Department for Transport

CPNI
Centre for the Protection of National Infrastructure

Impact of Hostile Vehicle Mitigation Measures (Bollards) on Pedestrian Crowd Movement

Phase 2 Final Report

October 2014

Impact of Hostile Vehicle Mitigation Measures (Bollards) on Pedestrian Crowd Movement - 2

by

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19/10/14

Document: BEX/CPNI_bollards/EG/02/0714/Rev3.00

EXECUTIVE SUMMARY

This work has been conducted by the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG) under contract to the Centre for the Protection of National Infrastructure (CPNI). This document represents the final report for the second series of trials conducted by FSEG on behalf of the CPNI. The overall aim of this project was to design, conduct and analyse a series of pedestrian flow trials to explore the impact of Hostile Vehicle Mitigation Measures (i.e. a Bollard Array, BA) upon pedestrian flows of simulated evacuation conditions. This report describes the performance of the second trial campaign and the subsequent analysis of the data produced.

FSEG, in consultation with CPNI, designed a series of trials in order to examine the impact that the presence of a bollard array (BA) might have upon an established pedestrian flow. The trials were conducted in two campaigns, the first in 2013 and the second in 2014. The trials were specifically designed to investigate the impact of several key parameters on the exit flow. Within the first trial campaign the following parameters were investigated: population density, BA position (large stand-off distances), a single bollard placed in the centre of the exit and the presence of a cross-flow. Within the second trial campaign these were: exit width, BA position (small stand-off distances) and the presence of luggage.

As these effects were expected to be dependent on population density, two initial population densities were examined in the first trial campaign, 3 p/m^2 and 4 p/m^2. These conditions reflected the maximum engineering design densities and were deemed representative of the conditions typically experienced by station users during egress at peak periods. The results from the first trial campaign suggested that at low population densities the impact of the BA was less significant. Thus the second trial campaign, reported here, concentrated on the higher crowd density of 4 p/m^2.

The second trial campaign, consisting of three trial series was conducted over a single weekend in March 2014 (29 and 30 March). These trials were conducted, as with the first trial campaign, on University of Greenwich grounds, in the Queen Anne Courtyard. On Day 1 24 trials were conducted, 9 in Trial Series 1 (TS1) and 15 in TS2 while on Day 2, 21 trials were conducted in TS3. Up to 192 people participated in the TS1 and TS2 trials which began at 09:00 and were completed by around 15:50. Up to 249 people participated in the TS3 trials which began at 09:00 and were completed at around 14:40.

TS1 was intended to further investigate the relationship between the proximity of the BA and the exit and the flows generated. While large stand-off distances (3m and 6m) were explored in the first trial campaign, the second trial campaign investigated small stand-off distances, in particular between 0m and 3m from the exit. Thus the 2.4m exit width, with 1m, 1.5m and 2m stand-off distances were investigated.

TS2 was intended to examine the impact of encumbrance upon the egress flow produced given the presence of the BA at 0m. These trials used the 2.4m wide exit. Participants were provided with a range of encumbrance including hand bags, brief cases, small roller bags, large roller bags, push chairs and bicycles. Three levels of encumbrance were investigated;

one in which 0% of the population was encumbered and ones in which 40% and 60% of the population were encumbered.

TS3 was intended to examine the relationship between exit width, BA stand-off distance and the flow generated by varying the stand-off distance and exit widths. Two exit widths were considered, 3.5m and 4.5m and three stand-off distances were investigated, 1m, 2m and 3m.

In total 45 individual trials involving 441 participants were conducted over two days. Each participant was compensated £45 for their day long involvement in the trials. The Transport Research Laboratory (TRL) was responsible for setting up the BA configuration required for each of the series of trials. On each trial day there were 12 FSEG staff members, 2 TRL staff members and 1 St.Johns first aider involved. The trials were recorded for later analysis by five video cameras at carefully selected positions.

The findings from the trials reflect the complexity of the impact of the BA upon performance. The key findings are listed below.

General Findings:

- ***Exit flows and travel speeds may be strongly affected by modest changes in environmental conditions.*** A 10% improvement in performance was achieved by improving weather conditions from cold (maximum day temperature 9^{o}C, light snow on occasions) to moderate (maximum day temperature 19^{o}C, sunny conditions). The possibility of reduced exit flows and individual travel speeds resulting from colder conditions should be taken into consideration when designing evacuation systems.

- ***High crowd density (4 p/m^2) exit flows are strongly affected by the presence of a moderate to high number of pedestrians encumbered with luggage.*** For the 2.4m wide exit, the introduction of a moderate (40% of the crowd) level of encumbrance reduces the exit flow by 10%, while the introduction of a high (60% of the crowd) level of encumbrance reduces the exit flow by 16%.
    - Both values of degraded exit flow are greater than any reduction in exit flow produced by a BA with stand-off distance from 0m to 6m.
    - The possibility of reduced exit flows and individual travel speeds resulting from pedestrians carrying baggage should be taken into consideration when designing evacuation systems, especially for rail and airport applications.

- ***As a high crowd density (4 p/m^2) flow exits from an opening, it diffuses outwards into the surrounding space and the degree of diffusion increases with distance from the exit.*** As a result the density of the central regions of the flow decreases with increasing distance from the exit. The diffusion of the flow is thought to be due to individuals in the high density flow moving to the outer lower density regions of the flow enabling individuals within the crowd to walk at their desired stride length and hence travel speed.

- ***The degree of diffusion is greater when a BA is present, the BA acting as a divergent lens.*** As a result, the density in the central regions with BA is less than that for the case without BA. The presence of the BA encourages the crowd to diffuse into the surrounding space to a greater extent than if the BA was not present.

- ***The unit exit flow for the 2.4m wide exit and the 4.5m wide exit without BA were identical.*** This confirms that unit flows for similar types of exits are the same regardless of exit width. The unit flow derived from these trials for an unobstructed exit was 1.93 p/m/s. This is some 45% greater than the unit flow recommended in the UK Building Codes (1.33 p/m/s).

Stand-Off Distance:

- ***Generally as the exit width increases from 2.4m to 4.5m, the greater the impact of the BA on the unit exit flow for 1m, 2m and 3m stand-off distances.*** However, this trend is thought to only apply to the range of exits widths examined in this study i.e. 2.4m to 4.5m with BA arranged such that there is a gap in the BA at the symmetry line of the exit.
    - For exit widths of 2.4m to 4.5m each row of exiting people are competing to access the central three gaps in the BA. As the exit width is increased from 2.4m, there are more people competing for the three central BA gaps and hence the density in the central regions of the BA increases. This increase in central densities results in greater conflicts between pedestrians as they compete to utilise the three central gaps in the BA.
    - However, it is suggested that increasing the exit width beyond 4.5m will not result in more pedestrians vying for the central three gaps and so the overall degradation in performance is not likely to increase further, assuming that there is sufficient space to the sides to allow the crowd to diffuse. If correct, the maximum impact on exit flow may be a degradation of around 10%. This hypothesis should be tested.

- ***The maximum impact on peak exit unit flow occurs with a stand-off distance of 2m across all the exit widths examined, with the maximum degradation in exit performance being 9% for the largest exit width (4.5m).*** Generally, the closer or further away the BA is located to the exit, the smaller the impact on the exit unit flow. The number of last minute bollard avoidance actions undertaken by pedestrians is at a maximum for the 2m BA for the 3.5m and 4.5m exit widths. This high number of last minute bollard avoidance actions disrupts the flow behind the person taking the avoidance action which impacts back onto the exit flow resulting in the reduced exit flow noted in these cases compared to the case without BA.
    - It is suggested that the 2m location of the BA is such that it does not allow sufficient time for the pedestrians in the flow to adjust their path so that they can take earlier avoidance measures and as such have to make a last minute avoiding action. The 3m location of the BA allows sufficient time for more of the population to take earlier avoiding measures and hence the exit flow is disrupted to a smaller extent.
    - While it is not clear what the precise critical stand-off distance is, it appears to be between 1m and 3m from the exit.
    - It is suggested that if the crowd were aware of the location of the BA they may be able to take avoiding actions before reaching the BA and hence reduce the disruption to the flow at the BA line. The introduction of taller bollards, such that they could be visible over the heads of the crowd, may reduce the number

of last minute avoiding actions and hence decrease the reduction on exit flow. This hypothesis could be tested in a series of trials.

- ***The 4.5m exit with a BA stand-off distance of 1m experiences a degradation in unit exit flow equal to the maximum degradation (observed at 2m stand-off).*** This observation is unique to the 4.5m exit width and does not occur for the 2.4m or 3.5m exit widths.
  - For both the 2.4m and 3.5m wide exits there were only 2 bollards positioned directly within the expanse of the exit opening. For the 4.5m wide exit there were 4 bollards positioned within the expanse of the exit opening.
    - The more bollards within the exit opening the more avoidance actions the population must make increasing the disruption to the flow just behind the BA line which impacts back onto the exit flow resulting in a degraded performance compared with the case without the BA.
  - It is also noted that it is not simply a matter of the number of bollards within the expanse of the exit width, as the 4.5m exit with 3m stand-off had the same number of bollards within the exit opening expanse but experienced fewer avoidance actions and produced a smaller degradation in exit performance. This is because the population had sufficient time to maneuverer to avoid the bollards without taking last minute avoidance action.
  - **This suggests that for BA's positioned close to an exit (within around 1m stand-off distance) if possible, the BA should be positioned such that the minimum number of bollards fall within the exit opening. Furthermore, the BA configuration should avoid positioned bollards in line with the inside edge of the exit.**
  - If correct, this suggests that:
    - For the 2.4m exit the impact of the BA on the exit flow would be ***reduced*** if a single bollard, placed on the symmetry axis of the exit was positioned across the exit opening, rather than the two used in the trials.
    - For the 3.5m exit, the impact of the BA on the exit flow would be ***increased*** if three bollards were positioned across the exit opening, with one bollard on the exit symmetry axis rather than the two bollards used in the trials.
    - For the 4.5m exit, the impact of the BA on the exit flow would be ***reduced*** if three bollards were positioned across the exit opening, with one bollard on the exit symmetry axis rather than the four bollards used in the trials.

