Pedestrian Flow Through Complex Infrastructure, Experiments, and Mass-Transport Processes

Pavel Hrabák, Marek Bukáček, Peter M. Kielar, and André Borrmann

Abstract Simple mass-transport model is used to describe the phenomenon of decreasing bottleneck flow during egress of pedestrians through complex infrastructure. The considered mass-transport model combines the macroscopic hydrodynamics approach with concept of queuing processes (thus belongs to the class of hand-calculation models). The realization of such process can be described by means of temporal evolution of the flow through individual bottlenecks and number of pedestrians in front of given bottleneck. These two state variables are used to compare the model prediction with experimental data from two original experiments. The commonly used approach of constant width-related bottleneck capacity cannot capture the observed decrease of flow caused by the loss of motivation while the room is getting empty. Therefore, the dynamical part of the bottleneck capacity derived from the slope of the temporal evolution of the crowd size has been introduced, in order to capture the phenomenon.

1 Introduction

Main goal of the pedestrian and fire safety engineering is to estimate the evacuation time, i.e., how long it takes before all people in the premises manage to leave it, a review of the concepts how to estimate the evacuation time, see, e.g., in [2]. One of the simplest ways how to calculate the evacuation time is to use the hydrodynamic approach and look at the crowd as it is a fluid. Such macroscopic methods are often referred to as "hand-calculation" methods since they are not based on simulations.

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For the applicability of such methods in evacuation time prediction we refer the reader to [5] or [6] and the references therein.

The hydrodynamics can be reduced to simple mass-transport model on the graph with vertices representing rooms (or rather exits) and edges representing possible routes between the vertices. Mass-transport process is based on the rules (usually probabilistic) of the transportation of part of the mass from one node to another. Theoretical description is summarized in [7, Chapter Three] and the references therein.

In order to use the hand-calculation method for evacuation time prediction, it is necessary to assign crucial parameters to individual elements of the network: the maximal flow intensity through the bottleneck, flow density relation (fundamental diagram) in the corridor, initial distribution of pedestrians, and others. A lot of experimental studies and their evaluation have been performed in order to capture such aspects, for review, see e.g., [6–8]. The study presented here leans mainly on the observation that the pedestrian flow through the bottleneck depends mainly on the bottleneck width, and hence rather smoothly due to the zipper effect. Since the experimental layout did not contain any corridor movement, the flow reduction due to the increasing density (the fundamental diagram) has not been considered.

In [8] the author suggested that the dependence of flow J on the bottleneck width w is linear and hence

$$J = 1.9 \cdot w\,. \tag{1}$$

The used mass-transport model, in more detail presented already in [4], is partially based on this assumption; however, we found out that the average flow through the bottlenecks was significantly lower in the second experiment than the first one (which was quite in agreement with Eq. (1)). Therefore, the characteristic flow C through the bottleneck was determined by means of the average flow through the bottleneck. Nevertheless, to exclude other external influence, it is reasonable to measure the characteristic flow in a steady state, determined by the levelling of crucial quantities as density, velocity, and flow [3].

It has been observed, see, e.g., [1], that the actual flow through the bottleneck is not given by the characteristic flow C only, but is influenced by the clogging size in front of the bottleneck as well. More precisely, while the crowd size is increasing, the flow is greater than C (maybe because more aggressive pedestrians are pushing forward), and while the crowd size is decreasing, especially in the last phase of the egress, the flow is lower than C (maybe because the loss of motivation or the less aggressive nature of the crowd). In such a case it is necessary to measure the actual flow in more smooth way than just counting pedestrians per time unit. The study on how to smoother the flow is presented in [9].

2 Experiments

Two original experiments, denoted as E5 and E6, were conducted at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague, namely in the lecture room T-201 and adjacent hallway. The pedestrian crowd consisting of second year students was rather homogeneous; however, differences in motivation to leave the premisses were observed.

The layout of the experiment is schematically depicted in Fig. 1. At the beginning of each trial, students were gathered in four groups at four staircases in the lecture room (level 3). After the given signal, students started to leave the lecture room. The pedestrian streams merged in front of the two exits (level 2). Both exits lead to one common vestibule with one main exit (level 1), through which the premises was left.

