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# Developing a New Microscopic Approach to Evacuation Modeling by Measuring the Biomechanical Processes and Cognitive Components of Pedestrians Walking in Close Proximities

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This article presents the findings of experimental work which underpins the development of a new approach to modeling evacuation. We intend that this model can be used in the future to more precisely and accurately model the movement of individuals, characterize complex crowd dynamics, and contribute to the design of safe buildings and infrastructures.

**Why do we, as fire engineers, need a new approach to modeling the crowd?**

A fire-engineered approach to means of escape provision is based on the concept that, for a safe evacuation, the Required Safe Egress Time (RSET) should be less than the Available Safe Egress Time (ASET) with an acceptable margin of safety (BSI, 2019). Many of the assumptions and data that underpin the means of escape provisions, and indeed many evacuation models, have their origins in empirical studies conducted in the 20th century and established so-called 'fundamental' relationships between speed/ density/ flow (Fruin, 1971, Predtechenskii and Milinskiĭ, 1978, Pauls, 1995). However, these relationships are variable and have been questioned by their originators, who suggest that they may not necessarily reflect the movement dynamics of building populations today or in the future (Pauls et al., 2007). It is, therefore, important, moving forward, that we shift from what is essentially a top-down approach to a bottom-up approach to representing crowd movement. The long-term objective is to more precisely and accurately reflect the movement of individuals of different demographics within a crowd and fully represent the complexities of walking in a congested space.

**A new model to predict crowd movement more precisely**

In recent years, the use of computer evacuation models as part of fire-engineered solutions for the design and construction of new buildings has proliferated, while the underlying modeling techniques have not undergone any major changes. One new proposed model is the "movement adaption model," developed by Thompson et al. (2020a), which is based on a series of pedestrian and biomechanical experiments (Thompson et al., 2020b). This model characterizes the space occupied by an individual during single-file walking as the sum of the maximum 'step extent' (maximum front toe to the back heel distance of an individual) and the minimum' contact buffer' (the minimum space left between two consecutive pedestrians, the front toe of the person behind to the back heel of the person in front in this case) with their leader in each gait cycle. The model is presented in Figure 1 and Equation 1.

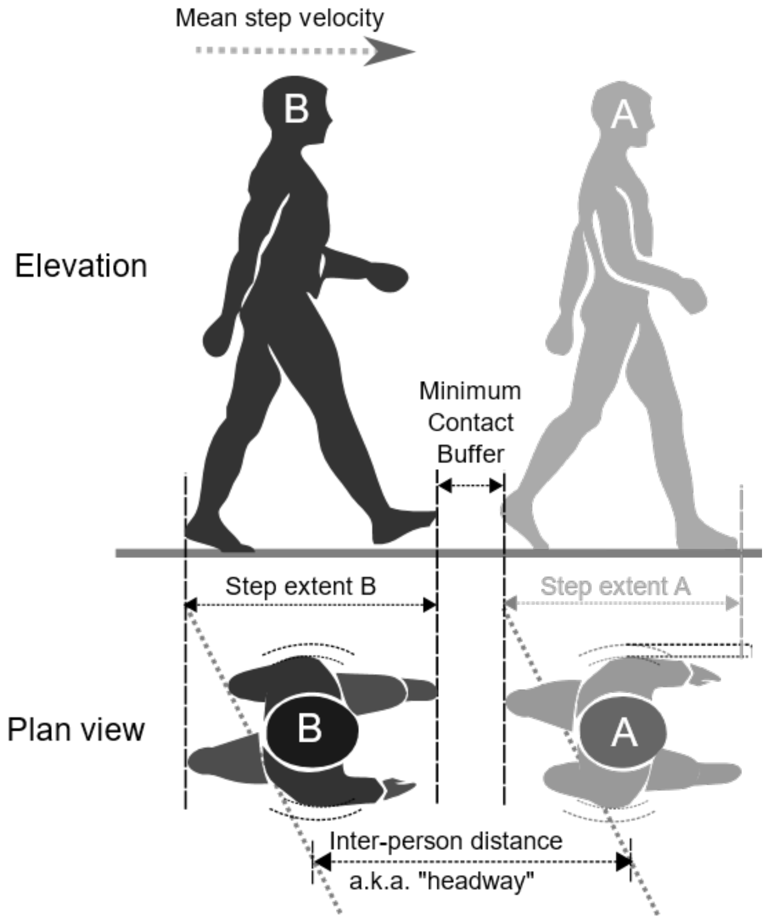


**Figure 1- Pedestrian movement components with the presence of others reproduced from Thompson et al. (2020a)**

Basic analyses:

