# Fluctuations in pedestrian evacuation times: Going one step beyond the exit capacity paradigm for bottlenecks

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**Abstract**

Building codes are often premised on the concept of exit capacity, i.e., the mean pedestrian flow rate through a bottleneck (at congestion). Thus, they rely on a deterministic vision of pedestrian flows through bottlenecks, at odds with the probabilistic nature of risk assessment. Here, I argue that one should duly take into account the evacuation time fluctuations when devising such guidelines. This is particularly true when the narrowing is abrupt and the crowd may behave competitively. I suggest a simple way to assess the extent of (part of) these fluctuations, on the basis of the statistics of time gaps between successive escapes through the considered bottleneck; the latter could be garnered by analysing recordings of future real evacuations or, perhaps, realistic drills. The proposed strategy is put to the test with a cellular automaton model, which confirms its validity in general. Some of its limitations are also brought to light: While moderate violations of the lower bound on fluctuations predicted by the relation are possible (but can easily be accounted for), in practice the main limitation will be the underestimation of the variability of actual evacuation times, as behavioural correlations in the crowd are overlooked. Still, from the vantage point of risk assessment, this first account of fluctuations represents a significant step forward.

*Keywords:* Pedestrian evacuation; pedestrian dynamics; clogging

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## 1. Introduction

Risk management requires to identify potential dangers and threats, evaluate their probability as well as their cost, and introduce control measures intended to reduce their negative impact. In the context of the design of buildings and public facilities, building codes should ensure that hazardous situations (whether it be a fire outbreak, an earthquake, a terrorist attack, etc.) are warded off by the possibility for the attendance to evacuate the premises quickly and safely, should such an emergency occur. In particular, corridors and doorways on the egress pathway must be wide enough to allow the occupants to egress without excessive delay and to reduce the risk of clogging at the bottlenecks. This plain condition is translated into a practical guideline by either prescribing minimal requirements in terms of width or setting the minimal standards (performances) that should be met with respect to the evacuation time.

Let us mention a few noteworthy examples, for illustration purposes. In the United States (for instance in Florida [1]) building codes prescribe a minimal clear width $w = \max\{813,\, 5.1\,N\}$ mm for doorways, where $N$ is the occupant load (note that $w$ is lowered to $\max\{813,\, 3.8\,N\}$ mm in suitably equipped low-risk buildings). In France, emergency exit doorways and corridors in public buildings must typically be larger than $\left(1 + \lceil \frac{N}{100} \rceil\right) \times 0.6$ m if $200 < N \leqslant 500$, where $\lceil x \rceil \in \mathbb{N}$ is the ceiling of $x$, or $\lceil \frac{N}{100} \rceil \times 0.6$ m if $N > 500$. French railway stations must be designed in such a way that they can be evacuated in less than 10 minutes. To evaluate the evacuation time, a walking velocity $v = 1.4\,\mathrm{m} \cdot \mathrm{s}^{-1}$ is assumed, along with a specific capacity $J_s = 1.67\,\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$, i.e., a maximal flow rate of 1.67 people per second per meter of corridor width (these figures are reduced to $v = 1.0\,\mathrm{m} \cdot \mathrm{s}^{-1}$ and $J_s = 1.0\,\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$ if it is a regional or national railway station) [2]. Finally, in the United Kingdom, the maximal evacuation time for sports stadiums is set to a value between 2.5 and 8 minutes, depending on the risks, and a specific capacity $J_s = 1.37\,\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$ is assumed for level walkways [3].

These guidelines are thus premised on the concept of exit capacity, or in other words mean flow rate. Not surprisingly, the values indicated in the above building codes are slightly lower, but comparable to the values measured in controlled experiments where participants were asked to walk through a bottleneck in normal conditions $J_s = 1.85\,\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$ [4] (but considerably lower than the values measured in controlled competitive conditions, $J_s \approx 3.6\,\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$ for a rather competitive flow through a narrow door [5]; $1.4 \leqslant J_s \leqslant 3.34$ (in $\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$) depending on the participants' eagerness to escape [6]). This underestimation can be interpreted as a safety margin, intended to absorb unforeseen delay. Nevertheless, from the vantage point of risk assessment, it is striking that these prescriptions rest on a purely deterministic vision of pedestrian flows, alien to the stochastic variability observed empirically.