The experiments were recorded by several synchronized cameras, the main focus was given to the precise determination of the passing times through all seven involved exits denoted as $v_1, v_2, \dots, v_7$, see Fig. 1. Here we note that the exits v_1-v_4 were associated with the last step of the staircase and there was no bottleneck in front of them. Furthermore, the flow through these "leaves" of the tree was partially controlled by the experimenters (slowed down or speeded up) and differed trial after trial. The used hand-calculation model was then considered in the data-driven sense, i.e., the measured flow through the leaves was input to the estimation, for details see [4].

The number of pedestrians in front of the bottleneck and flow through given bottleneck were the main measured quantities used for analysis. It is worth noting that the experiments were not equivalent, slight differences were present. In experiment E5, pedestrians were already standing on the staircases during the initiation, contrarily in experiment E6, pedestrians were gathered under the staircases and had to climb the stairs up. This was reflected in the average flow and free-flow velocity of the pedestrians. For details see overview in Table 1.

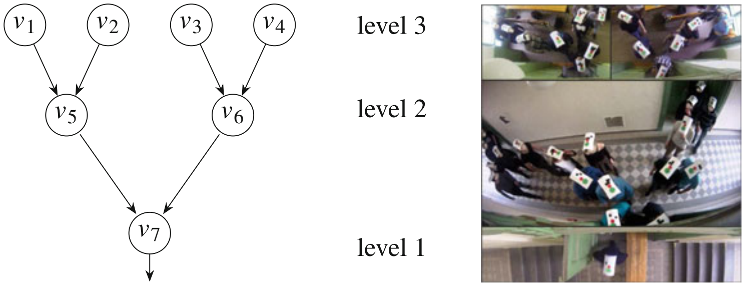

Fig. 1 Schematic illustration of the experimental layout. Students were leaving the lecture room via a tree-like structure of consecutive bottlenecks. The experiment was recorded by four cameras placed above the exits v_5 to v_7

Table 1 Experiment details

	Date	#part.	#trials	$\bar{T}_{evac}$	$\bar{V}_0$	$\bar{J}_7$	Note
E5:	07.03.16	54 ped	8 trials	43.2 s	1.7 m/s	1.45 ped/s	On staircases
E6:	20.12.16	53 ped	4 trials	49.7 s	1.4 m/s	1.25 ped/s	Below staircases

#part stands for number of participants, #trials for number of trials, $\bar{T}_{evac}$ for average evacuation time, $\bar{V}_0$ for average free-flow velocity, $\bar{J}_7$ for average characteristic outflow through the main exit

3 Estimation Method

The mass-transport process used to describe observed phenomena was developed under three main assumptions fulfilled by the experiment:

1. The capacity of individual rooms is never reached, i.e., the outflow from one room is not affected by the state in the consecutive room.
2. None part of the layout could be considered as narrow corridor, i.e., the flow intensity drop due to high density is not observed.
3. Pedestrians build a compact clogging in front of the exit.

Such assumptions enable to build a simple deterministic mass-transport process based on explicit/forward difference equations (the state in time t is calculated from the state in time $t-1$). The process is defined on the graph consisting in nodes $V = \{v_1, \ldots, v_7\}$ representing exits and edges $E = \{e_{15}, e_{25}, e_{36}, e_{46}, e_{57}, e_{67}, \}$ representing paths from one exit to another. The observable quantities are the actual flow $J_i(t)$ through the exit v_i and number of pedestrians $m_i(t)$ in the clogging in front of exit v_i. The model consists in coupled difference equations

$$J_i(t) = \min(m_i(t), J_i^c)\,, \tag{2}$$

$$m_i(t+1) = m_i(t) - J_i(t) + \sum_{\{j|e_{ji}\in E\}} J_j(t - t_{ji})\,, \tag{3}$$

where J_i^c is the capacity of the bottleneck, i.e., maximal possible flow through the exit v_i, depending mainly on the bottleneck width and shape; t_{ji} is the estimated time of a pedestrian to walk from exit v_j to the clogging in front of the exit v_i. The basic time step used in the difference equation was chosen as one second; however, the method can be used equivalently for arbitrary time interval: the longer the interval is, the smoother flow is observed; the shorter the interval is, the more sensitive is the prediction to fluctuations.

