On the Validation of Pedestrian Movement Models under Transition and Steady-state Conditions

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ABSTRACT

Validation of computer modules simulating pedestrian movement is discussed. Albeit not new, this subject is studied here for transition and steady-state regimes to show different manifestations of people dynamics. The goals of the validation, explanations of the simulation experiments, and interpretation of the simulation results are discussed. The velocity-density dependence under transition and steady-state conditions of people flow in a straight corridor has been investigated. The simulation results are compared with experimental data using specific and full flow rates as quantitative measures.

KEYWORDS: Pedestrian dynamics, evacuation modelling.

INTRODUCTION

Simulation of pedestrian dynamics is used in many applications including entertainment (e.g. cinema and computer games) and fire safety precautions in buildings, ships, and aircrafts. Different approaches, including the social force model based on differential equations and stochastic CA models have been developed [1]. The most attractive for application is the use of individual approaches, when each person is considered separately and the model can determine the coordinates of each person. In such a model, every person can have individual properties, including free movement velocity, evacuation delay time, size of projection, and direction of movement. These give wider opportunities to state a simulation task and reproduce real phenomena compared to a macroscopic approach.

When we speak about people's safety, the main goal of the simulation is to estimate the inflow and outflow travel times in different scenarios to check and/or provide safe conditions for visitors or passengers in normal and emergency situations. Validation of pedestrian movement simulation modules is not a new subject in the literature. The commonly used test is to check the velocity-density dependence under periodic boundary conditions as a main feature of people movement. The aim of this study was to present and discuss some issues related to the validation of this feature. We would like to explore more deeply the process and present a more complex set of tests for identifying different manifestations of the velocity-density dependence in different movement regimes. The tests were undertaken using the SigmaEva module [2-4].

The next section presents the main concept of the validation approach. Then we describe the tests, simulation experiments, expected results, and results obtained using the SigmaEva module.

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WHAT IS THE SUBJECT TO VALIDATE? WHAT FOR? HOW?

The purpose of this paper is not to discuss the pros and cons of the mathematics of the pedestrian movement models. A mathematical model, as well as its numerical presentation and program implementation, are considered as a whole. Thus, the objective of this study is testing computer simulation modules (hereinafter, the model is a computer module implementing it) and analyzing the simulation results.

People movement is a complex process, which can be divided into the movement (i.e., physical displacement which is mainly driven by a desire to reach a destination point) and behavioral contribution (e.g., decision-making aspects) [1, 5, 6]. To succeed in the validation, it is important to establish the range of the investigations. Here, we estimate the travel time under the so-called normal movement conditions, when only the movement component determines the process (no decision-making contribution). People are aiming to reach a destination point and they are aware of the environment (modeling area). In this study, the behavioral aspects are ignored. Thus, our goal is to discuss a way of testing a model to make sure that the model estimates correctly the "pure" travel time. It means that the movement dynamic reproduced by a model should be investigated. (It should be noted that, in contrast to [7-9], the aim here is not to consider the verification of the modules for program bugs, for instance, when people should not cross the modeling area boundary or should choose a certain exit, or if the pre-evacuation time should have a certain distribution. The behavioral aspects, including group behavior, social influence on choosing an exit, a decrease in the walking velocity with visibility degradation, and incapacitation, are not discussed.)

The next question is about the cases to be studied. We consider a set of basic geometrical situations, when certain people movement phenomena were observed repeatedly in real experiments, and compare the real-life data with the simulation data. The total path traversed by people (until reaching a destination) consists of several parts. We assume the correct simulation of people movement for each pattern to give the correct simulation for the entire path. The main geometrical patterns are a straight corridor, a corridor with a corner (90 and 180 degrees), bottlenecks, and up and down staircases.

People movement dynamics depends on the type of conditions (transition or steady). Here, a key factor is the existing velocity-density relationship [1, 10-12], which is different for the conditions of different types. Thus, we have to study the combination of geometrical patterns, density, and movement conditions.

We focus on the dynamics of people movement in a straight corridor at different densities and consider the following cases:

- flow spreading;
- speed independent of the local density up to a certain critical value (free movement speed invariable up to a certain density value);
- dynamics of people flow under steady conditions.

These cases allow us to capture if a model reproduces the velocity-density dependence under the transition and steady conditions.

