusses estimation of the unknown parameters for general continuous-time microscopic pedestrian models. The approach is applied in the next section to estimate parameters for individual pedestrians.

The parameter estimates provide not only insight into walking behavior but also information on interpedestrian differences for this behavior.

The available observations are trajectories (the location $\vec{r}_p$ as a function of time instant t_k, for $k = 1, \ldots, n$) of all pedestrians p. From these data, all relevant quantities can be derived either directly or by applying finite differences, such as velocities $\vec{v}_p(t_k)$, accelerations $\vec{a}_p(t_k)$, and distances between pedestrians. For the data considered here, observations are present each 0.04 s.

The applied calibration methodology is based on maximum likelihood estimation and has been described in detail elsewhere (*21, 22*). The most important aspects of the method are recalled here.

The acceleration $\vec{a}_p(t_k \mid \theta_p)$ depends on the model parameters θ_p to be estimated and an error vector $\vec{\varepsilon}_p$, which reflects the errors in the modeling, similar to the error term used in multivariate linear regression. For now, it is assumed that the error term is normally distributed with mean zero and standard deviation σ_p (pedestrian specific). This acceleration $\vec{a}_p(t_k \mid \theta_p)$ can be compared with the observed acceleration $\vec{a}_p^{\text{obs}}(t_k)$. According to the model, the difference between the prediction and the observation follows the normal distribution with mean 0 and standard deviation σ_p.

The likelihood L_k of a single prediction step, say, from time t_k to time t_{k+1}, is related directly to the probability density $g(\varepsilon)$ of the normal distribution:

$$L_k(\theta_p, \sigma_p) = \frac{1}{\sigma_p\sqrt{2\pi}} e^{\frac{\left(\vec{a}_p^{\text{obs}}(t_k) - \vec{a}_p(t_k)\right)^2}{2\sigma_p^2}}$$

subject to

$$\vec{a}_p(t_k \mid \theta_p) = \vec{f}_p\left(\vec{v}_p^{\text{obs}}(t), \vec{r}_p^{\text{obs}}(t) - \vec{r}_p^{\text{obs}}(t), \ldots, \mid \theta_p\right) \tag{5}$$

Considering an entire sample of subsequent acceleration observations and neglecting correlation between subsequent samples (serial correlation), the likelihood of the observation of an entire trajectory is simply the product of the likelihoods of the individual time moments. Maximum likelihood estimation involves finding the parameters that maximize this likelihood, or, since the likelihood usually is very small, for calculation reasons the log likelihood is maximized. A necessary condition for the optimum allows determination of the standard deviation:

$$\frac{\partial \tilde{L}}{\partial \sigma_p^2} = 0 \Rightarrow \sigma_p^2 = \frac{1}{n}\sum_{k=1}^{n}\left(\vec{a}_p^{\text{obs}}(t_k + \tau) - \vec{a}_p(t_k + \tau_p \mid \theta_p)\right)^2 \tag{6}$$

Equation 4 shows that the maximum likelihood estimate for the variance of the error term is given by the mean square error of the predictions and the observations. For the remaining parameters, the maximum likelihood estimates can be determined by numerical optimization:

$$\hat{\theta}_p = \arg\max \tilde{L}(\theta_p, \hat{\sigma}_p) \tag{7}$$

with

$$\tilde{L}(\theta_p, \hat{\sigma}_p) = -\frac{n}{2}\ln\left(\frac{2\pi}{n}\sum_{k=1}^{n}\left(\vec{a}_p^{\text{obs}}(t_k + \tau) - \vec{a}_p(t_k + \tau_p \mid \theta_p)\right)^2\right) - \frac{n}{2} \tag{8}$$

This expression shows that maximization of the log likelihood is equivalent to minimization of the mean squared error.