- ***A correlation exists to determine the minimum expanse of BA required to minimise the impact of the BA on the exit flow.*** The correlation, which links exit width and stand-off distance to required BA expanse is

$$B_g = 0.6026 + 0.5994 * E_w + 0.5782 * S_d + 0.0225 * E_w * S_d ,$$

where

- B_g — Minimum number of gaps in bollard array required to accommodate 90% of participant flow,

- E_w — Width of exit,
- S_d — Stand-off distance of bollard array.

The corresponding width (in metre) of the bollard array (B_w) is:

$$B_w = B_g * 1.200 + (B_g + 1) * 0.225 ,$$

where B_g is a rounded integer obtained from the above correlation.

- This relationship can be used to determine the minimum expanse of BA required for a given exit width and stand-off distance in order that the exit flow is not constrained i.e. the BA does not constrain the natural expansion of the exit flow as it leaves the exit and comes into contact with the BA.
- The correlation is based on experimental data concerning BA gap usage for the three exit widths (2.4m, 3.5m and 4.5m) and the three stand-off distances (1m, 2m and 3m) examined, for BA configurations where a bollard is NOT placed on the symmetry axis of the exit.

Encumbered Flows with Bollards:

- The following results apply to the 2.4m exit with a single bollard placed on the symmetry axis of the exit at 0m stand-off distance.
  - ***At moderate levels of encumbrance (40%) introducing the bollard has negligible impact on exit flow.***
  - ***At high levels of encumbrance (60%), introducing the bollard has little impact on the exit flow, the maximum degradation in exit flow being 3%.*** However, this is four times the impact of introducing the bollard at low levels of encumbrance (40%).
  - **Compared to the exit flow without a bollard and 0% encumbrance the introduction of a bollard and 60% encumbrance *reduces* the flow at the exit by 18%.** Thus introducing high levels of encumbrance (60%) AND a bollard in the exit will reduce the exit flow by almost one fifth.

This work suggests that it is possible to manage the impact that a BA may have on high density evacuation flows through careful positioning of the BA. However, consideration should also be given to the ambient weather conditions and the degree of encumbrance experienced by the population as these factors will have a significant impact on exit flow.

It is suggested that further work is required in order to better understand key factors impacting exit flow and BA configurations. It is suggested that additional trials be conducted to:

- Identify the critical BA stand-of distance between 1m and 3m,
- Determine whether the degradation in exit performance resulting from increased exit width in the presence of a BA is abated for exits greater than 4.5m,
- Explore the impact of BA's with a bollard placed at the symmetry axis of the exit,
- Explore the impact of BA height on reducing last minute avoiding actions and hence reduce the impact of the BA when it is close to the exit.
- Explore the impact of BA's on contra-flow,

- Explore the impact of low lighting levels on the number of last minute avoiding actions and hence the reduction in exit flow,
- Explore the impact of alternate/multiple pedestrian targets on exit flow,
- Explore the impact of people running.

Finally, it is suggested that a data-set be established for the validation of evacuation models together with a set of guidelines for the systematic and transparent use of the validation data-set.

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1 INTRODUCTION

This report was produced by the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG) under contract to the Centre for the Protection of National Infrastructure (CPNI). It is the second in a series of work conducted by FSEG in response to the CPNI produced Statement of Requirement [1] and detailed proposal by FSEG [2] for an analysis of pedestrian behaviour and performance in response to the installation of Hostile Vehicle Mitigation Measures. For a description of FSEG and their capabilities please refer to ANNEX A: FSEG DESCRIPTION.

Security bollards have become a common feature surrounding public spaces, in particular busy rail and underground stations, airports and many key commercial and public buildings. These bollards form part of the security infrastructure and are primarily intended as part of the Hostile Vehicle Mitigation strategy. A safety concern which has been raised is the potential impact that security bollards may have in the event of an emergency evacuation from the protected structure. The broad aim of the project was to identify and quantify the potential impact that Hostile Vehicle Mitigation bollards may have upon pedestrian movement when leaving rail/underground stations, in particular during emergency scenarios.

FSEG, in discussion with CPNI, designed a series of trials in order to examine the impact that the presence of a bollard array (BA) might have upon an established pedestrian flow. A number of experiments were conducted in order to assess this impact. These experiments were designed to investigate the impact of a number of key parameters on exit flow, specifically population density and BA position (large stand-off distances) in the first phase of the work [3] and exit width, BA position (small stand-off distances) and the presence of luggage in the second phase of work. In each case the scenario characteristics were assumed to be representative of the conditions generated by pedestrian movement from a rail or underground station.

1.1 SPECIFIC AIMS OF THE PROJECT

The aim of this project was to arrange and conduct a series of pedestrian flow trials to establish the impact of Hostile Vehicle Mitigation Measures (i.e. a Bollard Array - BA) upon exit flow at high population densities. The trials were designed to capture the conditions produced as the population left an exit of a simulated station or airport: both at the point of exit and when the population is incident upon the BA. A group of participants were recruited (deemed to be representative of the general passenger population) to take part in the trials. The trials were conducted in physical spaces that were representative of egress routes, without approximating the appearance of such a space. Given the focus of the trials upon the physical performance of the participants, this was felt to be reasonable and also reduced the number of trial scenarios required (e.g. not addressing different station/airport designs, liveries, etc.).

The first trial campaign investigated flows at specific crowd densities of 3 p/m^2 and 4 p/m^2. These conditions reflected the maximum engineering design densities and were deemed representative of the conditions typically experienced by station users during egress at peak periods. These trials suggested that at low population densities the impact of the BA was less significant [3]. Thus the second trial campaign concentrated on the higher crowd density of 4 p/m^2.

The earlier trials demonstrated that stand-off distances of 3m and 6m produced negligible impact on exit flow from a 2.4m wide exit. Furthermore, with a single bollard placed at a 0m stand-off distance the reduction in exit flow was not as great as may have been expected to result from the reduction in effective exit width. The presence of the bollard in the exit generated a more ordered exit flow which resulted in an improved exit unit flow that partially compensates for the loss of exit width due to the presence of the bollard [3].

While successful, the earlier trials did not address several key issues:

- The impact on exit flows of stand-off distances of between 0m and 3m.
- The impact on exit flows of the interaction between exit width and the BA.
- The impact on exit flows for a bollard placed at 0m with the exiting population encumbered with luggage.

These components, when taken together, provide insight into the impact BAs have on evacuation flows as the crowd exits the structure and moves through the BA. These additional issues were examined through a series of trials in the second trial campaign reported in this document.

1.2 DATE, WEATHER CONDITIONS AND LOCATION OF TRIALS

The second trial campaign was conducted over a single weekend in March 2014 (29 and 30 March). It was conducted, as with the first, on University of Greenwich grounds, in the Queen Anne Courtyard. This location was selected given that the adjacent arches approximate the exit dimensions required to replicate station exit conditions, the courtyard affords excellent opportunity for crowd management, and the courtyard also provided a number of excellent vantage points for video camera positions.

While the second trial campaign was conducted at the same time of the year as those of the first (in 2013), the weather conditions for the second series were significantly different to those of the first series. For the earlier campaign (held in 2013), the maximum day time temperature reported for London was around 9^oC with occasional light snow. For the second campaign (2014), the maximum day time temperature reported for London was a sunny 19^oC.

2 EXPERIMENTAL DEVELOPMENT

The experimental trials were conducted to provide insight into the impact on evacuating pedestrians of positioning bollard arrays at and around the points of exit from typical rail/underground stations. Given that the trials were not conducted at an actual station, experimental scenarios were designed in order to capture the key factors of interest evident in the real-world rail/underground environments. These are now described.

2.1 SCENARIO FACTORS

In reality, there are many ways in which a BA might be positioned in relation to a station exit. This position and the relative dimensions of the components involved may influence pedestrian performance. These relate to the stand-off distance of the BA from the exit (SO), the width of the exit (EW) and the width of the BA (BW). In this case, it is assumed that the BA covers the entire usable space beyond the exit, to fulfil the security objectives of placing the bollard array in the first place (although, it is certainly possible for this not to be the case). Thus the passage of the participants through the BA is not hindered by the width of BA available. The spacing of the bollard(s) (set to 1.2m as specified in [1,2]) and the diameter of the bollards (set to 0.225m as specified in [1,2]) are also prescribed. The distance between the exit and the BA (i.e. the stand-off distance, SO), is assumed to be one of the controlled variables that may impact pedestrian performance. The degree of encumbrance (E) the participant is burdened with may also have an impact on the exit flow, in particular for the case with 0m stand-off distance. Finally, the initial population density of the exiting flow was set to represent maximum design evacuation conditions of 4 p/m^2 [4].

In addition to the configuration, the manner in which pedestrians interact with the BA may also influence the impact that the BA has on pedestrian performance. For example, pedestrians may have various objectives beyond the BA towards which they wish to move, which may influence or bias the impact of the BA on pedestrian performance by increasing the usage of a particular part of the BA. Thus, the impact that the BA may have on pedestrian performance may not be uniform.

People leave the station exit, identify their objective (some distance beyond the BA), and then initiate their direction of movement accordingly, move to the BA, pass through the BA and continue moving beyond the BA towards their ultimate target. There is a large range of initial directions that a person may adopt once out of the station exit. It would not have been possible to capture all of these in a manageable number of controlled experiments. However, a trial design has been produced that captures the key underlying impact of the BA by assuming that the entire population had a single target at the end of the courtyard that meant that the entire population moved in a single direction. ***However, it may be important to examine the impact of targets off to one side. As this aspect was not tested in these trials it may warrant further analysis in future trials.***

To address the aims of the project and working within the constraints highlighted above, three trial series, TS1, TS2 and TS3 were planned.