In this contribution, I contend that the presence of significant fluctuations in strongly constricted flows, of diverse origins, may undermine this reasoning based on mean values (Section 2). Exclusively focusing on the time spent in narrow corridors and at bottlenecks, I argue that reasoning on the *distribution* of evacuation times would be more appropriate to develop risk management strategies. In Section 3 I propose a a simple method to roughly estimate the extent of the statistical fluctuations for an arbitrary number of occupants ($N$), on the basis of more readily accessible data. The method is then examined and put to the test in Section 4.

This paper is an extended version of the short report that I wrote for the *Proceedings of the 2017 Traffic and Granular Flow conference* (ed. Samer H. Hamdar, Springer) [7].

## 2. Beyond the mean exit capacity: Fluctuations

On account of its relevance for the development of evacuation strategies, the topic of pedestrian flows through bottlenecks (doorways, relatively narrow corridors, etc.) has been extensively studied; see for instance the references in the caption of Fig. 1. However, most of these studies focus exclusively on the mean flow values and overlook fluctuations, although a tentative parallel with constricted granular flows suggests that the latter are significant and even become prominent near clogging [8].

### *2.1. Empirical importance of fluctuations in bottleneck flows*

Empirical evidence supports the idea that fluctuations may be considerable. Lin *et al.* used mice as a model system and forced them to flee through a narrow orifice by filling their host chamber with smoke. They effectively observed that realisations conducted in virtually identical conditions exhibit significant dispersion, with standard deviations (std) that typically amount to 6% to 14% of the total evacuation time of about 90 mice, for a variety of settings [9, 10] (the lower bound was reached specifically in situations in which only 3 or 4 realisations were performed). Similar figures are found in the case of the entrance of 85 sheep into barn through a narrow gate, with an std-over-mean ratio of around 15% for the total time [11], and the importance of the dispersion of the evacuation times was underscored by the authors. Considering a crowd of about 90 participants walking through a narrow (69-cm-wide) door in a controlled experiment, the ratio was around 7%, with moderately competitive participants as well as with highly competitive ones [12]. (Note that the given std-over-mean ratios, summarised in Table 1, are the results of my own calculations using the data of the cited papers.)

Importantly, these fluctuations do not vanish when the constriction gets wider and may be very considerable if the crowd behaves frantically. A striking example is the huge clog that occurred in the running of the bulls during the 2013 San Fermín in Pamplona[1], when the people running in front of the bulls pushed so hard on the human clog formed at the entrance of the arena that, despite its being a few meters wide, not even a graspful of people could enter per second. This very large deviation from the mean flow rate is a sign of anomalously broad statistics.

[1] https://www.youtube.com/watch?v=OCKO0c6lihU

| System | # entities | $\frac{\text{std}(T_{\text{evac}})}{\text{mean}(T_{\text{evac}})}$ | Reference |
|---|---|---|---|
| mice | 90 | 6-14% | [9, 10] |
| sheep | 85 | 15% | [11] |
| pedestrians | 90 | 7% | [12] |

Table 1: Relative dispersion $\text{std}(T_{\text{evac}})/\text{mean}(T_{\text{evac}})$ of the global evacuation times $T_{\text{evac}}$ measured in controlled experiments of bottleneck flows using pedestrians and murine and ovine model systems (see the main text for details).

*2.2. Fluctuations in numerical simulations of bottleneck flows*

Considerable fluctuations are also present in numerical simulations of pedestrian evacuation dynamics. For example, Heliovaara *et al.* reported significant variations between runs made with their cellular automaton, in terms of the pedestrian flow rate or the number of egressees at a given intermediate time (see the error bars on the flow rate in Fig. 7 of Ref. [13] and the dispersion in the cumulative number of evacuees in Fig. 9).