The next important, yet still unanswered question concerns a measure of the quality [13]. The "yes-no" approach can be used when the test only results in detecting the presence or absence of a phenomenon. Such an approach is applied when a phenomenon takes place in real-life, but there is a lack of a quantitative method for measuring it. Here, we consider a test revealing the flow spreading.

If experimental data are available, then simulation results should be obtained under conditions similar to the experimental ones. In this case, the data can be directly compared. Obviously, strict coincidence between the simulation and real data is improbable and an acceptable deviation range should be established. Both cases are presented in the next section.

DESCRIPTION OF THE TESTS

General conditions

The specific and total flow rates were used as a quantitative measure for comparing the simulation results with the experimental data. To obtain flow rates, the travel times are measured. To present the results, we will use values that can be calculated exactly and only in one way, for example, the number of people in a modelling area, square of a modelling area, or travel times (total, between control points).

Since the people movement process is stochastic, many mathematical models contain stochastic components; for instance, the free movement speed is considered as a random variable for each pedestrian. For such models, a set of simulation experiments is conducted under the same conditions and the travel time is averaged over all the experiments. Certainly, stable results are obtained when a model is characterized by the low dispersion; then, the result of even one run is reliable. To ensure a convergence of results over repeated runs one can use a method proposed in [5,7].

Test 1: flow spreading

The flow spreading is caused by the fact that people tend to move under comfortable local density conditions. If there is an opportunity to keep distant from others, people will do so. This effect is especially pronounced when a dense body of people starts moving. In this case, the front line has a place to move and is characterized by the highest speed. Those people who are behind gradually start moving when there is a sufficient space for a step and their speed is controlled by the local density in front of them. This is a qualitative description of the phenomenon. Unfortunately, there is a lack of real-life data to make the quantitative comparison. Here, the problems to be solved are to design the simulation experiment conditions that would ensure the pronounced flow spreading and develop a method that would allow us not only to visualize it but also numerically estimate it.

To capture this phenomenon, we conducted the following simulation experiment. The nature of the phenomenon suggested that it could be carried out in the transition regime under so-called open boundary conditions: people leave two corridors 50×2 m and 100×2 m in size. Initially, people occupy the first 50 m of the corridor, Fig. 1. People are assumed to be uniformly distributed over the grey area and have identical individual characteristics. The person that crosses the control line is no longer involved in the simulation. A set of initial numbers of people (densities) is considered.

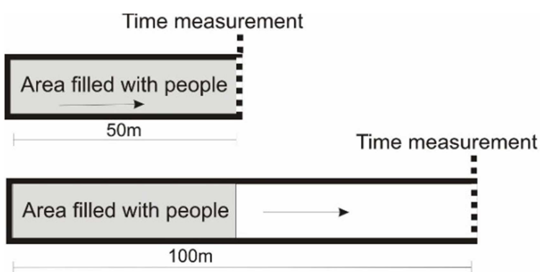

Fig. 1. Test 1. Geometry set up. Two corridors 50×2 m and 100×2 m in size, respectively, initial positions of people, and control lines.

Time T (s) in which the initial number of people N (persons) should cross the control line at the end of each corridor is a quantity to be measured. (In the stochastic model, the time is averaged over a series of experiments conducted under the same initial conditions.)

To estimate the flow rate for each initial number of people N, the following formulas are used: $J^{50} = N/\tilde{T}^{50}$, $J^{100} = N/\tilde{T}^{100}$, (person/s), where $\tilde{T}^{50} = T^{50}_{tot}$ is the (average) time of evacuation from the 50-m corridor, $\tilde{T}^{100} = T^{100}_{tot} - t^{50}$ is the (average) time of evacuation from the 100-m corridor without the time $t^{50} = 50/v^0$ for which the front line reaches the control line when moving with free movement speed v^0 (m/s) (thus, it is correct to assume the time $t^{50} = 50/v^0$ to be the same for all N values). The respective specific flows are $J^{50}_s = N/\tilde{T}^{50}/2$, and $J^{100}_s = N/\tilde{T}^{100}/2$ (person/(m × s)).

The flow in the 100-m corridor should be calculated using the above-mentioned approach, so the results for both corridors could be compared from one position; $\tilde{T}^{50}$ and $\tilde{T}^{100}$ are the periods of crossing the control line. Hence, the difference between flow rates at the same initial density (number of people in the starting area) is indicative of a difference in dynamics.