As the term capacity suggests, the maximal flow J_i^c has been considered constant in time accordingly to [4], i.e.,

$$J_i^c \equiv C_i\,. \tag{4}$$

Table 2 Calibrated values for vertices V

Exit	w [m]	$1.9 \cdot w$ [ped/s]	E5 C_i [ped/s]	E6 C_i [ped/s]
v_5	0.70	1.33	1.40	1.20
v_6	0.70	1.33	1.40	1.20
v_7	0.75	1.43	1.45	1.25

Table 3 Calibrated values for edges E

Edge	l [m]	E5 t_{ji} [s]	E6 t_{ji} [s]
e_{15}	3.3	2	2
e_{25}	1.7	1	1
e_{36}	1.7	1	1
e_{46}	3.3	2	2
e_{57}	5.7	3	4
e_{67}	4.1	2	3

As will be shown further, this assumption was not fulfilled by the experiment and dependence on other conditions is to be introduced. Furthermore, the experiments have shown that the capacity J_i^c cannot be considered as the geometric property of the bottleneck only (suggested by (1)), but reflects the crowd properties/motivation as well. Therefore, the values of C_i have been calibrated based on the average flow through given bottleneck over the time the bottleneck was saturated, i.e., there was a clogging of significant size in front of the bottleneck to maintain steady flow. The calibrated values used for prediction are given in Table 2. The value expected according to [6] is given for comparison as well.

Here we note that due to the list of assumptions given above the value of t_{ji} can be considered as fixed and the outflow from v_j as independent from the state of the target exit v_i. The value of t_{ji} has been estimated as

$$t_{ji} = \mathrm{dist}(v_j, v_i)/V_0 \,, \tag{5}$$

where the distance dist is the length of the shortest path between exits and V_0 is the expected desired free-flow velocity of pedestrians estimated from the data. As can be seen in Table 1, the average velocity has differed significantly among experiments, probably due to the different initial conditions (climbing up the staircase or not). The calibrated values of t_{ji} are given in Table 3. The value of t_{ji} has been rounded to the closer integer in order to fit to the difference equations without necessity of interpolation.

The comparison of the estimation model and the experiment was performed in the “data-driven” sense, i.e., the flow through the leaves $v_1, \ldots, v_4$ (level 1) was considered to be known (e.g. measured by kinects as suggested in [4]) and the measured flow served as the input to the mass-transport model. In order to do so, the input flow needs to be discretized, i.e., the mass of pedestrian flowing per each second to be expressed. Counting the number of passing pedestrian during each second is highly imprecise and “jumpy”. Therefore we used an interpolation approach for the flow estimation. More precisely, the cumulative flow function CFF has been defined as linear interpolation of the pairs (time of passing, number of pedestrians passed through given bottleneck). Then the flow $J_i(t)$ is given as $J_i(t) = CFF(t) - CFF(t-1)$. Such approach gives smoother flow and better sensitivity of the estimator to initial flow fluctuations.

It is worth noting that the values C_i and t_{ji} have been rather tuned to fit the experimental data. Of course, it would be beneficial to calibrate the estimation model to be applicable even in the case that only the geometric layout of the premisses is available, i.e., without the measurement of the characteristic flow and desired velocity. Such auto-calibration concept based on other information from the flow through the leaves may be subject to further investigation.

4 Observations

The goal of the estimation tool was to predict the observable quantities flow and occupancy at the main exit v_7. In Fig. 2 the time evolution of measured and predicted flow and occupancy is plotted. From the graph it can be observed that the overall