The cellular automaton that my collaborators and I developed to simulate the dynamics of competitive escape through a narrow door also leads to strong fluctuations. This model supposes that each cell of a regular grid tiling space is occupied by at most one agent, who behaves either patiently or impatiently. At each time step, the agents endeavour to move to a neighbouring cell, with a preference for cells that are closer to the exit; the preference is much more marked for impatient agents, who most of the time attempt to step to the cell closest to the exit. If two or more agents compete for the occupation of the same cell, the resulting conflict, and the pushes to which it gives rise, is supposed sterile, with no winner (i.e., we consider the limit of strong friction). Further details regarding the model are provided in Appendix A. The cellular automaton was shown to capture the experimental data of Zuriguel et al. [5], in particular the heavy-tailed, power-law-like distribution of time gaps, *viz.*, $p(\Delta t) \sim \Delta t^{-\alpha}$ for large $\Delta t$, with $\alpha > 0$ [14]. (The agreement is semi-quantitative in the sense that, while the exponents $\alpha$ are captured fairly well, the flow rates are smaller by a factor 2 or 3, as compared to the experimental ones, because of the considered limit of strong friction.) Figure 2 shows how broadly distributed are the global evacuation times obtained in several hundred runs of this cellular automaton for the evacuation of 1,000 pedestrians (100 impatient ones and 900 patient ones) through a door of width $L_d = 1$ (*i.e.*, alllowing no more than one agent to go through the door at a time).

*2.3. Distribution of evacuation times*

The significant fluctuations in the evacuation dynamics underscored in the foregoing paragraphs undermine any reasoning based exclusively on mean values (such as the exit capacity). Indeed, should one only consider the mean global evacuation time (displayed as a cyan line in Fig. 2), a large fraction of the evacuations (those to the right of the line) will exceed the prediction. Even if the mean value is inflated by, say, 10% (corresponding to the red line) to make the norm safer, some evacuations will last longer than the prescription. In other words, knowing that evacuations are quick enough *on average* does not tell you how often they will be excessively lengthy. Accordingly, in the context of risk assessment, if one wishes to quantify the risks associated with too lengthy evacuations into a scalar cost function $\mathcal{C}$, a simple approach consists in weighting the cost $C(T_{\text{evac}}, N)$ (in terms of casualties, etc.) incurred if the evacuation of $N$ occupants lasts $T_{\text{evac}}$ with the probability $p_N$ of having $N$ occupants in the facility and the probability density $p_N(T_{\text{evac}})$ that the evacuation should last $T_{\text{evac}}$ in this case, viz.,

$$\mathcal{C} = \sum_N p_N \int C(T_{\text{evac}}, N)\, p_N(T_{\text{evac}})\, dT_{\text{evac}}. \tag{1}$$

(Of course, in practice, the approach should be refined to account for the fact that the cost $C$ does not depend only on the expected global evacuation time, etc.) It follows that it is of paramount interest to have an idea of the distribution of the evacuation times $T_{\text{evac}}$, beyond its mean value. This distribution corresponds to an ensemble of realisations, for a fixed number of occupants $N$ and a fixed geometry. This could in principle be done with numerical simulations (even though the resulting amound of data would be cumbersome), but