During the gait cycle $C_b = \min(C_d)$ (1-a)

$S_{e(max)} = A(S_l+f_l)$ (1-b)

$d = S_{e(max)}+C_b$ (1-c)

Finally:

*Sum of linear distance components*

*Max. step extent* | *Contact buffer*

*Step* | *Foot*

*Walking with contact buffer above the minimum: where* $C_{b(min)} < v \times T_a$

$$d = A\left( s_u \left(\frac{v}{v_u}\right)^{0.631} + f_l \right) + (v \times T_a) \quad \text{(1-d)}$$

*At standstill or low speeds where contact buffer determines personal space*: $C_{b(min)} >= v \times T_a$

$$d = A\left( s_u \left(\frac{v}{v_u}\right)^{0.631} + f_l \right) + C_{b(min)} \quad \text{(1-e)}$$

*$v$ is walking speed (m/s)*
*$d$ is inter-person distance, at a given speed(m)*
*$A$ is step extent factor =0.92*
*$f_l$ is foot length allowing for footwear(m)*
*$C_d$ is contact distance*

*$v_u$ is unimpeded walking speed(m/s),*
*$s_u$ is unimpeded step length(m),*
*$T_a$ is contact adaption time (s)*
*$C_{b(min)}$ is minimum contact buffer(m)*

**Eq. 1- Movement adaption model reproduced from Thompson et al. (2020a) and Thompson et al. (2022)**

**Experimental work to confirm the model in a steady-state condition**

Experimental trials were conducted at Lund University, Sweden, and University College Dublin (UCD), Ireland. The main objectives of our experimental work were to (1) gain a deep understanding of the gait characteristics of individuals walking in a steady flow, (2) confirm and quantify the model parameters; in particular, we set out to test the hypothesis that the inter-person distance (the space between two consecutive pedestrians) could be decomposed and represented by the sum of the maximum step extent and contact buffer in each step, (3) validate the model presented above, specifically equations 1-a to 1-c.

In the Lund experiments, participants walked in a circuit with different starting densities (0.92-2.87 person/m) that restricted their gait and speed (Figure 2a). Their movement over the 4 m straight section of the circuit was recorded by two video cameras. In the UCD experiment, participants walked in groups of four with their speed being controlled in the range (0.2- 1.7 m/s) by a researcher who was the foremost person in the group and another researcher at the back of the group (Figure 2b). The precise movement of the participants was recorded by using 3D motion capture devices (Codamotion), i.e., small devices attached to their foot, hip, and shoulder, which can be tracked by high-resolution cameras to millimeter accuracy in 3D.