The so-called Cramér–Rao lower bound can be used to approximate the covariance matrix of the estimated parameters (*23*):

$$\text{Var}(\hat{\theta}_p) \geq -E(\nabla^2 \tilde{L}) \tag{9}$$

Because the maximum likelihood is asymptotically efficient, it can be shown that the asymptotic variance of the parameters is given by the right-hand side of Equation 9 (*23*). In this paper, this approximation is used to determine an estimate for the covariance of the estimates.

In addition to the correlation in the parameter estimates determined via the Cramér–Rao bound, interpedestrian differences can be determined. This is achieved by computing the mean, variance, and interpersonal correlation of the individual parameter estimates for the various pedestrians. These statistics provide insight into the behavioral differences between pedestrians and the interpedestrian correlation between the parameter estimates.

However, the drawback of this method is that convergence problems occur during estimation, in particular because the log likelihood is insensitive to changes in some of the parameters, and the parameter estimates are not always realistic. A solution for this is to include data from multiple pedestrians into a single estimate. Assume a set of N trajectories. The behavior of these pedestrians can be described by a pedestrian-specific set of parameters θ_p. The likelihood of observing this trajectory given that the behavior is described by θ_p can be determined with Equation 4. With trajectories combined, the joint likelihood of observing the trajectories of pedestrians $p = 1, \ldots, N$ can be determined with

$$L_{\text{mult}}(\theta_1, \ldots, \theta_N) = \prod_{i=1}^{N} L^{(i)}(\theta_i) \tag{10}$$

This expression can also be used to determine the likelihood that all pedestrians in the considered pedestrian population can be described by the same parameter set $\bar{\theta}$:

$$L_{\text{mult}}(\bar{\theta}) = \prod_{i=1}^{N} L^{(i)}(\bar{\theta}) \tag{11}$$

The log likelihood can easily be determined. If it is assumed that the parameters θ_p describing the behavior of individual pedestrians are drawn from some random distribution with mean Θ and covariance matrix Σ, it is known that

$$E(\bar{\theta}) = \theta \tag{12}$$

and

$$\text{Var}(\bar{\theta}) = \frac{1}{\sqrt{N}}\Sigma \tag{13}$$

This expression allows one to construct the mean and covariance of the distribution underlying the individual parameters from the joint-estimation results. This means that although multiple trajectories are considered jointly, inferences still can be made regarding population heterogeneity.

CALIBRATION RESULTS

In previous analyses, it was shown that both the school population and the population with disabled pedestrians showed specific behavior (*13*). As discussed, it was shown that heterogeneity might play an important role in pedestrian behavior. Here parameters are estimated for populations with the largest shares of children, adults, and the elderly, respectively. The school population (90% children 11 and 12 years old and 10% adults), the station population (100% adults), and the retirement home population (5% children, 20% adults, and 75% 65 or older) are used. For all populations, the trajectories for only the considered group were estimated. In each experiment, the trajectories of the first 15 pedestrians passing the door opening were removed, because these pedestrians did not have sufficient interactions and walked more in free-flow conditions than in the congested conditions relevant for the experiments. In the following, each of the four previously defined hypotheses is discussed in more detail.

Hypothesis 1. Free Speed

The estimation results for the free speed parameter are shown in Figure 2, which shows that the free speed estimations v^0 are highest for children and lowest for the elderly. This was in accordance with the hypothesis. However, the difference is very small. The estimates are lower than the free speeds usually observed in literature, because pedestrians walk not in free walking conditions but in congested conditions. Furthermore, it is well known that for constrained situations, the model predictions are insensitive to larger values of the free speed (*22*).

This could also be why the estimated speeds were similar for the three pedestrian types. The variation was highest for adults (although the difference with the variation for the children is very small) and lowest for the elderly.