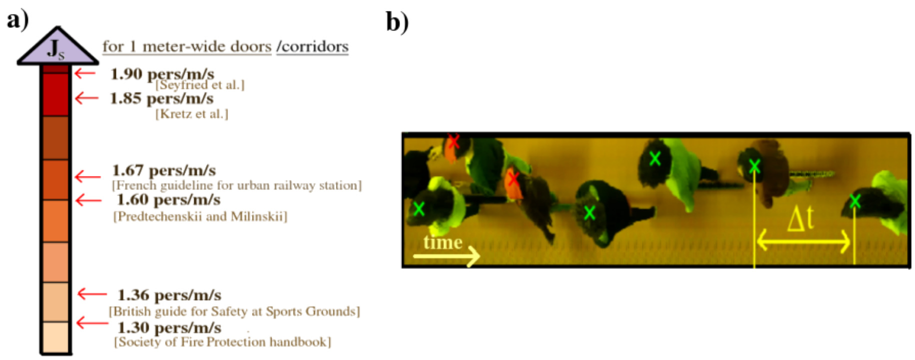


Figure 1: Pedestrian flow through a bottleneck. **(a)** Values of the exit capacity, *i.e.*, mean flow rate through an exit of unit width, reported in handbooks and academic publications [15, 3, 16, 4, 17]. **(b)** Time line of the bottleneck flow corresponding to the controlled evacuation experiments of Ref. [6], obtained by stitching together lines of pixels at the position of the door from successive video frames. The definition of the time gaps $\Delta t$ is explained on the picture.

it is *a priori* not clear how trustworthy the simulation results would be with respect to the fluctuations, or even how many simulations need to be run. On the other hand, for an empirical evaluation, it is completely unrealistic to expect the collection of such statistics for any $N$ and any geometry. In the following, I will propose a strategy to partly bypass this need.

## 3. A practical way to estimate a lower bound on the fluctuations in bottleneck flows

As a first step towards an assessment of the fluctuations, we need to gain insight into their origins.

### *3.1. Origins of the fluctuations*

*Statistical fluctuations..* First in line come the statistical fluctuations inherent in disordered systems. Indeed, the response of the crowd will always display some stochasticity, even in successive experiments performed on the same crowd and in the same conditions. This stochasticity stems from the possibly different initial positions of the participants, the inevitable variations in their individual responses, etc. These uncontrolled parameters induce statistical fluctuations, which are also present in the flow of purely mechanical systems (such as grains discharging from a silo) and particularly marked near clogging [18].

*Extrinsic variations..* In addition to these statistical fluctuations, further variations are expected in real evacuations. The composition of the crowd that might need to evacuate the building is not the same from day to day, which affects the flow rate: The latter has been reported to be larger for children than for adults, for a fixed door width, due to their smaller size [19]. Besides, their behaviours will also vary, notably depending on the conditions of the emergency, and it was shown that increasing the pedestrians' eagerness or competitiveness to egress, for instance, affects the flow dynamics and produces more intermittent (bursty) evacuation dynamics [5, 6].

### *3.2. Distribution of time gaps between successive egresses*

Having disentangled the origins of the fluctuations, I now propose a practical way to predict the statistical fluctuations of the global evacuation time.

Consider a given escape zone. Let $t_i$ be the time of the $i$-th escape (out of $N$) in a realisation of the evacuation and let $\Delta t_i$ be the time gap $t_i - t_{i-1}$, for $i \in [2, N]$. The premise of the approach is that it is possible to collect enough statistics about these time gaps to get a decent approximation of their distribution $p(\Delta t)$ for a typical crowd composition. This requires the observation of a reasonable number of real evacuations, which may be achieved in the near future, owing to the increased monitoring of public facilities. Alternatively, one may choose to perform evacuation drills in as realistic conditions as is ethically possible.

### 3.3. Micro-macro relation

To proceed, we remark that the total evacuation time of the $N$ occupants (*i.e.*, here, the delay at the bottleneck) reads

$$T_{\text{evac}}(N) = t_1 + \sum_{i=2}^{N} \Delta t_i.$$

If one focuses on the congested flow at the bottleneck, and thus sets $t_1 = 0$, $T_{\text{evac}}(N)$ can thus be regarded as a sum of $N' = N - 1$ variables drawn from the distribution $p(\Delta t)$. If we overlook possible correlations between successive time gaps, the distribution of $T_{\text{evac}}(N)$ is given by the following *micro-macro relation*, based on a convolution product $(*)$,

$$P_N\left(T_{\text{evac}}\right) = p^{*N'}\left(T_{\text{evac}}\right). \tag{2}$$

In particular, provided that the 'microscopic' distribution $p(\Delta t)$ has a finite mean $\overline{\Delta t}$ and a finite standard deviation $\sigma$, the central limit theorem implies that, in the limit of large attendance $N \gg 1$, $P_N\left(T_{\text{evac}}\right)$ is a normal law of mean $N'\overline{\Delta t}$ and of variance $N'\sigma^2$. Thus, we have managed to assess the global distribution $P_N\left(T_{\text{evac}}\right)$, whose direct assessment would require a hopelessly large amount of data because of its dependence on $N$, on the basis of the more accessible $p(\Delta t)$ [14]. This contribution from statistical fluctuations to the global variations of $T_{\text{evac}}$ provides a lower bound on the expected fluctuations.