This is a conventional way to relate the flow rate and density. The question arises as to what the density is. In this test, the density is the initial density given by $\rho = N/S_{inpos}$ (person/m^2), where S_{inpos} = 100 m^2, is the square of initial positions (grey area in Fig. 1).

It is worth noting that only exact values are used to calculate ρ. These are the initial number of people, N, and the square of the initially occupied area. In fact, when we say that the "initial density" is equal to ρ, we only assume people to be initially uniformly distributed over the gray area in Fig. 1 and assign our qualitative description of the initial conditions with the quantitative characteristic ρ.

If the model reproduces the flow spreading, the following qualitative behavior of the flow rates under initial density variation for both corridors should be observed. The specific flow J^{50}_s for the 50- m corridor has two typical phases; it should increase until a certain initial density and then reach a constant value. This indicates that the maximum capacity is attained and a growth the initial density does not lead to a corresponding increase in the flow. Such a behavior is consistent with the data from [12].

The flow J^{100}_s should increase to the highest density, but not attain the highest value of J^{50}_s. Such a behaviour shows that with increasing initial density people tend to use the available space to reach a comfortable density around them (in the 100-m corridor, there are such places, in contrast to the 50-m corridor), the flow spreading is implemented, and the maximum capacity is not attained.

Figure 2 presents the test results obtained with the SigmaEva evacuation module. The specific flows $J^{50}_s = N/\tilde{T}^{50}/2$ and $J^{100}_s = N/\tilde{T}^{100}/2$ as functions of the initial density $\rho = N/S_{inpos}$ are shown.

We considered a set of initial numbers of people $N_i, i = \overline{1,k}$. The corresponding initial densities were $\rho_i = N_i/100, i = \overline{1,k}$, (person/m^2). Each person was assigned a free movement speed of $v^0_1 = 1.75$ m/s in one series of experiments and $v^0_2 = 1.3$ m/s in the other series of experiments. All persons were assigned the same square of projection 0.125 m^2. For each pair $N_i, i=\overline{1,k}$, $v_j^0, j=\overline{1,2}$, a set of 500 runs was made and the average evacuation times were calculated:

$$T_{tot}^{100}(\rho_i)=\frac{1}{500}\sum_{j=1}^{500}T_j^{50},\ T_{tot}^{100}(\rho_i)=\frac{1}{500}\left(\sum_{j=1}^{500}T_j^{100}-t^{50}\right),\ i=\overline{1,k}.$$

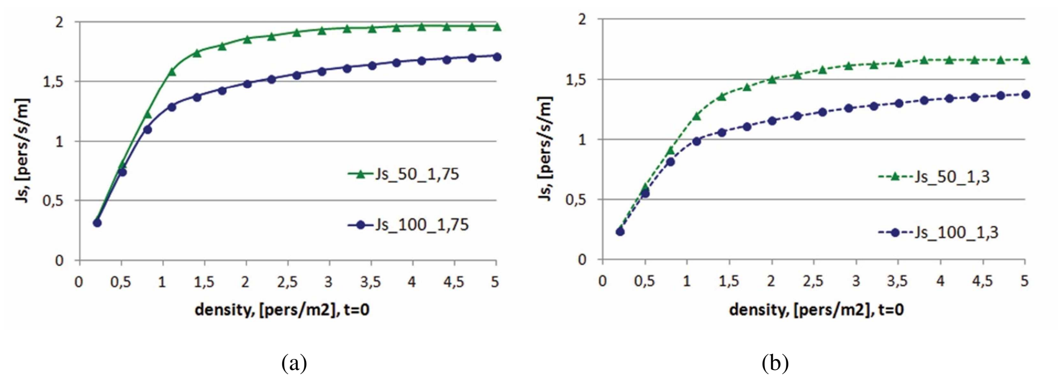

Fig. 2. Test 1. The SigmaEva module results: the specific flows for the 50-m corridor (Js_{50}) and 100-m corridor (Js_{100}) (on the left $v_1^0=1.75$ m/s and on the right $v_2^0=1.3$ m/s).