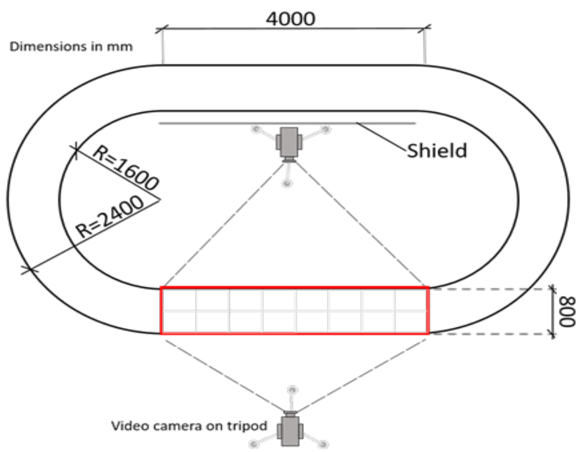


**Figure 2a- Lund single file experiments**

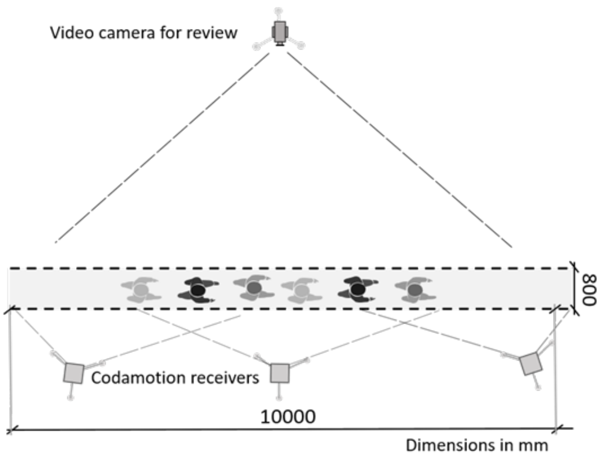


**Figure 2b- UCD experiments**

Tracking the feet, hips (in Lund trials), and shoulders (UCD trials) of individuals enabled us to extract the gait parameters (step length, step extent, speed) of each individual and distances between individuals (contact buffer, inter-person distance) in each step.

The step extent, contact buffer, and inter-person distance (banded by speed to compensate for sampling bias) are illustrated in Fig 3a, 3b, and 3c, respectively. Figure 3a shows that in both experiments, the step extent increases as the speed increases. It is clear, however, that the step extent in the UCD trials (shown in red) was greater than the Lund trials (shown in blue) for lower speed bands (up to 0.7 m/s). The possible reason for this may be the different protocols adopted in the experiments; in the UCD experiments, individuals were less pressured to move forward, and this led to a tendency for stop-and-go movement to have more space in front whilst, in the Lund experiments, people shuffled forwards by a few centimeters when space was available and also shuffled their feet forwards and back occasionally. Figure 3b illustrates that the contact buffer, i.e., the minimum contact distance between a follower and a leader, in both experiments was fairly constant at the lower speed bands, i.e., up to 0.4 m/s for Lund (blue line) and 0.7 m/s for UCD (red line) after which it increased linearly with speed. This could be due to people leaving more space in front to have enough time to react to the changes in speed when moving at greater speeds. It is also evident that in the Lund experiment, at the lower speeds, when the density was relatively high, and pedestrians were in very close proximity, the contact buffer was sometimes negative, i.e., representing an overlap between the steps of the followers with the person in front. Finally, Figure 3c shows that as speed increases, the inter-person distance increases. The intercept in this figure is the minimum inter-person distance at the standstill condition, and the gradient reveals the sensitivity of the follower to the distance from the leader in both experiments. Whilst there are differences between the results of the Lund and UCD experiments, due to the different protocols (in Lund, the speed and inter-person distances were an artifact of the density whilst in UCD, the speed was controlled by the researcher ahead of the group and the inter-person distance was chosen by the participant), they do provide important insights into these relationships which can inform the model moving forward.