TS1 is intended to further investigate the relationship between the proximity of the BA and the exit and the flows generated. The exit flow trials conducted as part of the previous analysis placed the BA at 0m (in the exit) and at stand-offs of 3m and 6m from the exit (with the approach width constrained) [3]. The results suggested that there was no appreciable effect on the exit flow as the BA moved from 6m to 3m. However, in real applications the BA may be positioned closer than 3m due to installation constraints associated with particular sites. It was noted that there was a slight reduction (less than 1%) in flow at the exit when the BA was moved to 3m. It was also noted that the diffusion of the crowd decreased with decreasing distance from the exit. This suggests that the closer the BA is to the exit, the smaller the extent of the BA utilised by the flow which in turn may amplify the impact of the BA on the exit flow. The impact of the BA at 0m is complex as there are two opposing effects, the first is a physical reduction in effective exit width due to the presence of the BA leading to a reduction in the exit flow and the second is an increase in the unit flow at the exit due to the influence of the BA resulting in an increase in the exit flow. Thus, it is unclear what overall impact a BA positioned between 0m and 3m from the exit may have on the exit flow.

To determine the impact of smaller stand-off distances a series of exit flow trials were conducted with the BA positioned at 1m, 1.5m and 2.0m from the exit. Each of the BA stand-off distances examined was repeated three times to allow some confidence in the consistency of the results produced.

Thus the purpose of TS1 is to establish the impact on exit flows of stand-off distances between 0m and 3m.

TS2 is intended to examine the impact of encumbrance upon the egress flow produced given the presence of the BA at 0m. The exit flow trials conducted as part of the previous analysis involving a BA placed at 0m stand-off produced complex flow dynamics [3]. The reduction in exit flow resulting from the reduction in effective exit width brought about by the presence of the BA was partially compensated for by the increase in the unit flow resulting from the more ordered flow generated by two lanes of exit flow. This increase in the unit flow partially compensated for the reduction in effective exit width and as a result, the impact of the 0m stand-off was not as significant as it could have been. In the first trial campaign the vast majority of participants were not carrying luggage or baggage (occasionally some participants carried very small handbags, umbrellas, books, etc.). In actual applications, especially those associated with transport terminals such as stations or airports, it is likely that pedestrians will be carrying an array of encumbrances. However, if the participants were encumbered by luggage/baggage, strollers etc., it is unknown whether the improvement in unit flow would have been as significant, or if it indeed occurs at all. If this is so, then the presence of the 0m BA could have a more significant negative impact on the exit flow.

To determine the impact of pedestrians carrying baggage/luggage an additional series of exit flow trials were conducted with and without the BA at 0m with pedestrians carrying a range of encumbrances. Two levels of encumbrance were investigated, one in which 40% of the population was encumbered and the other with 60% of the population encumbered.

Thus the purpose of TS2 is to establish the impact of the 0m BA stand-off on exit flow when participants are encumbered with luggage.

TS3 is intended to examine the relationship between exit width, BA stand-off distance and the flow generated by varying the stand-off and exit widths. The exit flow trials conducted as part of the previous analysis suggested that for a given exit flow population density there is a relationship between the exit width, stand-off distance and the expanse of BA required to ensure that there is no detrimental effect on the exit flow. However, only a single exit width (2.4m) was tested. In actual applications, the exit width may be considerably wider, allowing greater flows and hence the interaction with the BA may be more significant for a given stand-off distance. Furthermore, for a given width of exit, the extent of the BA utilised by the flow will diminish as the stand-off distance is reduced up to a distance of 3m from the exit. The trials conducted as part of the previous analysis only considered a single exit width and suggests (given that the relationship between exit width, stand-off distance and extent of BA usage scales for exit widths not considered in this work), that the relationship between the minimum BA width required so that the flow is not constrained and exit width is:

$$\text{BA width/Exit width} > 1.5 \text{ (with a 3m stand-off distance)} \qquad (1)$$

By examining two additional exit widths TS3 will establish if the above expression is valid for a range of different situations. Perhaps of greater significance, TS3 will determine whether exit width influences the interaction of the BA and exit flow.

In order to accommodate these trials, it will be necessary to move the TS1 trials from the archway in Queen Anne Courtyard to the centre of the courtyard. Two additional widths are examined: 3.5m and 4.5m.

Thus the purpose of TS3 is to establish the impact of the BA on exit flows for exits wider than 2.4m and hence determine the generality of the earlier findings. In addition, combining the TS3 results with the results for TS1 and the original trial series, will establish whether the BA Width/Exit Width relationship (equation 1) holds for distances less than 3m and for exits wider than 2.4m i.e. the general validity of the relationship.

The three sets of trials were examined over two days: TS1 (Trial Series 1) were the first trials conducted on day 1, TS2 (Trial Series 2) were the second series of trials conducted on day 1 and TS3 (Trial Series 3) were conducted on day 2. In all cases, the participants are informed to head towards a position ahead of them; i.e., there was a single target in the distance.

Although, the BA used spread across their field of view, there was a single objective; e.g., there was no need to turn left or right. In reality, pedestrians might be expected to move in a range of different directions given their objectives and the facilities available. Given this approach the TS1 and TS3 trials were focusing on the diffusion that may occur between exit and BA given that the participants were heading towards a single objective (see Figure 1). This was a deliberate attempt to capture the primary control variables (stand-off distance and population density), while reducing some of the extreme variability that might be present when pedestrians leave an exit (e.g. choice of route given the numerous objectives that may be present). Given this, the diffusion exhibited is due to the stand-off distance (i.e. the diffusion of people due to local densities and natural variation in their movement capabilities) and local navigation (pedestrian choice to fan out horizontally across the BA in order to improve their movement in order to reach a single objective). The TS1 and TS3 design therefore focused on the impact of the distance between the BA and the exit given the population density present. It is also assumed that there is sufficient width of BA so as not to adversely influence the movement of the pedestrians.

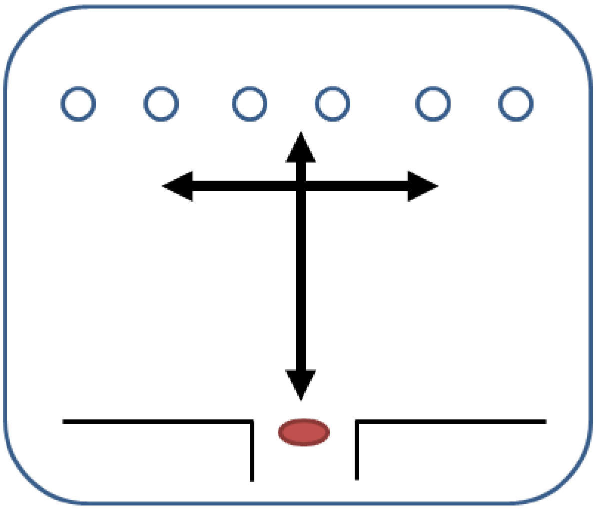


Figure 1: Opportunities for diffusion.

These trials were intended to represent an egress flow of pedestrians from a station/airport exit. Within the trials, the crowd density conditions were prescribed within the station/airport mock-up *just before the exit*. The exiting population was then allowed to naturally diffuse while moving between the exit and the BA as typically occurs in real situations. Thus, the crowd density at the BA was not controlled, but the crowd density at the exit was controlled. The crowd density at the BA was a function of the initial crowd density, the stand-off distance and the individual unencumbered travel speeds of the population. The impact of the BA on the exit flow is assessed by measuring the population densities and flows achieved at several locations within the experimental configuration, in particular just before the exit. Furthermore, the trials are repeated without the BA in order to gauge the impact of the BA on the exiting flow.

2.2 EXPERIMENTAL SCHEDULE

A total of 39 trials were planned to be conducted over the two trial days, 21 on day 1 (9 for TS1 and 12 for TS2) and 18 on day 2 (TS3). All three trial series were conducted with a single initial density of 4 p/m^2.

- For TS1, three stand-off distances (SD) and three repeats were conducted: 3 SD x 3 Repeats = 9 trials.
- For TS2, one stand-off distance, two bollard conditions (BA and NoBA – no BA), two levels of encumbrance (E) and three repeats were conducted: 1 SD x 2 bollard conditions x 2 E x 3 Repeats = 12 trials.
- For TS3, three stand-off distances, two exit widths (EW) and three repeats: 3 SD x 2 EW x 3 repeats = 18 trials.

As the data from these trials was intended to be compared with the data from the original trials, it was considered not necessary to conduct trials for TS1 and TS3 with NoBA as these were performed as part of the first series of trials. In addition, it was considered not necessary to conduct trials for TS2 with and without the BA at 0m without any encumbrance as these were run during the first series of trials.

On day 1 it was possible to run three additional trials. These were run at the end of the day and consisted of three repeats of the trial with no bollard array (NoBA). On day 2 it was also possible to run three additional trials. These were also run at the end of the day and consisted of three repeats of the 4.5m wide exit with NoBA.

Thus there were a total of 45 trials conducted over the two trial days, 24 on day 1 (9 for TS1, 12 for TS2 and 3 bonus trials with NoBA) and 21 on day 2 (18 for TS3 and 3 bonus trials for the 4.5m wide exit with NoBA).

The final trial schedule (and trial turnaround times) is described in Table 1 to Table 3.

On Day 1, up to 192 people participated in the TS1 and TS2 trials. Participants were requested to arrive at 08:00 so that they could be arranged into groups. The trials began at 09:00 and were completed by around 15:50. The trials were conducted faster than planned and so an extra trial series was performed at the end using no luggage and without the BA. This would allow comparison to the data from the previous trials, to see how factors like weather conditions could have affected the performance. The schedule for the day 1 trials is shown in Table 1 and Table 2.

