

COUNTERFLOW IN COMPUTATIONAL EVACUATION MODELLING - THE HYDRAULIC MODEL, MODELLING TOOLS AND TRIALS

Matt Arnott¹, Michael Spearpoint¹, Steve Gwynne², Anne Templeton³

¹OFR Consultants, Manchester, UK

²Movement Strategies, London, UK

³University of Edinburgh, Edinburgh, UK

E-mail: matthew.arnott@ofrconsultants.com

ABSTRACT

The hydraulic model calculates the flow through a door constriction for a unidirectional flow of people primarily based on physical constraints. The method requires the physical door opening width to be reduced by a boundary layer adjustment to determine the effective width. However, the hydraulic model does not provide any guidance on what the flow might be when there is a counterflow condition. One option might be to simply represent counterflow with an equivalent half-door opening effective width.

This paper compares the results from two agent-based, computational evacuation tools (Pathfinder and Evacuationz) to assess counterflow against the hydraulic model and data collected from people movement trials. The trials consisted of around 90 people travelling through an open doorway to generate unidirectional and counterflow scenarios. The trials also investigated how group identity might affect the counterflow measurements by gathering data when such identity was present or absent. Results suggest that the flow through the doorway in a given direction under counterflow conditions is greater than assuming half of the unidirectional flow. There appears to be an effect when in-group psychological behaviour is introduced such that the flow can show an overall increase when compared to having random groups. However, should participants interact then the in-group counterflow also exhibits a greater variability.

INTRODUCTION

The hydraulic model [1] has an equation to calculate the maximum expected flow through a door constriction for a unidirectional flow a people. The method requires the width of the door to be known and the effective width then determined by reducing the width by a boundary layer adjustment of 150 mm each side. However, the hydraulic model does not provide any guidance on what the flow through a door might be when there is a counterflow condition.

The purpose of the trials presented herein are to measure counterflow and to assess the results against the hydraulic model and two agent-based, computational evacuation tools. The paper examines whether counterflows can be simply represented as the equivalent half door width in the hydraulic model.

Furthermore, the trials investigated whether group identity may influence counterflow and whether having people identify themselves as being in groups affect the flow. The trials used the concept of

minimal group paradigm originally created by Tajfel, Billig, Bundy & Flament [2]. More recently Templeton et al. [3] used a similar approach in their counterflow trials. They found that members of a psychological group reduced their walking speed and increased their distance walked to move in closer proximity to members of their social group (in-group members), and this effect was increased when in the presence of another psychological group (out-group members) walking in counterflow.

Heliövaara et al. [4] note that counterflow situations are not common in emergency evacuations in which people are usually moving in the same direction. However there maybe instances where some of the people are moving against the predominant flow such as emergency response personnel entering the building.

PREVIOUS WORK

ISO 20414 [5] includes a counterflow verification test which assesses the impact on evacuation times for different ratios of agents in two-room and single corridor arrangement.

Heliövaara et al. [4] previously evaluated the counterflow capability in FDS+Evac [6] through a modified version of the social force model. The work evaluated counterflows through a corridor comparing FDS+Evac against versions of Simulex and the MASSEgress simulation tools. The corridor configuration was specified by the IMO Guidelines, equivalent to that given in ISO 20414 [5].

Kretz et al. [7] present the results of a counterflow experiment in a corridor. It was found that in counterflow scenarios the flux (or flow) of participants was slower than that observed in scenarios without counterflow, as would be expected. However, for the scenario with 0.5 counterflow (i.e., an equal number of participants walking in opposing directions), the resulting flux was larger than half of the flux in the corresponding scenario without counterflow, as one might postulate. Kretz et al. attributed this to the participants seemingly being able accept higher densities and use the space more efficiently. Lane formation, whereby participants opt to follow behind those in front that are moving in the same direction, was noted with these lanes either remaining steady for a period of time or disappearing, merging and splitting again.

Isobe et al. [8] and Nagai et al. [9] have previously investigated counterflow by experiment and simulation for pedestrians walking and crawling along a corridor. An extended version of the lattice gas model is used to compare to the experiment results with the model able to replicate, quantitatively, the pedestrian behaviour observed in the experiments. The results indicate that the arrival time is a function of the occupant density in the space, as would be expected. Lane formation was also observed in the experiments and was replicated in the simulations.