Hypothesis 2. Time to Accelerate to Free Speed and Planned Direction

Figure 3 shows the parameter estimates for the time to accelerate to free speed and the planned direction. This so-called acceleration time T indicates the time that pedestrians take to accelerate toward their free speed. The lower this time is, the more aggressively pedestrians try to walk with their free speed. This corresponds with behavior in which pedestrians actively look for gaps where they can overtake other pedestrians to pass the bottleneck as quickly as possible. However, the values in Figure 3 are very large, which means that pedestrians were not actively trying to walk with their free speed, but were just continuing with their current speed. The acceleration time is lowest for the elderly pedestrians, whereas the children behaved more aggressively. The findings thus contradicted the hypothesis.

Hypothesis 3. Interaction Strength

Figure 4 shows the parameter estimates of the interaction term. The size of the interaction term A is difficult to interpret in a behavioral way. The estimates also show that the values are not reliable, because the standard deviation is much higher than the average value of this

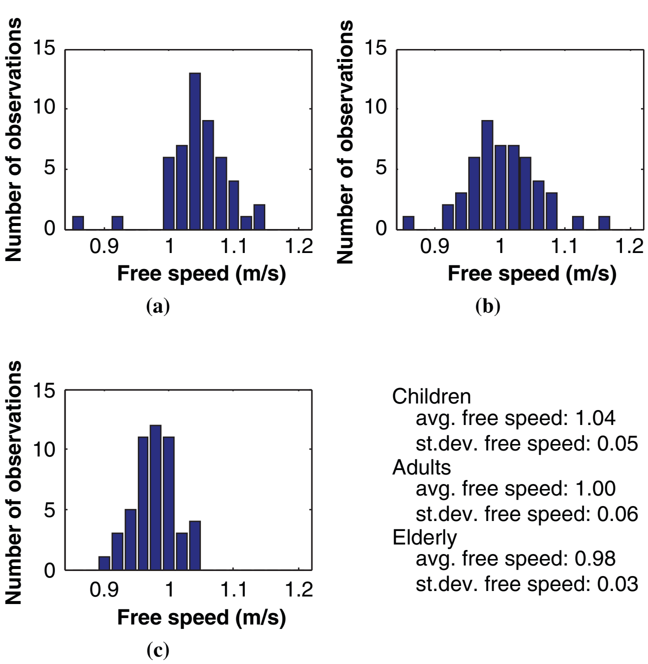

FIGURE 2 Parameter estimates for free speed for (*a*) children, (*b*) adults, and (*c*) the elderly (avg. = average; st.dev. = standard deviation).

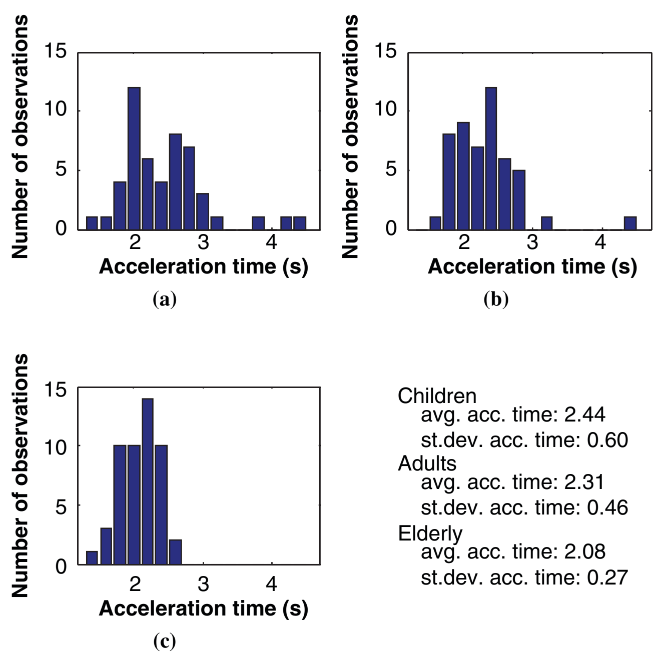

FIGURE 3 Parameter estimates for acceleration time for (*a*) children, (*b*) adults, and (*c*) the elderly.