Table 1: Final Schedule TS1 Day 1.

Trial	# People (Planned)	Actual Time (Planned Time)
SD1_1(1m)	191 (180)	09:00 (09:00 – 09:15)
SD1_2(1m)	191 (180)	09:13 (09:15 – 09:30)
SD1_3(1m)	191 (180)	09:25 (09:30 – 09:45)
Rest	N/A	09:26 (09:45 – 10:15)
SD2_1(1.5m)	191 (180)	09:52 (10:15 – 10:30)
SD2_2(1.5m)	191 (180)	10:04 (10:30 – 10:45)
SD2_3(1.5m)	191 (180)	10:14 (10:45 – 11:00)
Rest	N/A	10:16 (11:00 – 11:30)
SD3_1(2m)	189 (180)	10:46 (11:30 – 11:45)
SD3_2(2m)	189 (180)	10:57 (11:45 – 12:00)
SD3_3(2m)	191 (180)	11:11 (12:00 – 12:15)

Table 2: Final Schedule TS2 Day

Trial	# People (Planned)	Actual Time (Planned Time)	Luggage
Lunch (place BA in exit)	N/A	11:15 (12:15 – 13:15)	
BA1_CD1_1(0m)	183 (180)	11:59 (13:15 – 13:30)	40% participants with luggage (72)
BA1_CD1_2(0m)	191 (180)	12:13 (13:30 – 13:45)	40% participants with luggage (72)
BA1_CD1_3(0m)	191 (180)	12:25 (13:45 – 14:00)	40% participants with luggage (72)
BA1_CD2_1(0m)	191 (180)	12:54 (14:00 – 14:15)	60% participants with luggage (108)
BA1_CD2_2(0m)	191 (180)	13:10 (14:15 – 14:30)	60% participants with luggage (108)
BA1_CD2_3(0m)	188 (180)	13:24 (14:30 – 14:45)	60% participants with luggage (108)
Rest (remove BA)	N/A	13:25 (14:45 – 15:15)	
BA2_CD2_1(NoBA)	190 (180)	14:00 (15:15 – 15:30)	60% participants with luggage (108)
BA2_CD2_2(NoBA)	191 (180)	14:14 (15:30 – 15:45)	60% participants with luggage (108)
BA2_CD2_3(NoBA)	191 (180)	14:30 (15:45 – 16:00)	60% participants with luggage (108)
BA2_CD1_1(NoBA)	190 (180)	14:54 (16:30 – 16:45)	40% participants with luggage (72)
BA2_CD1_2(NoBA)	189 (180)	15:10 (16:45 – 17:00)	40% participants with luggage (72)
BA2_CD1_3(NoBA)	188 (180)	15:25 (17:00 – 17:15)	40% participants with luggage (72)
BA2_CD0_1(NoBA)	189	15:31	Bonus trial - no luggage and no BA
BA2_CD0_2(NoBA)	191	15:39	Bonus trial - no luggage and no BA
BA2_CD0_3(NoBA)	191	15:48	Bonus trial - no luggage and no BA

On Day 2, up to 249 people participated in the TS3 trials. Participants were requested to arrive at 08:00 so that they can be arranged into groups. Trials began at 09:00 and were completed at around 14:40. The trials were conducted faster than planned and so an extra trial series was done at 4.5m wide and without the BA. This would allow comparison of the exit unit flow for the narrow exits to determine whether a consistent unit flow was achieved across the different exit width trials. The schedule for the Day 2 trials is shown in Table 3.

Table 3: Final Schedule TS3 Day 2.

Trial	EW (m), SD (m)	# People (Planned)	Actual Time (Planned Time)
SD1_EW2_1	3.5m, 1m	239 (252)	09:05 (09:00 – 09:15)
SD1_EW2_2	3.5 m, 1m	241 (252)	09:19 (09:15 – 09:30)
SD1_EW2_3	3.5 m, 1m	241 (252)	09:35 (09:30 – 09:45)
Rest (EW change)			09:36 (09:45 – 10:15)
*SD1_EW1_1	4.5 m, 1m	241 (324)	10:12 (10:15 – 10:30)
SD1_EW1_2	4.5 m, 1m	241 (324)	10:20 (10:30 – 10:45)
SD1_EW1_3	4.5 m, 1m	242 (324)	10:29 (10:45 – 11:00)
Rest (SD change)			10:30 (11:00 – 11:30)
SD2_EW1_1	4.5 m, 2m	236 (324)	11:00 (11:30 – 11:45)
SD2_EW1_2	4.5 m, 2m	236 (324)	11:09 (11:45 – 12:00)
SD2_EW1_3	4.5 m, 2m	237 (324)	11:19 (12:00 – 12:15)
Rest (EW change)			11:20 (12:15 – 13:15)
SD2_EW2_1	3.5 m, 2m	238 (252)	11:46 (13:15 – 13:30)
SD2_EW2_2	3.5 m, 2m	239 (252)	11:55 (13:30 – 13:45)
SD2_EW2_3	3.5 m, 2m	240 (252)	12:05 (13:45 – 14:00)
Lunch (SD change)			12:06 (14:00 – 14:30)
SD3_EW2_1	3.5 m, 3m	211(252)	12:55 (14:30 – 14:45)
SD3_EW2_2	3.5 m, 3m	224 (252)	13:02 (14:45 – 15:00)
SD3_EW2_3	3.5 m, 3m	234 (252)	13:11 (15:15 – 15:30)
Rest (EW change)			13:12 (15:30 – 16:00)
SD3_EW1_1	4.5 m, 3m	238 (324)	13:40 (16:00 – 16:15)
SD3_EW1_2	4.5 m, 3m	240 (324)	13:47 (16:15 – 16:30)
SD3_EW1_3	4.5 m, 3m	238 (324)	13:56 (16:30 – 16:45)
Rest (SD change)			13:57 (15:30 – 16:00)
NB_EW1_1	4.5 m, NoBA	231	14:14 (16:00 – 16:15)
NB_EW1_2	4.5 m, NoBA	240	14:25 (16:15 – 16:30)
NB_EW1_3	4.5 m, NoBA	233	14:40 (16:30 – 16:45)

* This trial was repeated as the cameras were not recording when it first started at 10:02am.

2.3 EXPERIMENTAL DESIGN

A detailed design was produced to ensure the scheduling and management of the resources involved in the experimental trials was met. This was necessary given the scale and complexity of the operation and the importance of ensuring the credibility of the results produced.

2.3.1 RESOURCES

The resources fell into four different categories:

1. physical,
2. human,
3. data collection, and
4. administrative and miscellaneous.

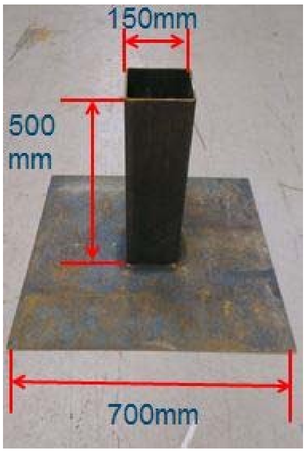
These categories are now discussed.

2.3.1.1 PHYSICAL RESOURCES

The trials were conducted on University of Greenwich grounds, in the Queen Anne Courtyard. This location was selected given that the adjacent arches approximate the exit dimensions required to replicate station exit conditions, the courtyard affords excellent opportunity for crowd management, and the courtyard also provided a number of excellent vantage points for camera positions. The assumption is that this physical environment provides results that can be translated to the external environment around a station.

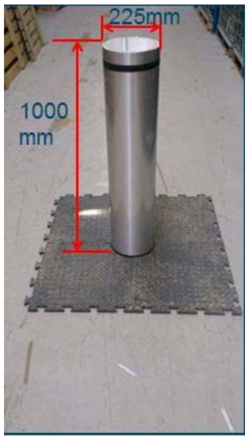
Given the intended arrival patterns of the participants, their movement during the trials and the length of the time that the participants were active, the trials required the road between the Queen Ann Courtyard arch and Queen Mary Courtyard Cafeteria to be closed during each of the trial days. In addition, UoG staff were positioned around the perimeter of the trial area to ensure that any unplanned vehicle arrivals were stopped and also to ensure that participants were appropriately registered. Two basic spatial configurations were required given the schedule described in Section 2.2. TRL (Transport Research Laboratory) were responsible for configuring the two locations to the required specification. The bollards used in the second trial campaign were identical to those used in the first trial campaign and consisted of:

- A solid square metal base plate (3mm thick and 0.7m wide) with a square column (0.15m wide) extending perpendicular from the base plate to a height of 0.5m (see Figure 2a)
- A cylindrical sheath with 0.225m outer diameter and 1.0m in height made of PVC drain pipe represented the actual bollard (see Figure 2b).
- The sheath was covered in brushed aluminium vinyl wrap with black duct tape used for the bands. The cap was made of acrylic and covered with the same wrap (see Figure 2c).
- The sheath was placed over the supporting column (see Figure 2d).
- Four floor tiles were used to cover the base plate and secure the bollard in place (see Figure 2e).
- In the TS1 trials, the spacing between bollards was 1.2m.
- In TS2 0m bollard trials, the exit opening measured 2.4m in width and the single bollard was placed in the centre of the opening, providing a clear distance either side of the bollard of 1.088m.
- In TS1 a total of 4 bollards were used in the 1m and 1.5m BA, two either side of the centre line while in the 2m BA, 6 bollards were used, three either side of the centre line.
- In TS3 a total of 10 bollards were used with 13m between the outer surfaces of the outer bollards in the array, providing 10.8m of effective space through which to move.