Let us interpret the results obtained. At both velocities, the flow J_s^{50} increases until the initial density takes a value of ≈ 3 person/m^2 and then reaches constant values of 1.8-1.9 person/(m × s) at $v_1^0=1.75$ m/s and ≈1.6-1.7 person/(m × s) at $v_2^0=1.3$ m/s. This indicates that the maximum capacity is attained and the initial density growth does not lead to a corresponding increase in the flow. Flows J_s^{100} (at both v_j^0 values) permanently grow to the highest initial density and do not reach the value of J_s^{50}. As the initial density increases, people start using the available free space to reduce the local density down to the possible comfortable conditions; as a result, flow spreading is implemented and the maximum capacity is not attained up to the highest N value. Thus, we may conclude that the model tested reproduces the expected behaviour of the specific flows as a function of the initial density and implements flow spreading.

Test 2: the velocity is independent of the local density up to the critical value

The experimental data reported in [1,10-12] show that the people moving in a flow maintain a free (unimpeded) movement speed under comfortable density conditions in the nearest neighborhood. It means that the nearest people do not influence each other and have enough space to keep their free movement speed unchanged. In other words, we can say that, all other conditions being equal, if there is an additional space, people will not fill it. The critical local density is $\rho^0\approx 0.5$ person/m^2, which corresponds to the data from [10-12].

This phenomenon is observed both under transition and steady-state conditions. One of the ways to capture this phenomenon is to use the conditions of Test 1 in the transition regime. The manifestation is as follows. Up to the critical initial density, conditions are comfortable and all persons should start moving simultaneously in both corridors. If the phenomenon is reproduced by the model, it results in the fact that, if people in the 100-m corridor do not use the available space (there is no flow spreading), the periods which people need to cross the control lines should be equal or very similar for both corridors ($T_{tot}^{50} \approx T_{tot}^{100} - t^{50}$). Thus, the flow rates J_s^{50} and J_s^{100} should be equal or very similar.

Let us now interpret the results of Test 1 in connection with this phenomenon. The SigmaEva module yields the following results. The flows coincide perfectly ((a) and (b) pictures in Fig. 2) for initial densities of up to 0.5-0.6 person/m^2. Therefore, in the two corridors the times that people need to cross the control lines are equal or very similar. It means that the density is comfortable and persons (in the 100-m corridor) do not take the opportunity to reduce the local density at the expense of the available space. Thus, the initial density remains invariant for the entire experiment.

Test 3: steady conditions of the people flow movement

Another manifestation of the density dependence of the velocity is implemented in the steady-state regime, when (in contrast to the previous case) the time-spatial density is assumed to be constant and there are no conditions for transformations of the flow. People are assumed to be uniformly distributed over the entire area (e.g., in an extended corridor without narrowing) and move in one direction. Under these limitations, the speed decreases with increasing density. This is the basic dependence called the fundamental diagram. In terms of the specific flow, the fundamental diagram looks as follows. As the density increases, the specific flow increases, attains its maximum, and then decreases.

There exist various fundamental diagrams determined by many factors, including demographics [15]; however, all have the same basic feature. For example, the velocity-density dependence can be presented in analytical form [8, 9]:

$$v^{KhS}(\rho) = v^0 \begin{cases} 1 - a_l \ln(\rho/\rho^0), & \rho > \rho^0 \\ 1, & \rho \le \rho^0 \end{cases} \tag{1}$$

where ρ^0 is the limit people density up to which people can move with a free movement speed (it means that the local density does not influence people's speed); a_l is the parameter of adaptation of people to the current density during their movement in different ways: $\rho^0 = 0.5$ person/m^2 and $a_1 = 0.295$ for the horizontal way, $\rho^0 = 0.8$ person/m^2 and $a_2 = 0.4$ for movement downstairs and $\rho^0 = 0.64$ person/m^2 and $a_3 = 0.305$ for movement upstairs; v^0 is the unimpeded (free movement) speed of a person; and ρ is the local density for a person.