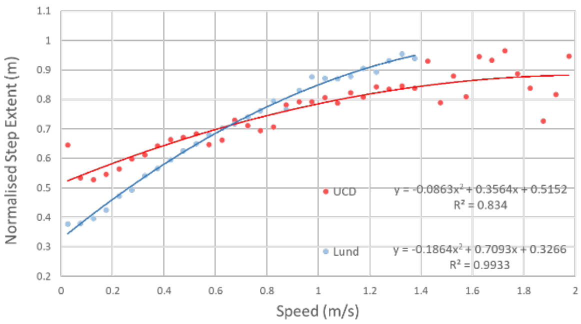


**Figure 3a- Step Extent banded by speed**

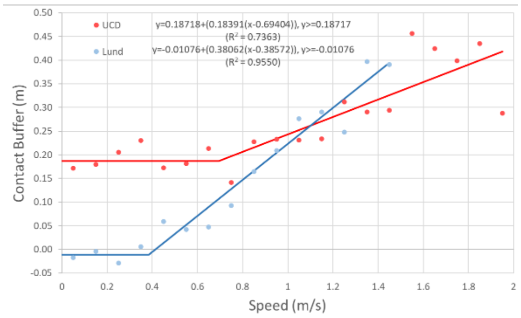


**Figure 3b- Contact Buffer banded by Speed**

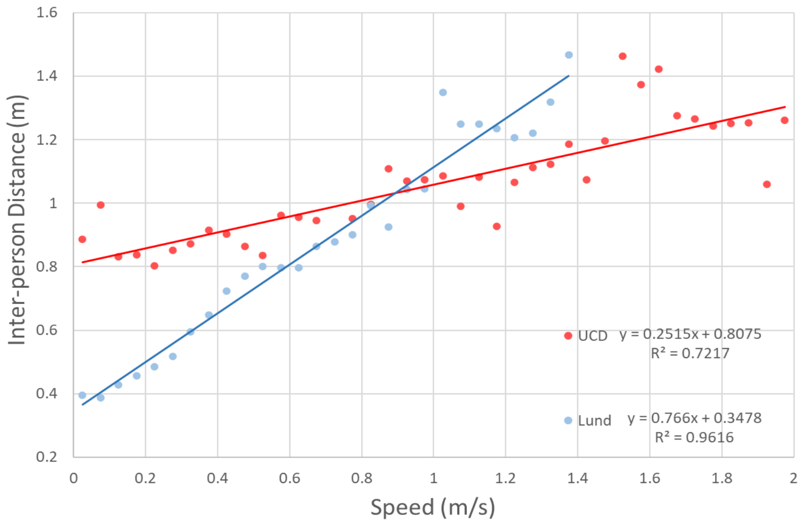


**Figure 3c- Inter-person Distance banded by speed**

As noted previously, one aim of the experiments was to confirm the premise of the model, i.e., that the distance between two individuals (inter-person distance) could be considered as the sum of the contact buffer and step extent. Figures 4a and 4b compare the sum of the average step extent and contact buffer in different speed bands with the measured inter-person distance for the Lund and UCD experiments, respectively. These figures show an encouraging alignment between the sum of the maximum 'step extent' and 'contact buffer,' and the measured 'inter-person distance,' especially given that we know that there will be some experimental errors causing a few centimeters variation.

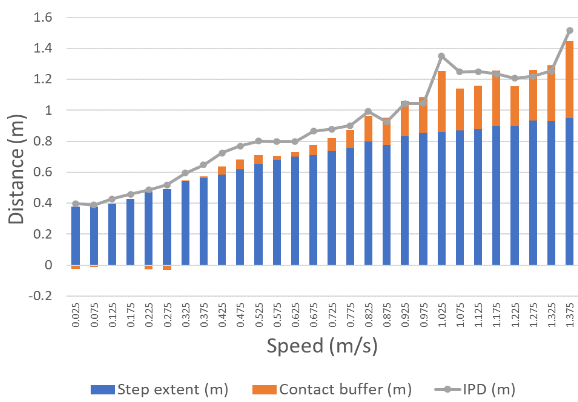


**Figure 4a- Lund**

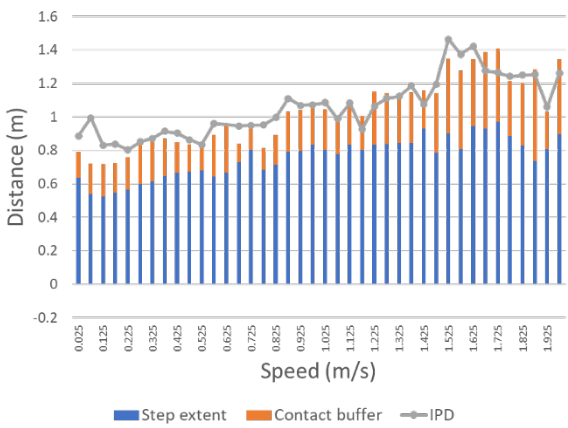


**Figure 4b- UCD**

**What about the reactions and interactions of individuals in the case of an interrupted flow?**

In Equation 1, we presented a parameter' $T_a$' which is the 'contact adaption time;' this is the time required by the follower to react and adjust their pace or stop in response to the speed changes or the stop of their leader. However, there is a gap in knowledge with respect to the reaction of one person to the speed changes of a person directly ahead. The reactions and stop/start walking process of individuals were, therefore, also explored in the UCD experiments where, in some trials, the researcher ahead of the participants stopped without notifying the other participants and 'interrupted' their walking. The interruptions were included in trials where the leaders' speed was 0.5, 1.0, and 1.3 m/s but were randomized with uninterrupted scenarios to ensure that the stops were unpredictable.