TRIALS

Methodology

A series of trials were undertaken to investigate the flow through a constriction (door) in unidirectional and counterflow conditions. The trials were part of an author-initiated company team-building exercise in which participation was voluntary. Between 88 and 91 participants took part in the trials, and this varied as a small number of individuals did not take part in every trial for various reasons. The age distribution of the participants is shown in Figure 1 with the median age being 30 yrs and the mean 30.2 yrs. Approximately 72% of the participants were male and the remainder female. None of the participants had any specific movement vulnerabilities; however, two participants were heavily pregnant (although one of the two only participated in a limited number of the trials). Groups of participants were generally known to each other as they came from the same working environment.

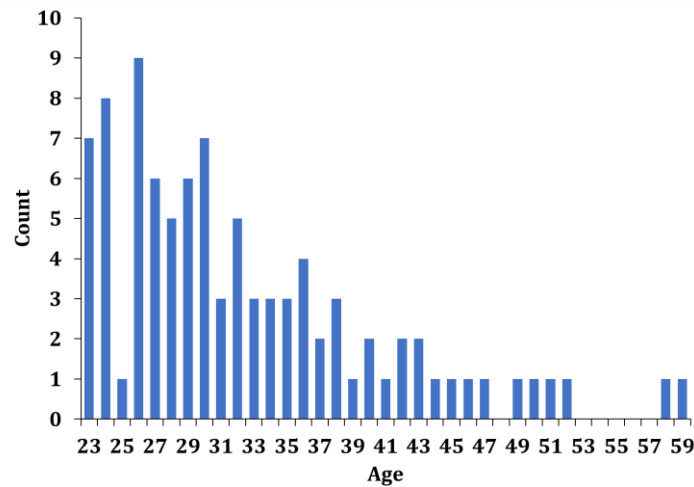


Figure 1. Participant age distribution.

The full-height door used in the trials was 1,720 mm wide and consisted of two leaves that were permanently held open. Touch-screen logging devices were used to measure the flow. Participants simply had to hit the screen as they passed the devices which then recorded the time and incremented a counter. A sound was played to indicate to the participant that their action had registered. It is possible that a small number of participants had double-pressed the screen or had not sufficiently touched the screen to register, however the videos showed these were rare instances. The trial arrangement is shown in Figure 2.

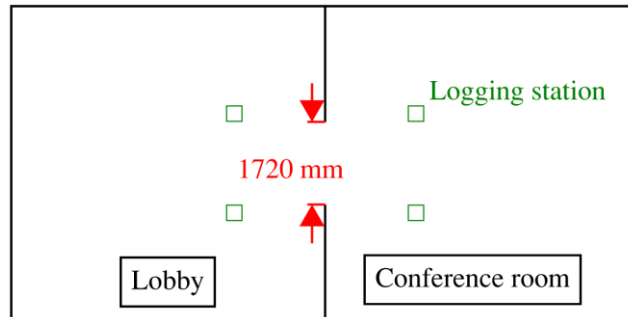
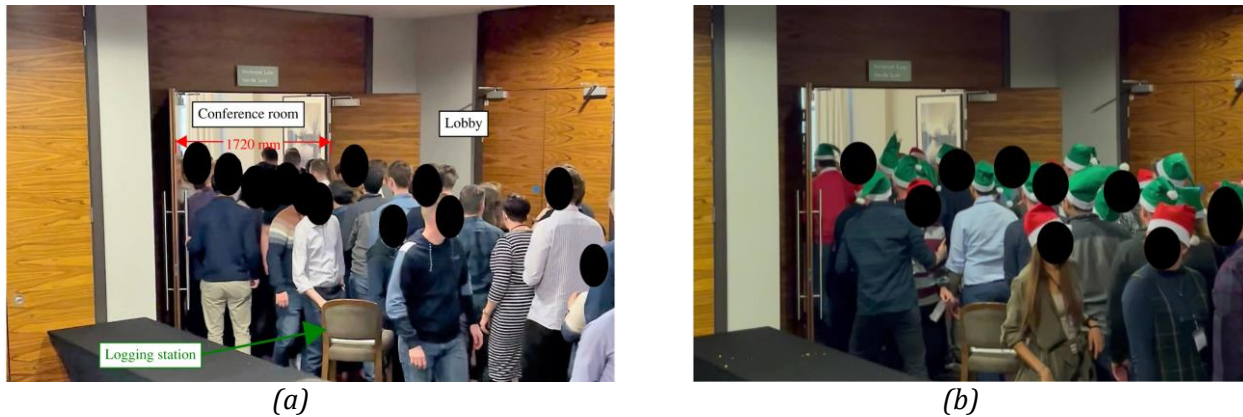


Figure 2. Trial arrangement.