In [14] and [15] speed versus density are given in the following ways correspondingly:

$$v^{WM}(\rho) = v^0 \begin{cases} 1, & \rho = 0 \\ 1 - \exp\left(-1.913\left(1/\rho - 1/\rho_{\max}\right)\right), & \rho < \rho_{\max} \\ 0, & \rho \ge \rho_{\max} \end{cases} \tag{2}$$

$$v^{SFPE}(\rho) = v^0 \begin{cases} 1 - \rho/\rho_{\max}, & 0 \le \rho < \rho_{\max} \\ 0, & \rho \ge \rho_{\max} \end{cases} \tag{3}$$

In Eq. (2) and Eq. (3), ρ_{max} is the acceptable maximum density. The original forms of the velocity-density dependences from [16] and [17] were transformed in the formulas to the explicit input ρ_{max} value, which was made a parameter. It was assumed that $\rho_{max} = 5.4$ person/m^2 in Eq. (2) and $\rho_{max} = 3.8$ person/m^2 in Eq. (3). Note that, in Eq. (1), $\rho_{\max}$ is not a parameter and cannot be varied.

However, Eq. (1) contains ρ^0 as a limit people density up to which people can move with a free speed.

Figure 3 shows the specific flows $\hat{J}_s = \rho v(\rho)$, (person/(m × s)), for Eq. (1)-(3) (curves KhS, WM, and SFPE, respectively; $v^0 = 1.66$ m/s).

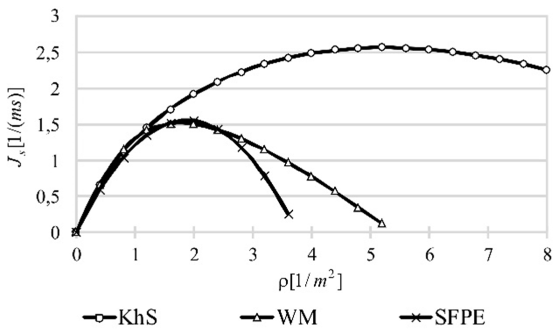

Fig. 3. Test 3. Specific flows for Eq. (1)-(3), $v^0 = 1.66$ m/s.

To see if the model reproduces this phenomenon, we consider the simulation experiment under the so-called periodic boundary conditions. A straight corridor 50 × 2 m in size with the control line in the right-hand side is the modeling area, Fig. 4. People uniformly fill the entire area.

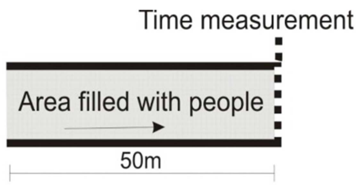

Fig. 4. Test 3. Geometry set up. Corridor 50 × 2 m in size, initial position of people (modelling area), and control line.

To reproduce the steady regime (periodic boundary conditions), the initial number of people N should be maintained. It means that when a person reaches the control line (leaves the modeling area from the right-hand side), another person with the same parameters appears from the left (i.e., the inflow should tend to the outflow value).

Time T required for M people (for example, $M = 1000$) to cross the control line at the end of the corridor at given N is a quantity to be measured. In the stochastic model, the time should be averaged over a set of K runs under the same initial conditions.

To estimate the flow rate, the formula $J = M / T$, (person/s) for each density $\rho = N / 100$ is used, where $T = \sum_{j=1}^{K} T_j / K$ is the average time over K runs required for M people to cross the control line. The corresponding specific flow is $J_s = M / T / 2$, person/(m × s).

In this test, the density $\rho = N / 100$ is used to estimate the distribution of people over the modeling area (grey area in Fig. 4) in the simulation experiment.

When comparing the simulation and reference data and interpreting the results, it is very important to pay attention to the acceptable ρ_{max} value in the mathematical model and reference data. For example, if a square of the person's projection in the model is assumed to be 0.125 m^2, the projection has the form of a circle with a radius of 0.2 m; then, we can put closed circles with $\rho_{max} = 6.25$ person/m^2. Thus, it is the most accurate to compare the simulation and reference data with similar ρ_{max} values.

As an example, let us now discuss the results obtained with the SigmaEva evacuation module. We considered a set of numbers of people $N_i, i = \overline{1,m}$ involved in the simulation. The corresponding densities are estimated as $\rho_i = N_i / 100, i = \overline{1,m}$, (person/m^2). Each person was assigned a free movement speed of $v^0 = 1.66$ m/s. All persons were assigned the same square of projection, specifically, 0.125 m^2.

Since the shape of a person's projection is a solid disc, the maximum number that can be placed in an area of 100 m^2 is 625 and the maximum density is $\rho_{max} = 6.25$ person/m^2. In accordance with the reference data, it was reduced (see below).