(a) Base plate

(b) Sheath



(c) Covered sheath

(d) Sheath over base plate

(e) Floor tiles used to lock bollard in place

Figure 2: Bollard Arrangement

TS1 and TS2 made use of the archway at the south end of the Queen Anne courtyard. This required the floor area around the arch to be enhanced to ensure a reliable and consistent surface. It also required the insertion of a BA at various locations (stand-off positions of 0m, 1m, 1.5m and 2m from the arch) within the artificial flooring to ensure that the BA standoff distances (outlined in Section 2.2) were achievable. TRL staff developed a reliable and flexible flooring system enabling the BA positioning using a simple tiling approach (see Figure 3).

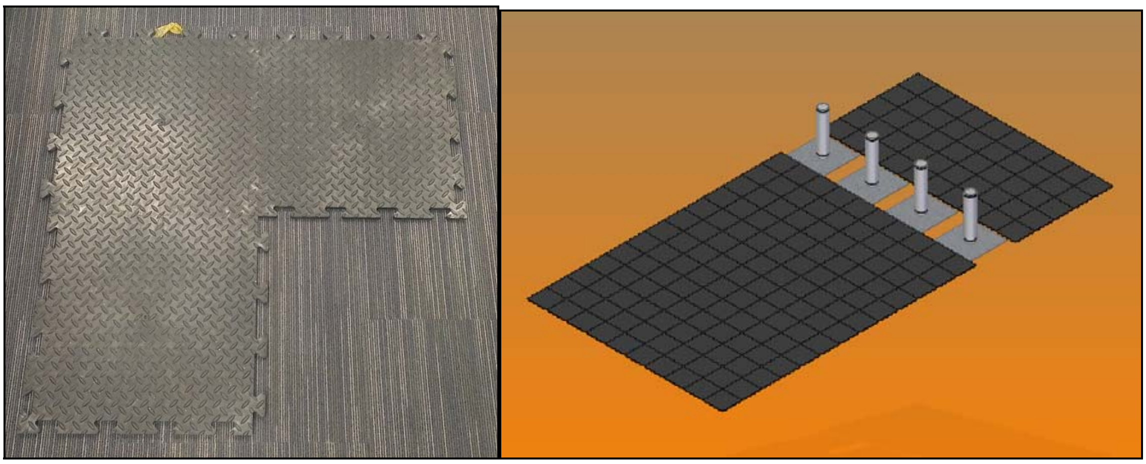


Figure 3: (a) Interlocking floor tiles. (b) BA base plates slipped under custom cut tiles.

The spatial configuration for TS1 is shown in Figure 4. TS2 required a single bollard to be located at the arch itself, in order to represent the 0m stand-off condition. Again, this required modifications to the flooring in order to facilitate this configuration.

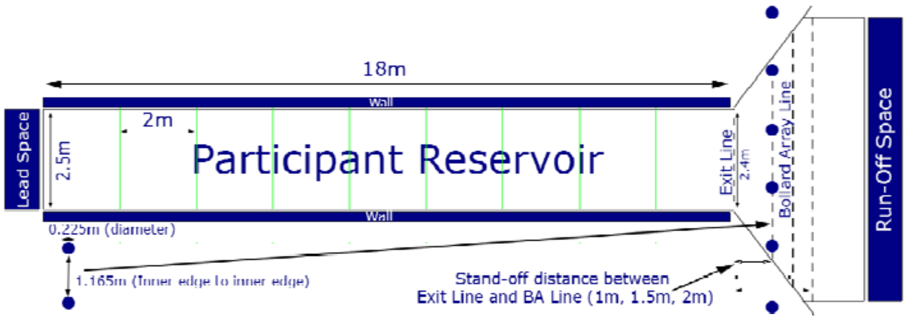


Figure 4: Dimensions of archway in Queen Anne Court.

In order to ensure the consistency of the population density within the arch, TS1 and TS2 required nine sections to be marked off. These started at the northern limit of the arch and then extended back beyond the southern end of the arch, where the arch was effectively extended using side barriers. Each section measured 2.5m x 2m. Each section was filled with 20 participants to produce the required population density. These marked out sections aided in the management of the participants and the control of the conditions during the trials. They also facilitated a range of measurements and calculations to be made (see Figure 4).

Similarly, a location also had to be prepared for the TS3 trials. These made use of the centre of the Queen Anne courtyard. Again, this required the floor area used to be enhanced to ensure a reliable and consistent surface. It again required the insertion of a BA within the artificial flooring. The trials in TS3 were performed with the BA present and without a BA.

TS3 presented the participants with 10 bollards (with approximately 13m between the outer surfaces of the outer bollards in the array), providing 10.8m of effective space through which to move. TS3 required nine sections to be marked off in the storage area. Two exit widths were used, 3.5m and 4.5m. Each section measured either 2m x 3.5m or 2m x 4.5m and were filled with either 28 or 36 participants in order to produce the desired 4 p/m^2 (see Figure 5).

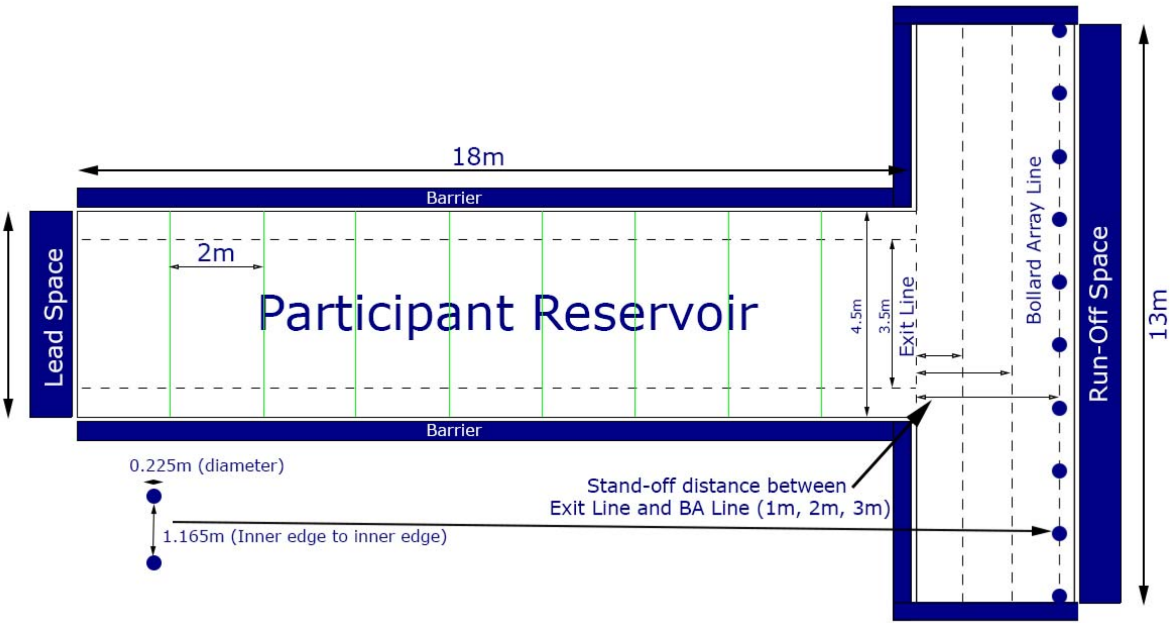


Figure 5: TS 3 configuration.

TRL staff visited the site on several occasions prior to the trials in order to get a better understanding of the space and ensure the flooring, side barriers and BA set-up were appropriate. They then prepared the site for the two trial dates as shown in Figure 6 (where TS1/TS2 preparations are shown) and Figure 7 (where TS3 preparations are shown).

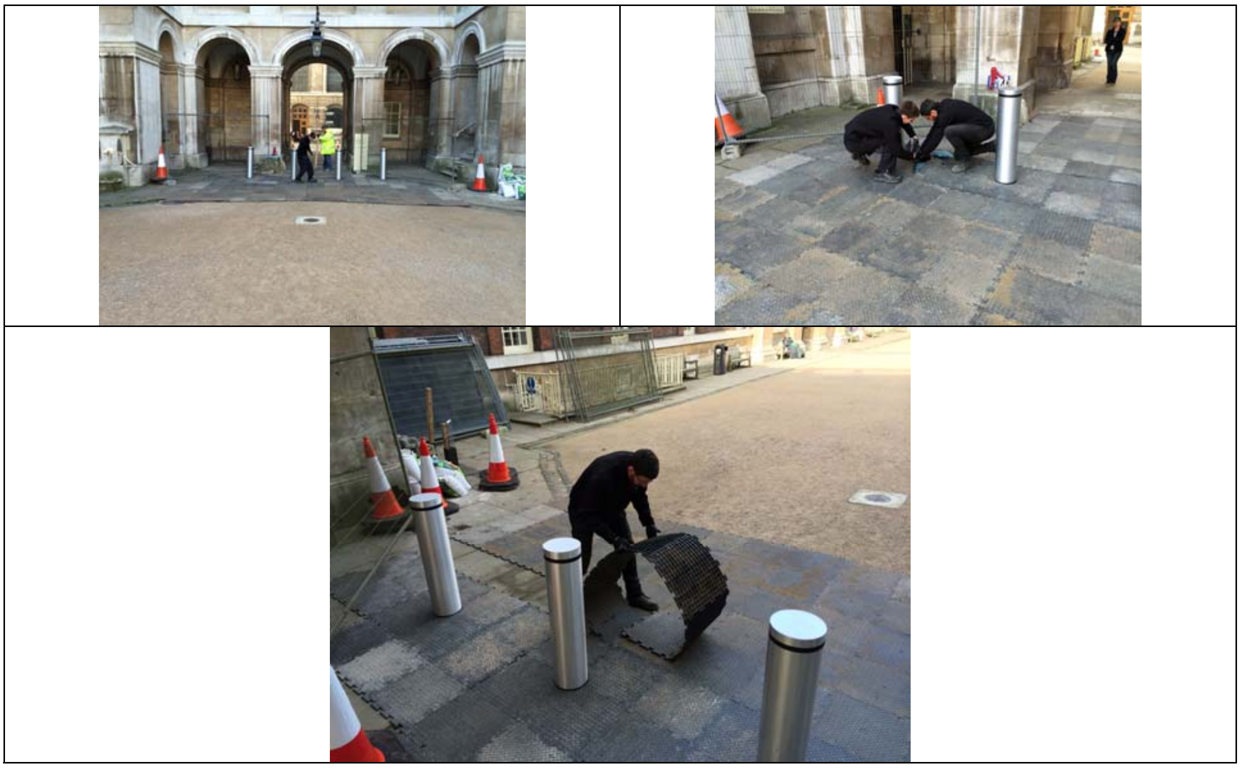


Figure 6: TRL staff preparing the BA and flooring set-up for TS1 and TS2 on Day 1.