For the unidirectional trials two logging stations were located approximately 2 m from the door positioned such that participants could pass either side without creating any congestion. Similarly, in the counterflow trials a pair of logging stations for location each side of the door in a similar configuration as the unidirectional trials.

Trials were recorded on video from various locations. The views were not necessarily ideal to capture all of the details of the trials but were sufficient to get a broad view of the participant actions. Images from two of the recordings are shown in Figure 3.



(a) (b)
 Figure 3. Photograph of (a) random group trial (b) in-group trial.

Eight trials were carried out: two trials had unidirectional flow involving all participants and six trials consisted of counterflow conditions with approximately half of the participants travelling in the two directions. In the two unidirectional trials, one had the participants move from the lobby to the conference room (Trial 1), while in the other trial the participants travelled from the conference room to the lobby (Trial 8). In two of the counterflow trials the participants were told they had been randomly split into two groups (random group trials). In the remaining four counterflow trials the participants were split into two groups that the participants were told had specific distinguishing characteristics (in-group trials). In reality the participants were again split into two random groups.

To create the new group identities and override any pre-existing social connections as colleagues, the participants were asked to complete individual questionnaires. The questionnaires asked three questions regarding the participants' choice of musical artist, a place they might choose to go on holiday, and their choice of headache medicine, as well as asking for the participants' approximate age. In each question the participant could express no preference. The questions were designed to get the participants to believe that there were specific behavioural characteristics that placed them within one of two groups. The sense of group identity was reinforced in the trials by asking the people to think about why they were placed in each group. During the 'in-group' counterflow trials participants were given one of two coloured hats (red and green) to distinguish them from the other group and to further reinforce a sense of group identity. The participants remained within their same groups for all four of these trials in an effort to maintain the saliency of the new group identities.

During the 'in-group' trials it was observed that there was more interaction between the participants flowing in the two directions with instances of gentle pushing and shoving occurring. It is possible this is a result of the 'in-group' identity or simply the participants were already familiar with one another. However, these interactions were not observed during the random group counterflow trials.

Results

The data gathered from the four logging stations was adjusted and combined (for the counterflow trials). The results of the two unidirectional and random group trials are presented in Figure 4.

Generally, the results show marginally faster flows where participants walked from the lobby side to the conference room, than vice versa. This is likely due to the greater restrictions beyond the logging stations in the lobby when compared to the conference room where participants could flow into more freely.

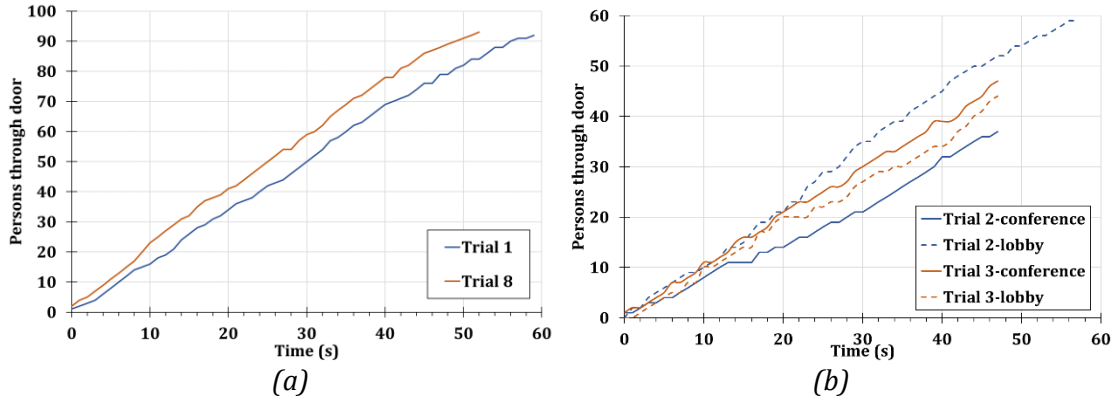


Figure 4. (a) unidirectional flow, Trials 1 and 8; (b) random group counterflow, Trials 2 and 3.

The difference in flow was exacerbated in Trial 2 which had an uneven distribution of participants, with the greater number starting in the lobby further restricting the flow into this space. The results also showed that in one direction only a single recording station was used suggesting that lane formation played a key part in this trial. Interestingly when the remaining people in larger group unidirectionally moved through the door the flow did not appear to increase as might be expected. For Trial 3 some participants were transferred to the smaller group from the larger one and the recorded flows differ less between the two streams thereafter.