In our analysis, we were inspired by the approach adopted in vehicle traffic studies which break down the stop/start walking process into two phases; 'perception-reaction time' and 'slow-down time.' The 'perception-reaction time' is the time taken for individuals to perceive a change in speed of a person in front and start changing the speed, and the 'slow-down time' is the time taken to biomechanically react accordingly and come to a stop. Due to the high frequency of the data recording (100 frames/second), we first had to define a 'stopped state' for each individual; this was defined as being when their speed dropped below 0.2 m/s, which was characterized by a 2 mm movement in each frame. We then developed a novel approach to understanding when and where the follower reacted to the speed reduction of their leader by considering the relative inter-person speed along with the inter-person distance, Figure 5.

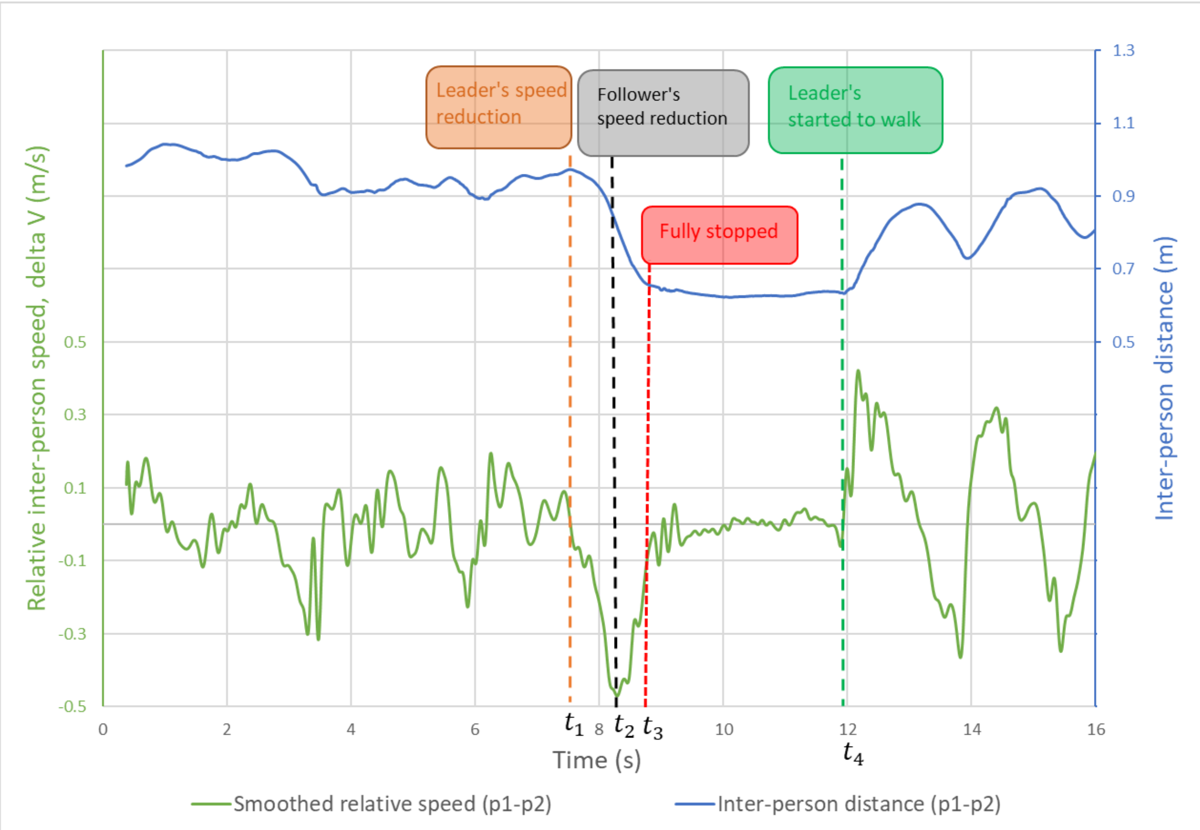


**Figure 5- Inter-person distance and smoothed relative speed vs. time**

In Figure 5, it can be seen that at $t_1$, i.e., the moment when the leader starts to reduce their speed, the relative speed (shown in green) is zero m/s and after that moment, i.e., when the leader is slowing down, but the follower has not yet perceived or reacted, both the relative inter-person speed and inter-person distance (shown in blue) reduce. The decrease in both parameters continues until $t_2$, i.e., the moment that the follower reacts by starting to reduce their speed to avoid a collision. Indeed, at $t_2$, the relative inter-person speed reaches its own minimum and then increases, while the inter-person distance is still decreasing because the speed of the leader is still less than the speed of the follower. This continues until $t_3$, i.e., the moment that both follower and leader stop and is then constant until $t_4$, i.e., the moment that the leader starts to walk again.

We have, therefore, characterized the stopping process of individuals with different timed components in a similar way to traffic analysis; $t_1$ (the speed reduction of the leader), $t_2$ (the reaction moment and start reducing the speed of the follower), and $t_3$ (extracted full stop of both). The stopping process, therefore, can be characterized by the perception-reaction time, which is calculated as $t_2 - t_1$, and the slow-down time which is calculated as $t_3 - t_2$. The time interval between two consecutive individuals to start walking again was also defined as the start-up time delay showing the required time for the follower to react to the start walking of their leader.

The mean perception-reaction time, slow-down time, and start-up time delay for the participants are given in Table 1.

**Table 1- The Quantified Stop/Start Walking characteristics**

| | Mean (s) | S.D. (s) |
|---|---|---|
| Perception-reaction time | 0.48 | 0.25 |
| Slow-down time | 0.58 | 0.31 |
| Start-up time delay | 0.39 | 0.22 |