The SigmaEva evacuation module implements a stochastic discrete-continuous model [2-4], so a set of 500 runs for each $N_i, i = \overline{1,m}$ was performed and the average times were calculated: $T(\rho_i) = \sum_{j=1}^{500} T_j(\rho_i) / 500, i = \overline{1,m}$, where $T_j(\rho_i)$ is the time required for $M = 1000$ people to cross the control line in one run at given ρ_i.

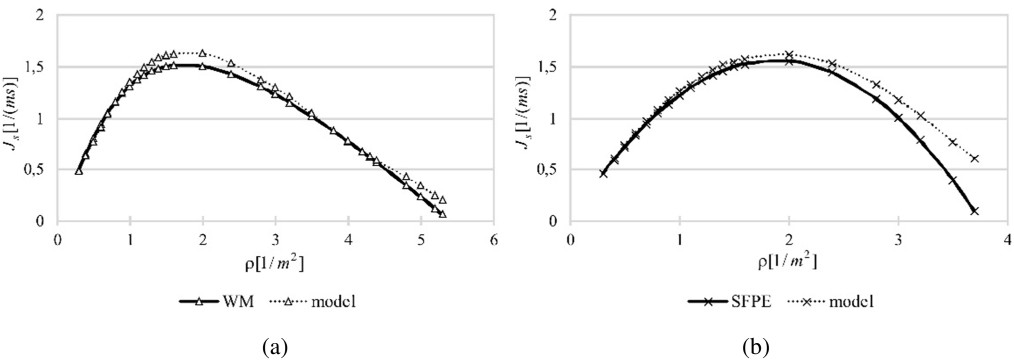

Fig. 5. Test 3. (a) Original Weidmann data ("WM") with $\rho_{max} = 5.4$ person/m^2 and simulation data ("model") with Eq. (2) as an input model data, $N_{max} = 540$ persons; (b) Original SFPE data with $\rho_{max} = 3.8$ person/m^2 and simulation data ("model") with Eq. (3) as an input model data and $N_{max} = 340$ persons.

Figures 5-6 show the specific flows as a function of density $\rho = N_i / 100, i = \overline{1,m}$. The simulation data are compared with the Weidmann, SFPE, and Kholshevnikov and Samoshin diagrams [10]. The Kholshevnikov and Samoshin data were obtained under similar real-life conditions and the same movement regime (the densities for these curves are given in the literature).

It can be seen that the data in the two figures are very similar. In both cases, $\rho_{max}^{model} > \rho_{max}^{data}$: 6.25 person/m^2 versus 5.4 person/m^2 in Fig. 5 a, 6.25 person/m^2 versus 3.8 person/m^2 in Fig. 5 b.

The other important factor is that the conditions of real experiments ensure the same body size at all densities. This is consistent with the model statement that the projections of persons are solid discs with a constant radius.

The Kholshevnikov and Samoshin data give a considerably higher flow at the middle and higher densities. Equation $v^{KhS}(\rho)=0$ gives $\rho_{max}=15$ person/m^2. This density can be obtained at smaller body sizes (square of projection) only. However, there is a lack of data on the impact of body size reduction.

In Fig. 6, the model reproduces the expected behavior of the specific flow under density variation: the flow J_s increases until a density of ≈ 2.5-3 person/m^2, attains a value of 1.7-1.8 person/(m × s), and then decreases.

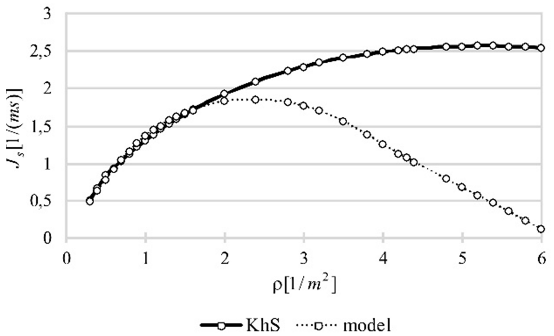

Fig. 6. Test 3. Kholshevnikov and Samoshin data ("KhS") and simulation data ("model") with Eq. (1) as an input model data; $N_{max}=600$ persons.

At the low and middle densities, the model flows agree very well with the real data. At the high densities, the model flow is much slower than the Kholshevnikov and Samoshin flow. This is apparently related to the strong impact of the constant square of a person's projection.