The in-group counterflow trials have been grouped together based on the direction the groups of participants were walking. Figure 5a presents the results of the in-group trials where those with red hats began in the lobby and those in green hats began in the conference room. Similarly, Figure 5b presents the results for the converse of this. The results of the in-group trials are largely consistent. Analysis of the videos showed an increase in participant interaction in Trials 6 and 7 when compared to Trials 4 and 5 with participants more actively forcing through the crowd. It is possible the group identity increased as the trials were repeated. However, this did not correlate to an increase in flow with the average flow in both directions in Trials 6 and 7 being marginally less than that of Trials 4 and 5.

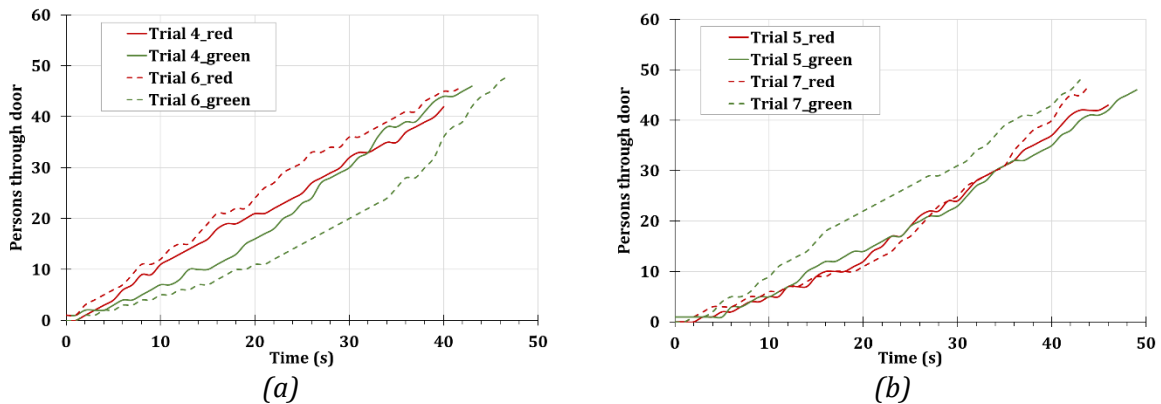


Figure 5. In-group counterflow, (a) Trials 4 and 6; (b) Trials 5 and 7.

A summary of the flow measurements is shown in Figure 6. Counterflow results are only taken while people were moving in both directions. As expected, the unidirectional flow is higher than the counterflow cases. Trial 8 exhibited a faster flow than Trial 1 (1.79 pers/s vs 1.56 pers/s) which may indicate that participants had become more practiced at doing the trials, but the higher flow is still less than obtained using the hydraulic model.

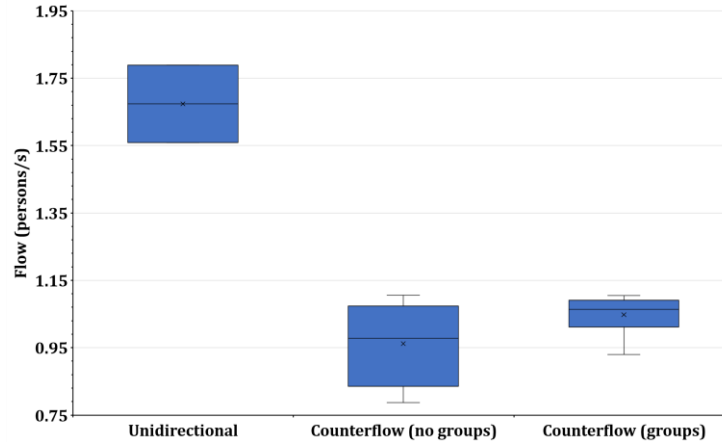


Figure 6. Measured flows over trial periods.

For the counterflow trials the average flow in each direction in the random and in-group cases are similar (0.97 pers/s vs 1.05 pers/s). However, the in-group trials had range within the first and third quartiles and the lowest and highest flows were greater than the equivalent random group results. Furthermore, the in-group flows exhibited greater variation in two of the four trials when compared to the random trials and the other two in-group trials. Taking the half of the measured unidirectional flow would give a flow of 0.84 pers/s which is 13 – 20% less than the measured counterflow.

The following sections introduce three evacuation models that aim to simulate the trials to compare the results of these.

EVACUATION MODELS

Hydraulic Model

The SFPE Handbook of Fire Protection Engineering introduces the hydraulic model as a means of quantifying egress performance, as described by Gwynne and Rosenbaum [1]. The hydraulic model describes the evacuating population using a set of equations. With regards to flow, the model considers the effective width of the component in question (e.g., a door). This is the useable width of the component, taken as its clear width minus the sum of the boundary layer distances.