Table 1 shows that the mean perception-reaction time is significantly less than the slow-down time (p-value =0.006) and has a lower standard deviation. This means that, for individuals, it took less time to perceive and start reacting to the speed changes of their leaders than to slow down and stop. It is possible that these times may be related to speed, i.e., at higher speeds it takes more time for individuals to slow down and stop. The start-up time delay is similar in concept to the perception-reaction time, i.e., both parameters reflect the time taken by individuals to perceive and react to the movement changes of their leader, i.e., starting up after a stop and slowing down in reaction to a stop, respectively. Table 1 shows that the mean start-up time delay was slightly smaller than the perception-reaction time (p-value = 0.095) and had a smaller standard deviation. It is thought that these differences may be due to differences in focus and expectations of a change in the movement of the leader, biomechanical differences in the stop and start walking process, and the different mental workload while walking compared to the standstill condition.

The novel methodology presented above and extracted values from the experiments are expected to be of interest to researchers and can inform the development of novel models that can predict changes in the gait cycle of individuals in different conditions.

**What are the next steps?**

Looking towards the future, the original steady-flow 'movement adaption' model (Thompson et al., 2020) becomes a 'contact adaption' model with these new stop/start timed components. The model seeks to utilize the microscopic characteristics of individuals moving in a crowd and has the potential to be developed to predict the movement of different cohort demographics, conditions, and densities. However, more effort needs to be put into collecting more empirical data to calibrate and develop the model.

Future experimental work will explore the movement of individuals across different age ranges, and walking abilities, in different conditions, both in a single line and wider flow. Additionally, the cognitive reactions of pedestrians to any deceleration and acceleration, i.e., not simply stopping and starting, of the nearest obstructing person (leader) should be investigated.

**Note:** This paper is a summary of Hossein Tavanarezaei's PhD project entitled "Investigation into the microscopic characteristics of pedestrian movement in congested space". The results have been published in the paper entitled "Experimental analyses of step extent and contact buffer in pedestrian dynamics" (Thompson et al., 2022), and two other papers entitled "An Analytical Approach to the Quantification of the Stop/Start Process in Pedestrian Flow" submitted for presenting in TRB conference and another paper entitled "A novel approach to the investigation and quantification of the stop/start process for pedestrian traffic using motion capture devices" is currently under preparation.

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