Figure 7: The TS3 configuration prepared by TRL and UoG for TS3 on Day 2.

The TS2 trials (0m BA and NoBA trials) involved participants carrying different levels of encumbrance. The population were provided with different types of encumbrance ranging from handbags to pushchairs and bikes (see Table 4). The roller bags and pushchairs were weighted down with a 15kg sand bag. The smaller luggage items were packed with bubble wrap in order to pack them out (see Table 4). Three levels of encumbrance were investigated involving set proportions of the population carrying some form of encumbrance. These were 0%, 40% and 60%. This represented the proportion of the population that had some level of encumbrance.

In total TRL purchased 160 pieces of luggage with 76 pieces being used for the 40% level of encumbrance and 122 pieces were used for the 60% level of encumbrance (actual level of encumbrance was 64%). Efforts were made to ensure that the number and type of encumbrance were the same through repeat trials, but this proved to be difficult given the time constraints.

Table 4: Luggage used in the 0m BA trials

Type	Available	40%	60%	Nature of Encumbrance
Handbag	66	34	49	 
Satchel	36	15	29	 
briefcase	24	11	19	 
rucksack	22	9	13	 
Small roller bag	3	2	3	 
Large roller bag	3	2	3	 
bike	3	1	3	
Push Chair	3	2	3	 
	160	76	122	

2.3.1.2 HUMAN RESOURCES

During the trials a number of people were required to adopt specific roles to ensure several key activities:

(1) ACTIVITY 1 - Management of the participants.
(2) ACTIVITY 2 - Data collection activities.
(3) ACTIVITY 3 - Administration activities.
(4) ACTIVITY 4 - Overall coordination.
(5) ACTIVITY 5 - Configuring the space.
(6) ACTIVITY 6 - Health and safety of the participants.
(7) ACTIVITY 7 - Cafeteria service.

FSEG staff fulfilled activities (1-4). In total 12 members of FSEG were on hand during each day of the trials. Each member of staff had predefined roles and responsibilities during each day of the trial (see example plan shown in Table 5).

Table 5: Example role description.

Staff	Role
EG	Coordinator
CH	People Management
MP	People Management
DC	Camera / Resources
AV	Camera / Resources
XH	Camera / Resources
SD	Camera / Resources
LH	People Management / Administration
KJ	Administration
LF	People Management
A	People Management
SG	People Management

The activities were carefully planned prior to the trials, with the activities of the staff carefully choreographed to ensure that the conditions were appropriate for the trials at hand. Activity 5 was conducted by TRL staff on each day of the trials and also during preparation days where necessary. Activity 6 was fulfilled by a St. Johns First Aider who was onsite at all times during the trial. Activity 7 was conducted by UoG cafeteria staff who were onsite at all times.

2.3.1.3 ADMINISTRATIVE AND MISCELLANEOUS

As part of the preparation for the trials, the entire process had to be submitted to the UoG Research and Ethics Committee (REC) review to ensure that the participants were not being placed in undue danger, that appropriate data handling, in particular the use of video footage was put in place and that all necessary precautions were being taken. This also required a detailed risk assessment in order to establish where hazards might appear, their potential impact and what might be done about them (see ANNEX C: RISK ASSESSMENT). The submission document is extensive and can be provided on request. However, the submission was successful allowing the trials to proceed.

In addition to the REC submission, a number of key tasks needed to be completed in preparation for the trials. These included advertising to recruit volunteers, purchase of required luggage forTS2, etc. The advertisements used to attract the participants are shown in ANNEX D: ADVERTISEMENT and ANNEX E: WEB ADVERTISEMENT. More detailed descriptions of tasks/resources related to the planning and preparation of the trials can be found in ANNEX F: BRIEFING to ANNEX H: EQUIPMENT DETAILS.

UoG were acutely aware of the time constraints placed on the trials. The registration process was then similarly choreographed to ensure that undue time was not wasted. It was also necessary to limit the time that the payment funds were exposed to potential theft; i.e., not in a secure safe. This was also necessary given the modest space available in the cafeteria given the number of expected arrivals.

2.3.1.4 DATA COLLECTION

The following discussion describes the equipment setup and usage for the experimental trials, showing the locations of cameras with an example view from each camera and of each camera in position. While a maximum of four cameras were required for the trials, a total of 10 cameras were provided to ensure backups were available. A more detailed description of the equipment is provided in ANNEX H: EQUIPMENT DETAILS.

A different camera configuration was used for each series of the trials: TS1/TS2 (Exit flow trials) and TS3 (exit width trials). Irrespective of the camera configuration, the same procedure was adopted:

- Each location took approximately 10 minutes to setup, plus some movement and checking time. Therefore, an hour was allocated to safely setup the camera locations employed in each series of trials.
- The view from each camera was checked to ensure that all areas of analytical interest were covered, the battery levels confirmed and that the camera and clamps were securely fixed in place.
- In each trial, recording started shortly before the start of the trial and was stopped once all the participants had cleared the area.
- Each person at these locations had a Walkie-Talkie.

In the TS1 and TS2 configurations, the cameras needed to capture participants entering the Queen Anne (QA) Courtyard from under the arch (2.5m wide) and moving towards the other end of the Courtyard. Four different Bollard Arrays (BA) were positioned in the path of the participants at stand-offs of 0m, 1m, 1.5m and 2m. The movement of participants was recorded using 4 cameras (see Figure 8). This approach was used during the first day of trials that were conducted over the first weekend 29th of March.

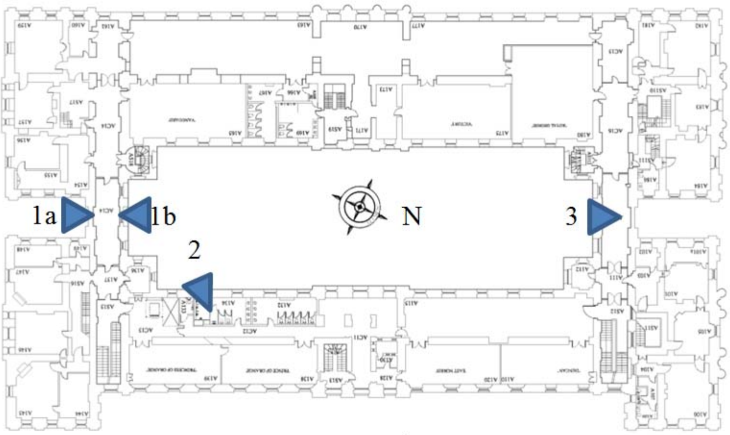


Figure 8: TS1 and TS2: Exit Flow Trials.

The four camera positions used during TS1 and TS2 are shown in Figure 9 and the views captured by the video cameras are shown in Figure 10 in relation to several trial examples.


Camera 1a


Camera 1b


Camera 2


Camera 3

Figure 9: TS1/TS2: Camera Positions employed.

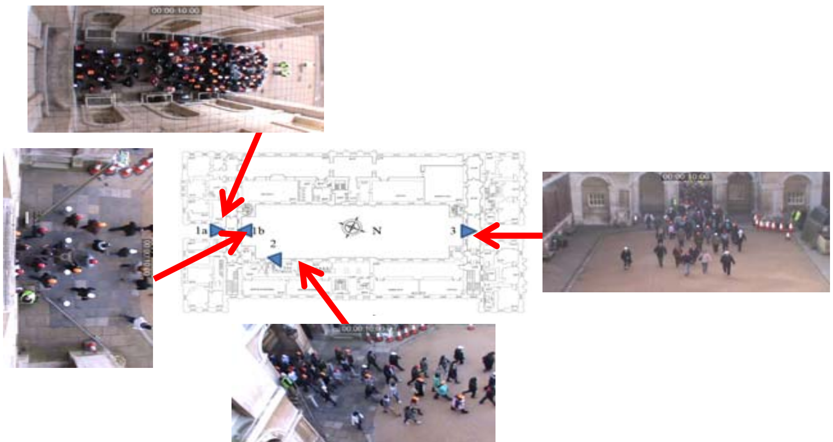


Figure 10: TS1/TS2: Exit Flow Trials – Camera Views.

In the TS3 configuration, the cameras needed to capture participants moving through the BA in the centre of the QA courtyard confined to an artificial corridor created using barriers to maintain density. The movement of the participants was recorded using four cameras setup at four locations (see Figure 11).