The hydraulic model has been used as an initial estimate of the flow rates measured in the trials whereby, for counterflow conditions, half of the door width is taken as the clear width.

From the SFPE Handbook, a specific flow of 1.3 pers/s/m is given for doorways. For the 1,720 mm wide door with 150 mm boundary layer each side, the effective width is 1,420 mm and thus the calculated unidirectional flow is 1.85 pers/s. For counterflow conditions, the flow is taken as 0.92 pers/s based on half of the unidirectional flow.

Pathfinder

Pathfinder is an agent-based egress simulation model. The evacuating population is represented as a set of individual agents defined by attributes attached to each individual. It employs a combination of steering behaviours and physical constraints to simulate evacuee response and generates evacuation times based on the movement and interaction of these agents.

The model has two simulation modes that can be selected at the outset of the simulation. The default in Pathfinder is 'steering' mode whereby agents use a steering system to move and interact with other agents in an attempt to emulate human behaviour and movement as much as possible [10].

The alternative 'SFPE' mode uses a set of assumptions and hand-calculations from the SFPE Handbook. In this mode, agents make no attempt to avoid one another to emulate reality and can interpenetrate (i.e., will become superimposed in the same space within the model), with constrictions imposing a flow limit and velocity as a function of density.

With regards to counterflow, the Pathfinder Verification and Validation Guide [11] includes a discussion on the counterflow capability of both Pathfinder simulation modes by testing these against Test 8 of IMO 1533 [12]. The results show that in each mode, a greater counterflow increases the evacuation time. However, it is noted that the SFPE mode does not account for counterflow interaction and this increase in evacuation time is attributed to the increased population density reducing travel speeds.

Figure 8 shows the Pathfinder (v2022.1.0422 x64) model used to describe the trials. The two rooms are 20 m × 20 m connected by the 1,720 mm door. The widths of the final exits from the space were increased so that agents can freely exit the simulation without additional queuing. Each room was populated with agents corresponding to the number of participants in the trials. The agents were randomly in the spaces. Given the queuing dominated nature of the simulation, agent location within the geometry has a minimal impact on the results, although it slightly impacts queuing densities during the initial stages of the simulation. For the simulations, agents placed in the left room are directed towards the right exit and vice versa for agents starting in the right room. Agents were assigned an unimpeded walking speed of 1.2 m/s and the default agent characteristics were used in the simulation, including the collision reduction and personal space factors which are of relevance to this study.

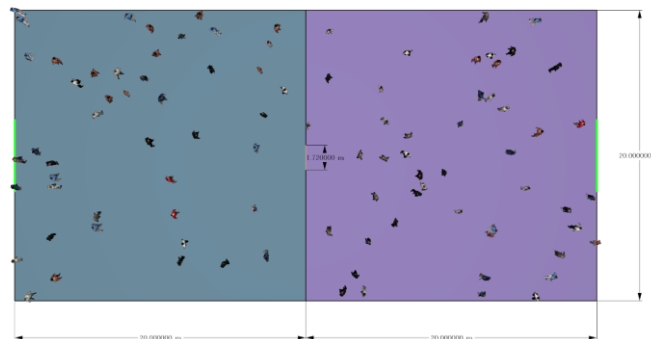


Figure 7. Pathfinder simulation setup.

Evacuationz

Evacuationz is an agent-based network model that uses the hydraulic flow model described above. Agents can be assigned individual movement and behaviour characteristics and are directed towards exit nodes by the use of different route-finding algorithms.

Spaces are described by nodes with user-defined dimensions which are linked by connections that can be used to represent doors etc. Simulations can either deterministic or incorporate sampling of statistical distributions for parameter input. Previous work [13] has verified the capability of the tool for a range of cases similar to some of those defined in ISO 20414 [5].

The counterflow model in the latest release of Evacuationz (v2.14) assumes a fixed effective half door width as is described previously with regards to the hydraulic flow model. However, the model can easily be modified to alter the fraction and it could be made a user-defined parameter in a future release.

The same test used to assess the counterflow capability of Pathfinder has been undertaken for Evacuationz. The results of this assessment show agreement with the expectations set out in IMO 1533 [12], with a greater counterflow resulting in longer evacuation times.

Figure 8 shows the network used in Evacuationz to describe the trials. The two nodes (Space 1 and Space 2) are 20 m × 20 m to mitigate overcrowding in the nodes (which would otherwise reduce the travel speed and flow at higher population densities). As with the Pathfinder model, the widths of the final exits from the space were increased and the nodes were populated with agents corresponding to the number of participants in the trials. Similarly, the initial distance of the agents from the door was assigned randomly. For the simulations, agents placed in the ‘Space 1’ node are directed towards the ‘Exit 2’ node and vice versa for agents starting in the ‘Space 2’ node. Agents were assigned an unimpeded walking speed of 1.2 m/s.