## 4. Successes and limits of the micro-macro relation

In this section, we examine the validity of the micro-macro relation proposed in the previous chapter.

### 4.1. Validation within a simple model

Within the framework of the cellular automaton introduced in Section 2.2 (and further detailed in Appendix A), we run about 500 simulations of the evacuation of a crowd of $N = 1,000$ patient agents through a narrow door of width $L_d = 1$. From these simulations, we extract the statistics of the time

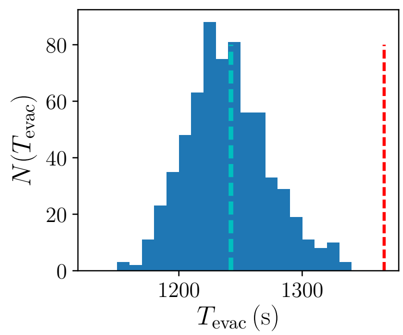


Figure 2: Histogram of global evacuation times through a very narrow door of width $L_d = 1$, simulated with the cellular automaton of Ref. [14] for a crowd composed of 1,000 people (100 impatient ones and 900 patient ones). The dashed cyan line represents the mean value $\overline{T}_{\rm evac}$ of the evacuation time, and the dashed red line corresponds to the inflation of this value by 10%, *i.e.*, $1.1\,\overline{T}_{\rm evac}$.

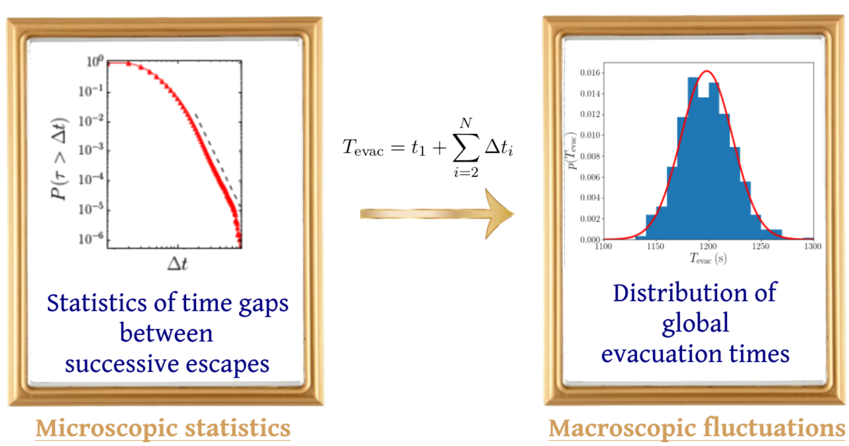


Figure 3: Sketch of the *micro-macro relation*, which takes as input the 'microscopic' statistics of time gaps $\Delta t$ at the door and predicts the global distribution of evacuation times $T_{\rm evac}$ for the $N$ occupants (the prediction is represented by the solid red line, while the histogram in blue shows the results of the numerical simulations.

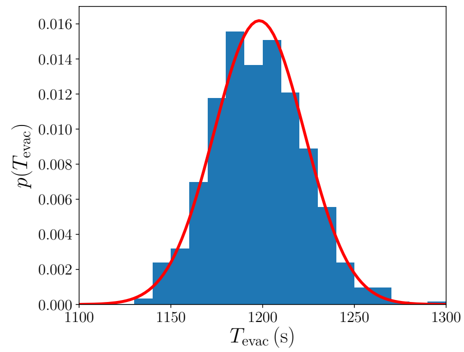


Figure 4: Distribution of global evacuation times $T_{\mathrm{evac}}$ of a crowd composed of $N = 1,000$ people (all patient) through a narrow door of width $L_d = 1$, obtained with the cellular automaton model. The solid red line is the prediction of the micro-macro relation, based on the 'microscopic' statistics of time gaps $\Delta t$.

gaps $\Delta t$ between successive egresses and use them to assess the distribution $P_N(T_{\mathrm{evac}})$ of global evacuation times on the basis of the micro-macro relation. This prediction is shown as a solid red lin in Fig. 4. We notice that it accurately matches the actual results of the simulations, thereby confirming the validity of the proposed relation in this context.