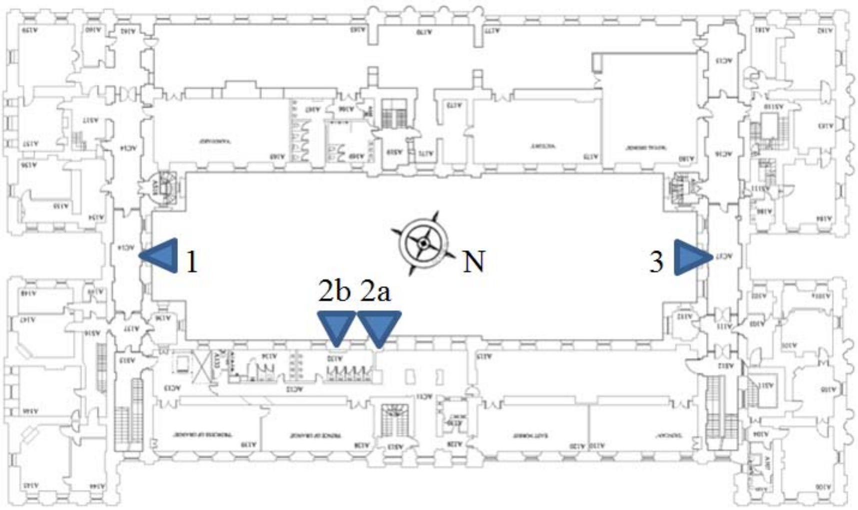


Figure 11: TS3: Exit Width Trials.

The four camera positions used during TS3 are shown in Figure 12.

Figure 12: TS3: Camera Positions employed.

The views captured by the video cameras from these positions are shown in Figure 13 in relation to several trial examples.

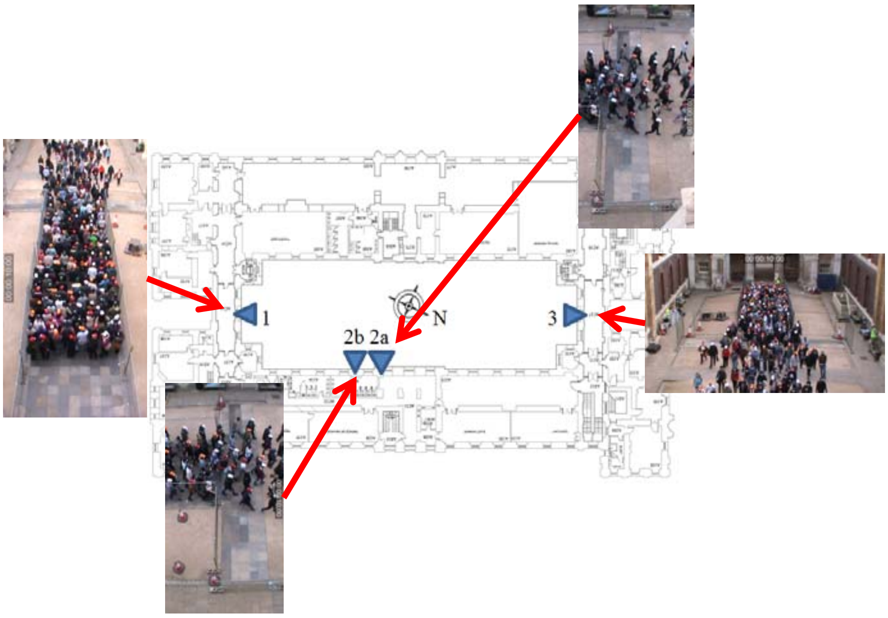


Figure 13: TS3: Exit Width Trials – Camera Views.

2.3.2 PARTICIPANTS

Participants were recruited using advertising placed in local newspapers and on the web (see ANNEX D: ADVERTISEMENT and ANNEX E: WEB ADVERTISEMENT). Given that participants were expected to be involved for the entire trial day (8 hours) it was necessary to provide them with financial compensation for participating. The participants were therefore provided with £45 per person per day to cover their travel and incidental costs.

In order to ensure that sufficient numbers were available, a target number of recruits were specified that included a buffer population that would be used should people not turn up or be forced to drop out during the trials. Given this, a minimum of 180 participants was needed to fully fill the nine sections at $4p/m^2$ in TS1/TS2 and 324 were needed for TS3. In addition, a 10% buffer population was also recruited – producing an overall participant population of 560 (i.e., 200 + 360). At the end of the recruitment process, 648 participants had registered for day 1 (TS1 and TS2) and 599 participants had registered for day 2 (TS3). The required number of people were selected from the list of volunteers in order to provide as close to an even gender mix and age distribution on each of the trial days as possible. The remainder of the volunteers were held in reserve in case additional people were required due to drop outs. 242 participants were invited to participate in the day 1 trials and 399 participants were invited to participate in the day 2 trials, all those invited indicated that they would attend. Of the 631 participants invited to take part in the trials, 436 participants actually attended the trials.

The actual number of attendees for each of the days is shown in Table 6 (also see ANNEX G: PARTICIPANT DETAILS). On day 1 approximately 18% (41) of the registered volunteers failed to attend day 1 and on day 2 approximately 39% (154) failed to turn up. However, during the trials, no volunteers withdrew from the trials.

Table 6: Demographic distribution of attendees for each day of the trials.

Trial day	Total attendees	Breakdown of attendees				
		Gender		Age		
		Male	Female	18-30	31-50	51+
Day 1	191 (2)*	85	104	75	60	54
		45.0%	**55.0%**	**39.7%**	**31.7%**	**28.6%**
Day 2	245 (3)*	104	138	104	75	63
		43.0%	**57.0%**	**43.0%**	**31.0%**	**26.0%**

*On Day 1 and 2, 2 and 3 people respectively provided no gender and age information.

There were two types of dropouts, those that gave prior warning, thereby enabling the recruitment of other volunteers and those that failed to provide any warning. These are described in detail in ANNEX G: PARTICIPANT DETAILS). Presented in Table 7 is a description of all the registered participants who failed to turn up.

Table 7: Total number of registered participants that dropped out before the trials.

	Drop-outs				
	Male	**Female**	**18-30**	**31-50**	**51+**
Day 1 (29.03.14)	34	33	29	6	6
Day 2 (30.03.14)	98	56	102	39	13

Although different from the number of invited participants originally stating that they would participate, the actual number of attendees was deemed sufficient for the trials to be conducted as planned. A key criteria in this decision was whether sufficient steady-state flow was generated during the trial and whether this then had the potential for feeding back into areas of interest. For instance, whether the length of the participant flow was long enough to be engaged with the BA (up to 3m away) and the exit point simultaneously and for a sufficient period of time in order to make meaningful measurements. Given the numbers available, this was deemed to be the case after the performance of several engineering calculations; this assertion was proved to be correct during the trials. The large number of dropouts for day 2 was anticipated as the 30 March was mother's day. Thus additional participants were recruited for day 2. The actual and planned number of participants involved in each trial is show in Table 1- Table 3.

2.3.3 OUTPUT

The trials were designed to produce results that allowed the examination of the impact of the presence and location of BA upon the pedestrian dynamics generated. Key outcomes of the analysis are an assessment of the following:

- The flow produced leaving the exit given the presence/absence of bollards. This is measured in persons per minute (ppm or p/min).

- The unit flow produced leaving the exit given the presence/absence of bollards. This is measured in persons per metre of available width per minute or per second (p/m/min or p/m/sec).
- The flow produced at the bollard location given the presence/absence of bollards. This is measured in persons per minute.
- The population densities produced at the bollard location given the presence/absence of bollards – *the impact of bollards on the population conditions at the bollard location.* This is measured in persons per metre squared (p/m^2).
- Use of the routes available between the bollards in the BA. This is referred to as gap analysis.
- Diversionary action taken by participants at the BA due to the presence of a bollard. This is referred to as collision avoidance analysis.
- Qualitative description of pedestrian flows - *the impact of bollards on the general flows at and around the BA.*

The full-set of original results are presented in ANNEX I: RESULTS. A sub-set of these results are presented in the body of the report. This sub-set represents the steady (peak) flow conditions with the initial and final time periods excluded.

The data reduction was performed to account for (a) the initial time period where the flow at the exit was more sensitive to the acceleration of individual participants starting from a standing start (ramp up period), (b) the final time periods where the flow at the exit was more sensitive to the small number of participants exiting over the measurement period (ramp down period), and (c) that in the periods described in (a) and (b) the trials would not reflect the impact of the BA upon the flow conditions of interest. In the ramp up period, the flow conditions produced were not reflective of the appropriate travel speed while in the ramp down period, the flow conditions were not representative of the density requirements of the trial. Therefore, the steady-state conditions are included for detailed analysis, where steady-state reflects the desired experimental conditions available after performing actions (a) and before (b).

It is felt that the resultant data-sets produced after the data-reduction exercise undertaken are more reliable, more representative and provide a more consistent indication of the conditions produced during the trials. This is also consistent with the data analysis undertaken for the first trial campaign.

2.3.4 LIMITATIONS

It is important to recognise the limitations of any set of experimental trials. This may be down to limitations in the experimental design/execution, the presence of uncontrolled variables, issues with the data collection/analysis or in the achieved similarity between the experimental conditions and real-world phenomena of interest.

Experimental Design/Execution

(1) **Population Demographics.** The demographics of the population used in the second trial campaign were deliberately meant to resemble, as much as possible, that of the first trial campaign. The demographics of the first trial campaign was selected to represent as wide a spread of age and gender mix as possible and also to resemble

typical commuter populations. While it was difficult to maintain an exact agreement between the two populations, the demographic mix for both trial campaigns are broadly similar (see Table 8).

Table 8: 2013 vs 2014 NoBA trials.

Trial day	**Total number**	**Breakdown of participants**							
		Gender		**Age**					
		Male	**Female**	**18-30**	**31-50**	**51+**	**Male**	**Female**	**overall**
2013 Day 1&2	319	155	164	149	109	61	35.1	38.0	36.6
		48.6%	**51.4%**	**46.7%**	**34.2%**	**19.1%**			
2014 Day 1	191 (2)*	85	104	75	60	54	36.3	41.0	38.9
		45.0%	**55.0%**	**39.7%**	**31.7%**	**28.6%**			

* 2 people on this day have no gender and age information.

As the population in the second trial campaign is slightly older with a slightly larger female proportion, we may expect the walking speeds for the second trial campaign to be slightly lower than that of the first trial campaign and hence the flows in the second trail campaign to be slightly smaller.