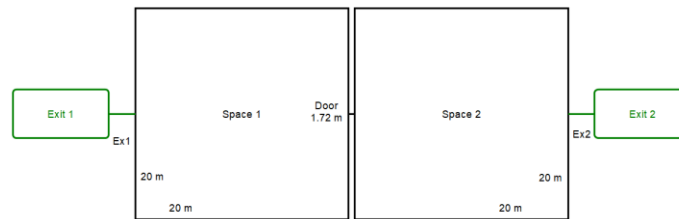


Figure 8. Evacuationz network.

RESULTS AND DISCUSSION

The results of the trials are discussed previously. This section compares results of the different evacuation models and those observed in the trials. An example of the visualization results of Pathfinder and Evacuationz (through the Smokeview software [14]) are shown in Figure 9.

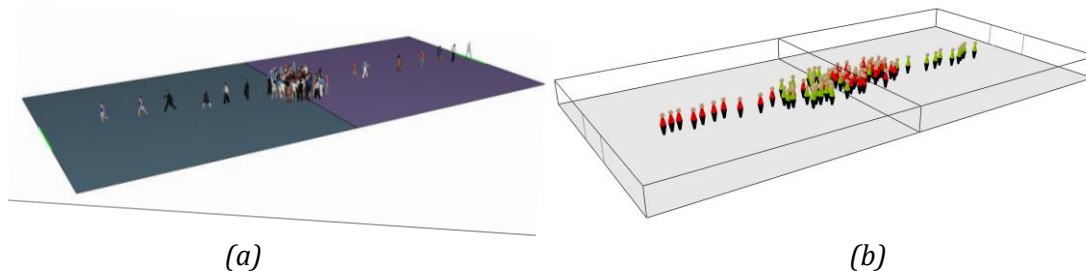


Figure 9. Example of (a) Pathfinder steering mode counterflow model visualization and (b) Evacuationz counterflow model in Smokeview.

Figure 10a shows the results from the two unidirectional flow trials compared to the two Pathfinder simulation modes and Evacuationz results. As can be seen, under unidirectional flow conditions the results of the computer models are broadly similar, and closely align with the results of the two trials.

Trail 2 has been selected as representative of the random group counterflow trials with the results of this, the two Pathfinder simulation modes and Evacuationz results shown in Figure 10b. As discussed previously, the results from Trial 2 showed that the random groups were not evenly split (37 people in the conference room and 60 people in the lobby). When the remaining people in larger

group unidirectionally moved through the door the flow did not appear to increase as might be expected.

Having the two groups of unequal size led the unintended benefit of assessing how the computational models would respond to this scenario. The algorithm within Evacuationz shows a change in the flow gradient once the counterflow ceased with a final prediction less than measured in the trial. The same is noted for both Pathfinder simulation modes as shown by the inflection in the orange dashed curves in Figure 10b.

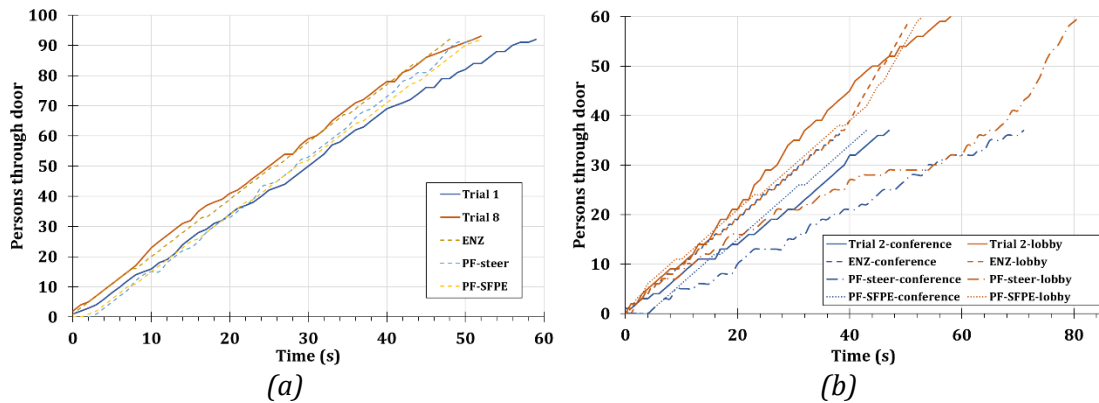


Figure 10. (a) unidirectional flow, Trial 1 and Trial 8; (b) random group counterflow, Trial 2.