It naturally follows that, if one does not want to make use of the micro-macro relation and relies on the results of simulation software, enough simulations should be run to obtain a well defined distribution of evacuation times, with a standard deviation equal to at least that predicted by the micro-macro relation?

### *4.2. Rationalisation of possible (moderate) violation of the lower bound on the amount of fluctuations*

Next, we run simulations for a slightly larger door, of width $L_d = 2$ and once again compare the prediction of the micro-macro relation to the actual simulation results, in Fig. 5. Although the prediction looks acceptable, quite surprisingly, it seems to moderately overestimate the fluctuations of $T_{\mathrm{evac}}$; the lower bound on fluctuations thus seems to be violated.

To rationalise this moderate violation, we remark that the micro-macro rela-

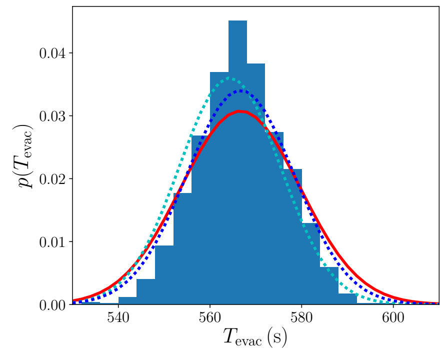


Figure 5: Distribution of global evacuation times $T_{\mathrm{evac}}$ of a crowd composed of $N = 1,000$ people (all patient) through a narrow door of width $L_d = 2$, obtained with the cellular automaton model. The solid red line is the prediction of the micro-macro relation, based on the 'microscopic' statistics of time gaps $\Delta t$ for individual pedestrians, while the dotted cyan and blue lines are the predictions obtained if successive egresses are clustered by groups of $n = 2$ and 3, respectively.

tion overlooks any temporal correlations between time gaps. At odds with this assumption, some degree of anticorrelation is widely observed in flows through a bottleneck. In Ref. [20], we demonstrated that this effect, which implies that long time gaps $\Delta t$ tend to alternate with short time gaps, is a very generic consequence of the possibility for two (or more) pedestrians coming from distinct directions or lanes to evacuate within a short time interval. These short-term anticorrelations reduce the level of fluctuations, but only to a moderate extent. This issue can be remedied easily, by reasoning on 'clustered' time lapse $\Delta t'$ for a graspful ($n$) of successive escapes, *e.g.*,

$$\Delta t'_i = \sum_{p=0}^{n-1} \Delta t_{i+p},$$

instead of the individual time gap $\Delta t_i$. The resulting predictions for $n = 2$ and $n = 3$ are plotted as dotted lines in Fig. 5. Clearly, this extension allows to better capture the amount of fluctuations and to mitigate the apparent lower-bound violation.

Another caveat lies with the assumption that the microscopic statistics $p(\Delta t)$

are independent of $N$. However, granted that $N$ is large enough (typically $N > 100$ for a narrow door [12]), this dependency can probably be overlooked (unless huge pressure builds up at the door, in which case pressure itself will cause a tragedy, regardless of the delay at the door). Indeed, in the controlled experiments that my colleagues and I performed (see [6] for details), the flow rate was not found to vary substantially when there were fewer people left in the room.