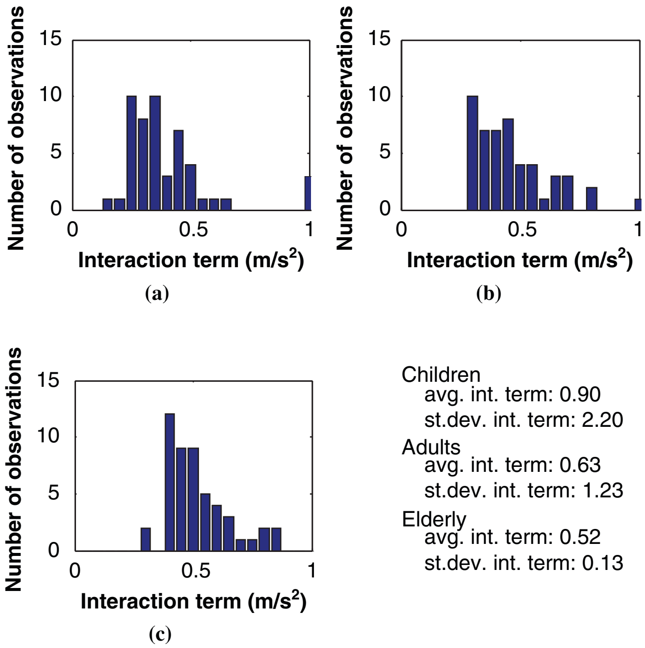

FIGURE 4 Parameter estimates for interaction term for (*a*) children, (*b*) adults, and (*c*) the elderly.

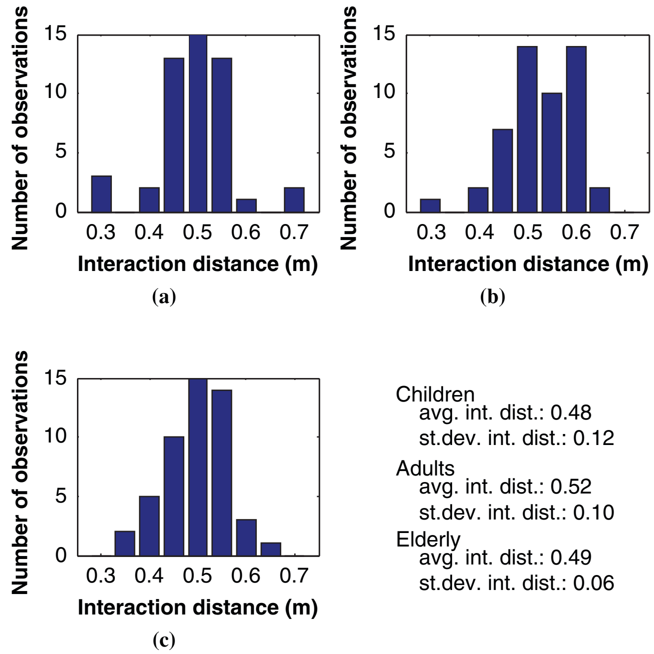

FIGURE 5 Parameter estimates for interaction distance for (*a*) children, (*b*) adults, and (*c*) the elderly.

parameter. This means that the strength of the interaction differs considerably between pedestrians, assuming a large heterogeneity between pedestrians. The interaction between children is much stronger than the interaction between adults and the elderly, which is according to expectations.

Hypothesis 4. Interaction Distance

Figure 5 shows the parameter estimates with respect to the interaction distance, which indicates the distance that pedestrians prefer to keep from each other. This variable is directly related to density. Children have the lowest interaction distance, which would correspond to the highest densities. This can be explained by their smaller physical size. The elderly have only a slightly higher interaction distance, which corresponds to earlier findings that their density is higher than that for adults (*13*). The findings for the macroscopic traffic characteristics therefore correspond to the findings on the microscopic level.