During the counterflow period (i.e., when there is flow in both directions), the results of Evacuationz and Pathfinder SFPE mode are comparable to the trial results for both directions. The Pathfinder steering mode, however, results in an extended flow through the door when compared to the other computer models and the trial results. From reviewing the visualization results within Pathfinder, agents can be seen colliding with one another and taking a significant period of time to negotiate the collision, resulting in the door becoming blocked. This was not observed in the trials as participants generally formed lanes to pass through the door and where participants actively cut across the path of the opposing flow, the ‘collision’ was resolved quickly, and flow continued.

Lastly, Trial 6 has been selected as being representative of the in-group trials and the results of this trial compared with the three computer models, as shown in Figure 11. This trial comprised of a more equal number of participants on either side (46 people in the conference room and 48 people in the lobby). While agent interaction or in group identity could be implicitly represented within the computer models (e.g., by altering relevant parameters), this has not been incorporated due to a lack of data to support any changes in value of these parameters.

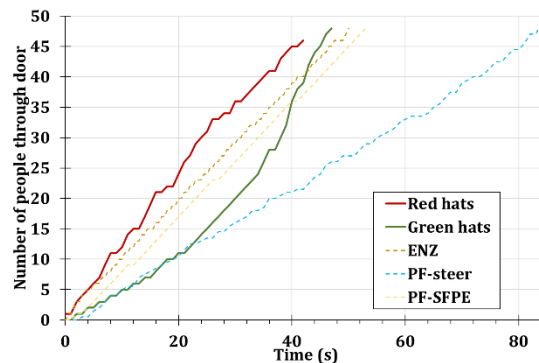


Figure 11. In-group counterflow, Trial 6.

As with Trial 2, the results of Evacuationz and Pathfinder SFPE mode are comparable to the trial results, though being marginally conservative (i.e., with a lower counterflow rate). Again, the steering mode in Pathfinder results in a counterflow rate that is of the order of half that of the other simulations and the trial counterflow rates.

A summary of the average results from the trials (random and in-group) and of the evacuation models are given in Table 1. As can be seen, five of the six methods yield comparative results for the counterflow rate (0.90 – 1.05 pers/s); however, the Pathfinder steering mode yields a significantly lower value.

Table 1. Summary of results.

Method	Counterflow rate (pers/s)
Random trial average	0.96
In-group trial average	1.05
Hydraulic model	0.94
Pathfinder steering mode	0.57
Pathfinder SFPE mode	0.90
Evacuationz	0.96

As discussed previously, the steering mode in Pathfinder attempts to emulate human behaviour and movement as much as possible. In counterflow conditions, this leads to occupants colliding and 'bouncing' off one another for protracted period of time when compared to the observations of participant behaviour during the trials. The result being an overly onerous simulation of the counterflow condition in this mode.

In steering mode, consideration has been given to select variables that are considered to impact the results of the simulations, namely, the ability of agents to reduce their diameter to resolve congestion and the agents' personal distance. For the former, the default in Pathfinder is to allow occupants to reduce their diameter by a factor of 0.7 and is considered a means to get the benefit of elliptical agent shape, corresponding to persons turning sideways to 'squeeze' by one another in congested areas [11]. This parameter has been reduced to 0.5 to assess its impact on the results, with the results showing an increase of 11% in the counterflow rate to 0.63 pers/s.

For the second parameter, the default value of personal distance (i.e., the desired distance one agent will try to maintain with others in a queue) is 0.08 m. This parameter has been reduced to 0.05 m to assess its impact. The results obtained show that this parameter has negligible impact on the flow (c. 0.2% increase in counterflow rate). While these parameters could be further reduced to increase the counterflow rate in the steering mode simulations, consideration should be given to what realistic values would be and suitable substantiation provided for these.

The Pathfinder Verification and Validation Guide states that SFPE simulation mode does not account for counterflow interference. However, the results obtained from the simulations show a comparable reduction in counterflow rate to Evacuationz and the trials. This may be attributed to the increased population density at the door threshold slowing the flow.

Both Evacuationz and the hydraulic model (in the context of this research) assume an effective half door width under counterflow conditions. These yield comparable results to one another and to the results obtained from the random group trials. It is interesting to note that the SFPE mode in Pathfinder, which is understood to not account for counterflow, yields a result similar to these models.