Table 1. Quantitative measures for results presented in Figs. 5-6

	Relative difference	Cosine	Projection coefficient
KhS	0.570195	0.852454	1.364238
WM	0.067695	0.998818	0.954949
SFPE	0.142952	0.992588	0.929509

To compare curves quantitatively one can use a method from [18]. There are three measures: Relative difference, Cosine, and Projection coefficient (Table 1). The first norm provides a measure of the difference in the overall magnitude for the two curves normalized to the experimental data. The norm approaches zero when the two curves are identical in magnitude. In the second, Cosine, the angle between the two vectors represents a measure of how well the shape of the two vectors match. As the cosine of the angle approaches unity, the two curves represented by the two vectors differ only by a constant multiplier. The third, Projection coefficient, provides a measure of the best possible fit of the two curves. When the projection coefficient approaches unity, remaining differences between the two curves are either due to random noise in the experimental measurements or physical effects not included in the model.

Figure 7 shows the velocity field for one simulation step at different densities. The length of each vector is the length of the person's shift in this time step. One can see a strong decrease in the step length (and, correspondingly, in the velocity) with increasing density. The directions of the vectors show that the model provides the expected movement direction.

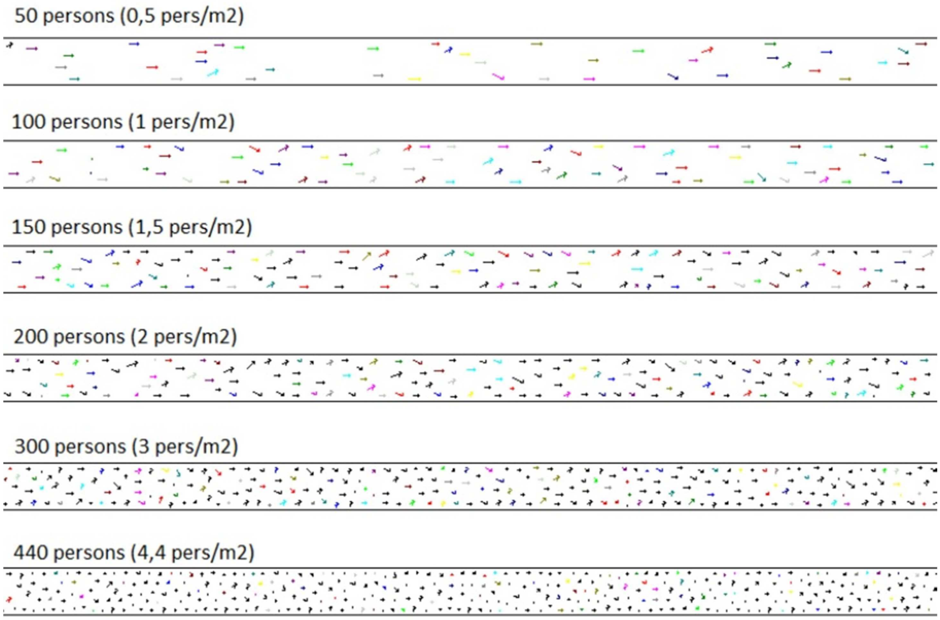

Fig. 7. Test 3. Screenshots of velocity fields in one time step for different densities.

CONCLUSIONS

The approach to validation of the pedestrian movement simulation modules was considered. The focus of the study was the velocity-density dependence as a self-organized phenomenon without influence of the simulation space geometry. Transition and steady-state conditions were considered.

The transition condition implies a flow transformation (spreading), which is pronounced stronger or weaker, depending on the initial density and available space, due to the interrelation between the velocity and local density. The tests for flow spreading and maintaining a free (unimpeded) movement velocity were considered for the first time.

The steady-state condition implies a constant density in the movement area, no flow transformations, and the speeds of individuals and flow controlled by the current density. In this regime, the velocities of individuals and flow coincide.

While people move from their initial positions to a destination, both conditions can be implemented and should be correctly reproduced by a model.

Another series of obligatory tests for checking the ability of a model to reproduce the movement component should be focused on the effect of geometry (bottleneck flows, movement around the corner, stairway case, etc.) on the model dynamics.

The correct simulation of people movement for each part separately is assumed to give the correct simulation for the entire path.

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