Comparison of Parameters with Normal Conditions

A comparison of the estimated parameters for these evacuation conditions near door openings and the parameters estimated in normal walking conditions (*21*) shows some remarkable differences. The mean free speed in normal conditions was 1.32 m/s, and the mean acceleration time was 0.96 s. With a lower free speed and an acceleration time twice as high, the influence of the first term on acceleration is much smaller than in normal walking conditions. This would imply that pedestrians are not eager to keep their free speed. The influence of other pedestrians on the acceleration (interaction) is also much lower, because of the much lower value of the interaction term A (11.46 m/s^2 in normal conditions), whereas the remaining part of the term remains similar because the interaction distance is comparable in the two situations (0.33 m in normal conditions).

These results, as well as further observations during the estimation process, show that pedestrian behavior in this experiment is considerably different from normal walking behavior. In the latter, especially in higher densities, pedestrians look for gaps, which they can use to overtake other pedestrians when they have a higher free speed. This is how the Nomad model, and most other models, is set up. In the experiments described here, pedestrians appear to have determined a path leading toward the door (the bottleneck), along which they progress slowly but to which they stick rather consistently. This would require a different model formulation in which only the size of the acceleration is determined, while its direction depends on the route choice. Both types of behavior cannot be covered with a similar model type, and a multiregime model would be more appropriate, in which situations with low and high densities can be distinguished and dedicated models can be applied in the specific situations (regimes).

CONCLUSIONS AND RECOMMENDATIONS

This paper described the parameter estimates for the microscopic pedestrian simulation tool Nomad by using trajectory data from laboratory experiments. With these parameter values, it is possible not only to identify pedestrian behavior near doors in evacuation conditions but also to predict this behavior with Nomad. Three types of pedestrians that were assumed to have different behavior—children, adults, and the elderly—were addressed.

The parameter estimates were achieved by extending the existing estimation methodology to estimate not only individual parameters but also parameters of groups of pedestrians. This way, convergence problems, as well as the problem that parameters are not always realistic, were solved. From the total set of trajectories, a random selection of trajectories was made, for which the best (average) parameter set was estimated. This process was repeated several times; the number of repetitions was related to the reliability of the average parameter set, and the size of the selection influenced the probability of outliers in the estimated parameters.

The results of this new calibration methodology showed different parameter distributions, and thus different behavior was observed for children, adults, and the elderly. Children appeared to have the highest free speed and the elderly the lowest, which was expected. However, the differences were very small and were much lower than in the literature. One of the reasons for this is that since pedestrians are only walking in congested conditions, the model predictions are insensitive to larger values of the free speed. The aggressiveness of the elderly appeared to be larger than that of children, which is counterintuitive. However, the parameter values found were relatively high, implying that pedestrians are not actively trying to walk with their free speed but are trying to continue with their current speed. The estimates of the interaction term were not reliable, because the standard deviation is larger than the mean value. However, the interaction between children appeared to be much stronger than the interaction between adults and the elderly, which was according to expectations. Finally, the interaction distance was smallest for children, which corresponds to the highest densities found for populations of children (because of physical size).

The final conclusion relates to the comparison of the estimated parameters in evacuation conditions and the parameters estimated in normal conditions. These showed a large difference: with a lower free speed and a much larger acceleration time, the influence on the acceleration was much smaller than in normal walking conditions. This implies that pedestrians are not eager to keep their free speed (they are blocked by congestion). The influence of other pedestrians on the acceleration (interaction) was also much lower, because of the much lower value of the interaction term A, while the remaining part of the term remains similar because the interaction distance was comparable in both situations. This could imply that pedestrians behave very differently in congested or evacuation conditions than in normal conditions, and the question arises of whether these different behaviors can be covered within a single model (with different parameter sets) or whether a multiregime model would be more appropriate, in which situations with low and high densities can be distinguished and dedicated models can be applied in the specific situations (regimes). This is subject for future research.

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