CONCLUSION

Results from the trials (albeit limited in number and scope) suggest that counterflow rates through doorways are around 13 – 20% greater than assuming an equivalent half unidirectional flow. There appears to be an effect when in-group psychological behaviour is introduced such that the flow can show an overall increase when comparing the maximum and minimum flow compared to having random groups. However, the in-group counterflow also exhibits a greater variability during stages of the flow should participants interact.

Applying the hydraulic model to a counterflow situation would suggest using a half door width would provide conservative results, and as such, taking a half door width is reasonable in Evacuationz. The Evacuationz model can easily be modified to alter the fraction and it could be made a user-defined parameter in a future release.

If a Pathfinder user anticipates counterflow during a simulation, consideration should be given to the simulation mode adopted. In attempting to emulate human behaviour and movement, the steering mode in Pathfinder underpredicts the counterflow rate when compared to those observed in the trials. This may lead to overly onerous evacuation times. The SFPE mode in Pathfinder yields more comparable results to the trials.

The work presented herein is limited in its scope with a limited number of trials carried out and specific demographic conditions include the age and sex distribution and also that participants already had social connections that may have influenced their interactions.

Further work to compare the results from the Evacuationz and Pathfinder to the corridor counterflow work of Kretz et al. [7] and Isobe et al. [8] is planned. Additionally, publication of the counterflow assessment of Evacuationz to IMO1533 is anticipated.

REFERENCES

- [1] S. Gwynne and E. Rosenbaum, 'Employing the hydraulic model in assessing emergency movement', in *SFPE Handbook of Fire Protection Engineering*, 5th Edition., Springer, 2016, pp. 2115–2151.
- [2] H. Tajfel, M. G. Billig, R. P. Bundy, and C. Flament, 'Social categorization and intergroup behaviour', *Eur. J. Soc. Psychol.*, vol. 1, no. 2, pp. 149–178, 1971, doi: 10.1002/ejsp.2420010202.
- [3] A. Templeton, J. Drury, and A. Philippides, 'Placing large group relations into pedestrian dynamics: Psychological crowds in counterflow', *Collect. Dyn.*, vol. 4, pp. 1–22, Mar. 2020, doi: 10.17815/CD.2019.23.
- [4] S. Heliövaara, T. Korhonen, S. Hostikka, and H. Ehtamo, 'Counterflow model for agent-based simulation of crowd dynamics', *Build. Environ.*, vol. 48, pp. 89–100, Feb. 2012, doi: 10.1016/j.buildenv.2011.08.020.
- [5] ISO, 'ISO 20414:2020 Fire safety engineering — Verification and validation protocol for building fire evacuation models', ISO, Geneva, ISO 20414, 2020.
- [6] T. Korhonen and S. Hostikka, 'Fire Dynamics Simulator with evacuation: FDS+Evac', VTT Technical Research Centre of Finland, Finland, VTT Working Papers 119, 2009.
- [7] T. Kretz, A. Grünebohm, M. Kaufman, F. Mazur, and M. Schreckenberg, 'Experimental study of pedestrian counterflow in a corridor', *J. Stat. Mech. Theory Exp.*, vol. 2006, no. 10, pp. P10001–P10001, Oct. 2006, doi: 10.1088/1742-5468/2006/10/P10001.
- [8] M. Isobe, T. Adachi, and T. Nagatani, 'Experiment and simulation of pedestrian counter flow', *Phys. Stat. Mech. Its Appl.*, vol. 336, no. 3–4, pp. 638–650, May 2004, doi: 10.1016/j.physa.2004.01.043.

- [9] R. Nagai, M. Fukamachi, and T. Nagatani, 'Experiment and simulation for counterflow of people going on all fours', *Phys. Stat. Mech. Its Appl.*, vol. 358, no. 2–4, pp. 516–528, Dec. 2005, doi: 10.1016/j.physa.2005.04.024.
- [10] Thunderhead Engineering, 'Pathfinder User Manual', 2022.
- [11] Thunderhead Engineering, 'Pathfinder Verification and Validation', 2022.
- [12] IMO, 'Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships - Technical Report MSC.1/Circ. 1533', International Maritime Organisation, Jun. 2016.
- [13] M. J. Spearpoint, 'Comparative verification exercises on a probabilistic network model for building evacuation', *J. Fire Sci.*, Jun. 2009, doi: 10.1177/0734904109105373.
- [14] G. Forney, 'Smokeview, a tool for visualizing fire dynamics simulation data volume I: User's guide', National Institute of Standards and Technology, Gaithersburg, MD, NIST SP 1017-1 Sixth Edition, 2022. [Online]. Available: <https://pages.nist.gov/fds-smv/manuals.html>