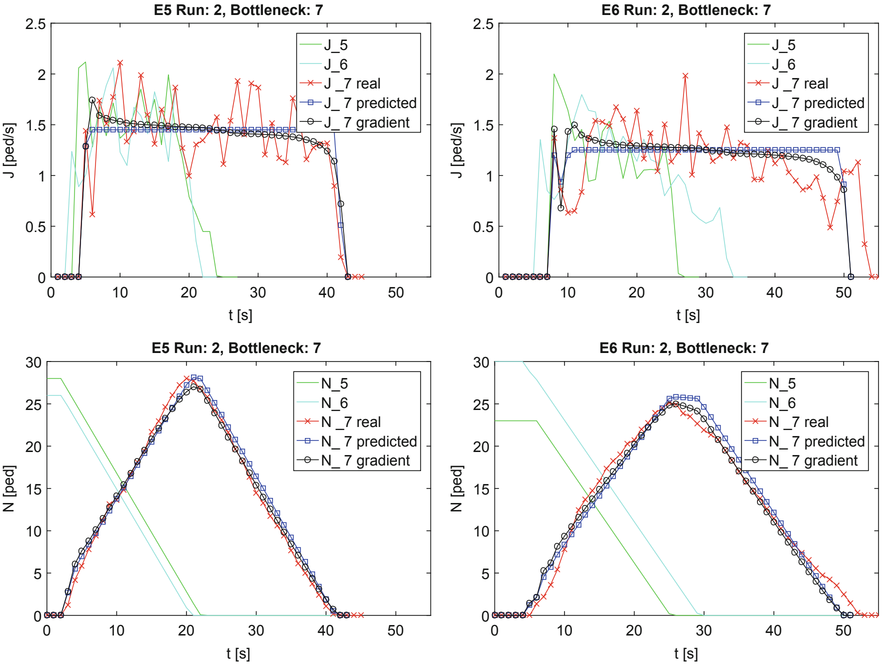

Fig. 2 Comparison of the actual flow (upper row) and actual occupancy (lower row) of the main exit v_7. The measured data (red crosses) compared with the constant flow prediction (blue squares) and the modified flow prediction (black circles)

flow and evacuation time are in a good agreement for both experiments. However, the estimation tool is not able to capture the increased flow at the beginning of the evacuation and the decreasing flow at the end of the evacuation.

That motivated us to introduce the dependence of J_i^c on the gradient of the mass $m_i(t)$, since it is observed that during the emptying of the room the motivation of pedestrians to leave is decreasing and therefore even the flow is decreasing. The suggested dependence is

$$J_i^c(t) = C_i + \frac{\mathrm{d}m_i(t)}{\mathrm{d}t} / m_i(t)\,. \tag{6}$$

The idea behind this equation is as follows. While the size of the clogging is increasing, pedestrians are more motivated to leave the room (or alternatively, more motivated pedestrians reach the door room faster than the less motivated) and therefore the flow through the door is higher. Contrarily, while the clogging size is decreasing and the room is getting empty, the pedestrians are less motivated to leave the room (or alternatively, more motivated pedestrians already left the room and less motivated pedestrians are leaving) and therefore the flow is lower. The slow-to-start effect plays an important role as well. Further, the flow through the bottleneck is less affected when the clogging size is high since the propagation of the information about the increasing or decreasing number of pedestrians is dampened by the crowd.

The constant C_i can be then characterized as the steady-state flow through given bottleneck. In the case of mentioned experiments, the steady-state like behaviour can be observed at the time between the increase and decrease of pedestrian mass $m_i(t)$. In the case of this study, the values of C_i for both approaches (4) and (6) can be chosen identical, since the estimation techniques give similar values of C_i.

The results are plotted in Fig. 2. The lower graph represents the number of pedestrians in the room, i.e., waiting in the clogging plus walking towards the clogging. The reason is that the actual size of the clogging cannot be derived exactly from the experiment records.

5 Summary and Conclusions

Main goal of this study was to describe some bottleneck flow phenomena using a simple “hand-calculation” method for evacuation time estimation. Contrarily to common approach, not only the evacuation time was examined, but even the temporal evolution of observable quantities as actual flow and number of pedestrians in the clogging in front of given bottleneck.

A simple mass-transport model based on difference equations has been used as the estimation tool. It has been shown that the estimated quantities are in quite good agreement with the experimentally measured data; however, some aspects cannot be captured by the classical concept of constant capacity of the bottleneck.

The presented experiments as well as earlier works evince significant decrease of the bottleneck flow at the end of the evacuation when the space in front of the bottleneck is getting empty. This phenomenon can be explained by the loss of motivation of the evacuees. On the other hand, the performed experiments have shown that the flow at the beginning of the experiment is higher that the steady-state flow causes probably by the fact that the more motivated pedestrians reach the bottleneck earlier than the less motivated.

To capture such phenomenon, the dependency of the capacity on the gradient of the clogging size has been introduced as given by Eq. (6). The comparison of the measured and predicted quantities given in Fig. 2 shows that such modification makes the estimation more accurate with respect to the temporal evolution of the quantities preserving the evacuation time and overall flow.

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