### *4.3. Factors leading to an underestimation of fluctuations*

In practice, instead of a violation of the lower bound given by the micro-macro relation, we expect that the actual distribution of global evacuation times will in fact be broader than what this relation predicts, even if one restricts their attention to the flow at bottlenecks. Indeed, extrinsic variations (in particular, variations in the crowd composition and in the behaviours of the people) are expected to significantly contribute to the fluctuations. Furthermore, since one deals with emergency conditions, another factor should be taken into account, which may lead to strong correlations throughout the crowd: social contagion and collective effects. Indeed, in an emergency, the nervous or aggressive behaviours displayed by some people (which may be referred to as 'panic', but perhaps improperly) may affect their neighbours and make them more nervous. If the crowd is very susceptible to fear, so that the contagion strength is high, contagion may pervade the whole crowd in some evacuations, while it remains latent in other ones, in which 'panic' did not nucleate [14]. The ensuing bimodal-like distribution of global evacuation times will strongly deviate from the prediction of the micro-macro relation.

## 5. Conclusion

To ward off risks in the event of an emergency evacuation, buildings should be designed with adequate means of egress, and the emergency exits should be unlocked, unobstructed, and clearly marked. Historical examples abound, in which an insufficient outflow capacity led to a crowd disaster. In this paper, I emphasised the need to take due consideration of the fluctuations in the flow rate, beyond its mean value (the exit capacity), in order to get a better idea of the probability of occurrence of excessively lengthy evacuations. A simple approach was proposed to extract a distribution of global evacuation times from the statistics of time gaps between individual egresses (which, unlike the global one, can potentially be compiled). The proposed micro-macro relation only takes into account the 'stochastic' (statistical) contribution to the fluctuations and therefore is only expected to bound by below the actual fluctuations. We found that, because of short-time anticorrelations between successive time gaps, the dispersion of evacuation times measured numerically could in fact sometimes be slighly smaller than this lower bound. However, in practice, it is likely that the micro-macro relation strongly underestimates the actual variability in the flow rate, due to unaccounted effects of crowd compositions and behavioural responses to the emergency. Nonetheless, in terms of risk assessment, this approach still represents a significant step forward with respect to the traditional use of a single flow rate value (e.g., an exit capacity of 82 persons per meter width per minute, according to the British Guide to Safety at Sports Grounds [3]). Finally, it is worth recalling that only delays due to congestion at the exit have been contemplated; these delays, as well as their variations, are naturally less marked when the doors are wider and the crowd scarcer.


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## Appendix A. Cellular automaton model

In this section, I recall the main rules of the cellular automaton model that was introduced in Ref. [14].

Space is discretised into a regular rectangular lattice, in which each cell hosts at most one agent. At each time step, all pedestrians start by selecting the site that they target among the adjacent cells (denoted $k$ and including the present one). A move from site $i$ to site $j$ has probability $p_{i\to j} \equiv e^{\frac{A_j - A_i}{x}} / \sum_{\langle i,k\rangle} e^{\frac{A_k - A_i}{x}}$, where $A_k$ is the attractiveness of the site (how close it is to the exit) and the noise intensity $x = 1$ has been introduced to avoid the artifacts caused by strictly deterministic moves. If the target site is occupied or if other people have selected it as target site and are therefore competing for it, the agent simply waits. Otherwise, (s)he moves to the target site. Following this round of motion, some sites have been vacated. This allows other agents to move to their target cell. The round is iterated until all possibilities of motion have been exhausted. The limit of strong friction considered in the model is noteworthy: As soon as two or more agents are competing for a site, the conflict is sterile and nobody can move. Further details can be found in [14].

Simulations showed that this model is able to capture the exponential distributions of burst sizes (*i.e.*, egresses in rapid succession). But adding one last ingredient was crucial in order to replicate the heavy tails in $p(\Delta t)$, namely, some amount of disorder. This was achieved by introducing behaviours: Each agent ($i$) is endowed with a propensity to cooperate $\Pi_i \in ]0,1[$. At each time step, this propensity determines whether agent $i$ cooperates (which occurs with probability $\Pi_i$) or not. Nothing changes if the agent behaves cooperatively. In the opposite case, the agent is impatient to move to another site, so (s)he undervalues the attractiveness of the current site, *viz.,* $A(x_i, y_i) \overset{\text{impatient}}{\longrightarrow} A(x_i, y_i) + \frac{1}{2}\ln \Pi_i$.