(2) **Approach to the outer gaps for the 2m BA.** There was a slight difference in the barrier configuration relative to the BA between the first trial campaign and Day 1 of the second trial campaign. In the first trial campaign as the BA was at least 3m away from the exit there was a portion of straight perimeter barrier flanking the sides of the pedestrian flow area (see Figure 14). This allowed the participants to have an unrestricted approach to the gaps at either end of the BA. In the second trial campaign as the BA was between 1m and 2m from the exit the BA was placed within the pedestrian flow area flanked by the angled perimeter barriers (see Figure 15). This meant that the approach to the outer gaps of the BA were slightly restricted. This slight restriction may have discouraged some use of the outer gaps which may have in turn restricted the degree of spread of the participants and hence impacted the exit flow. This configuration was necessary as it was considered important to maintain as much commonality between the first and second trial campaigns as possible. This difference may negatively impact the comparison of the first trial campaign with the results of the second trial campaign.

Figure 14: Trial campaign 1 in 2013, 6 m BA

Figure 15: Trial campaign 2 in 2014, 2m BA

(3) **Expanse of BA for 1m and 1.5m BA.** In the first trial campaign 5 gaps between 6 bollards were available for the 3m and the 6m trials (see Figure 14). However, in the second trial campaign, as the BA was placed much closer to the exit and so the diagonal barriers had an impact on the expanse of BA that could be used and on the available free width of the BA (see Figure 16). At 1m from the exit, only 4 bollards and 3 gaps were available (see Figure 17). The clear width without BA was 5.46m, the width to the inside edge of the outer bollards was 4.05m and the clear width with the BA was 3.6m. At 1.5m from the exit, only 4 bollards and 3 gaps were again available (see Figure 17). The clear width without BA was 6.37m, the width to the inside edge of the outer bollards was 4.05m and the clear width with the BA was 3.6m.

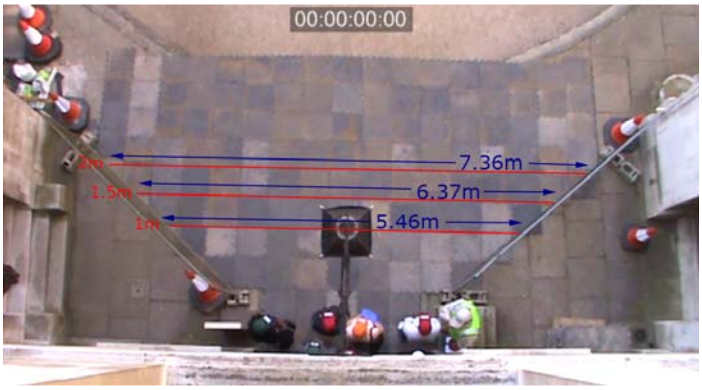


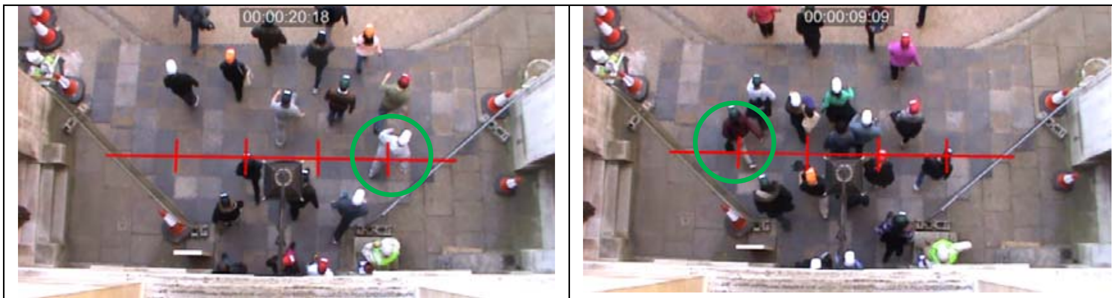
Figure 16: Exit geometry for Day 1 2014 trials.

a) 1m BA	b) 1.5m BA

Figure 17: BA at 1m and 2m stand-off.

Thus at 1.5m the BA is identical to that at 1m. The expanse of BA for the 1m and 1.5m are identical and smaller than that at 2m. This restriction in BA width may impact the exit flow. Furthermore, the width of BA at 1.5m has been made artificially smaller than it should be as the outer edges were blocked as they did not constitute sufficient space to make up a 1.2m gap (Figure 17b).

Without the BA present, there is a natural tendency for the crowd to spread out the further they are from the exit point [3]. This has been shown to be even more pronounced with the presence of a BA which tends to act as a divergent lens spreading the crowd [3]. At a distance of 1.5m without BA, participants were observed to use the outer most regions (see people highlighted by green circles in Figure 18) which were effectively blocked off in the BA trials. Thus with the BA at the 1.5m stand-off we are constraining the flow more than that which would be achieved simply due to the BA. This reduction in effective exit width at 1.5m due to the blocking of space will impact the flow at the BA line and also at the exit. Because of these reasons it is suggested that the 1.5m BA stand-off results may have been severely impacted by the nature of the experimental setup and hence the results from these trials should not be considered when attempting to identify overall trends.



a) Person passing to the right of right most bollard location

b) Person passing to the left of left most bollard location

Figure 18: NoBA observations at 1.5m line.

(4) **Repeat trials with the same population.** The population on each day participated in a number of repeat trials, and some participants participated on more than one day of trials. Normally it is undesirable to reuse participants in behavioural trials due to learning effects. However, as these trials did not focus on the observation of participant behaviour, but were more concerned with physical performance the reuse of participants was not considered to have a significant negative impact. Indeed, it may be argued that in reality, most commuters at stations will have a good knowledge of the station layout and exit configuration through repeated use of the facility and so the reuse of participants may be considered representative. Furthermore, it is important to note that the participants were not informed of the detailed nature of the trials, and so they were not aware of what aspects of the exercise were being monitored or measured.

(5) Fatigue. The reuse of participants and the resulting fatigue that this may cause may impact the quality of some of the results. In particular the NoBA trials which are the basis for comparison. For the second trial campaign the NoBA trials on Day 1 were performed as bonus trials as it was expected that the results from the first trial could be used for comparison purposes. These trials were completed at the end of the day at around 16:00 with the participants completing a total of 24 trials. This is compared to the first trail campaign, where the participants completed the trials by 13:00 and completed far fewer trials (12 on day 1 and 20 on day 2). Thus the NoBA trials for the second trial campaign may be influenced by the impact of fatigue.

(6) Encumbrance levels. For TS2 efforts were made to ensure that the number and type of encumbrance was the same through repeat trials, but this proved to be difficult to achieve with a high degree of certainty given the time constraints. However, the variations between the trials are not thought to be significant.

(7) **Direction targets.** Participants broadly moved in the direction that they were facing given that all of the participants had the same objective located directly ahead of them. The trials focused on examining only a section of a BA outside of an exit. In reality, pedestrians would have had more degrees of freedom in their choice of routes given the range of objectives that might have been present. Furthermore, these choices may have been made inside the station (entirely based on their final objective) or before they had reached the BA (based on their objective, local conditions or everyday routine). The approach adopted may therefore have excluded the complexity of pedestrian route selection that may exist in reality. However, the presence/absence of the BA is unlikely to influence this form of route selection – they are unlikely to influence the final objective of pedestrians in reality. Although the additional crowd dynamics that might be produced by these route selection decisions are absent, this absence should equally influence those trials with and without BA. Therefore although the limitation should be acknowledged, it should not act to prevent the comparison between the two conditions – the presence or absence of the BA. Route selection may also favour one part of the BA over another. In the trials, while the target was directly ahead of the participants, the participants could fan out and use the entire width of the BA. Indeed, in TS1 participants were seen to use the entire width of the BA, albeit to a significantly lesser extent for the outer parts of the BA. However, had the target point been off to one side, this may have meant that the participants would focus on only one part of the BA. It may be important to examine the impact of targets off to one side. As this aspect was not tested in these trials it may warrant further analysis in future trials.

Uncontrolled Variables

(1) The trials were conducted in an uncovered environment i.e., outside. They were therefore subject to the weather conditions. During both trial days the weather was very good compared to the inclement weather of the first trial campaign (see Section 1.2). The differences in weather conditions between trial campaign 1 and 2 may have influenced performance, making direct comparison between the trial campaigns difficult.
(2) The participant population was not as large as desired. However, the conditions produced were sufficient (in longevity and nature) for the trials to produce meaningful results.

Similarity between the experimental conditions and real-world phenomena of interest

(1) Although the population did represent a cross-section of the general population, it may not necessarily have been representative of the pedestrian population at peak times at particular stations of interest.
(2) A station/airport was not used during the trials. Although the configuration approximated the exit route out from a station/airport, it did not have the appearance of a station/airport. The impact of this upon performance is unknown, although it would have been consistent throughout the trials.
(3) TS2 involved participants with differing levels of encumbrance. In situations involving airports, rail and underground stations it is highly likely that pedestrians will be encumbered with large pieces of luggage; e.g., brief cases, suitcases, pushchairs, etc. While these trials took this into consideration, it is not known with certainty what levels of encumbrance would be representative of these types of crowds. However, the upper level of encumbrance used in these trials is thought to be representative of crowds using London rail/underground stations.

2.4 ADDITIONAL TRIALS

On Days 1 and 2 of the trials, additional trials were made possible by efficient participant management and turnaround times. On Day 1 this meant that three additional runs were undertaken for the NoBA condition with no luggage. On Day 2 three additional trials were also run involving the 4.5m exit width with NoBA. In both cases the additional trials were run at the end of the day (see Table 2 and Table 3).

3 DATA ANALYSIS METHODOLOGY

A large volume of data was produced from the trials. This was due both to the number of trials conducted and also due to the number of video cameras employed. As a result an analytical framework was created to manage the data produced and ensure that the analysis was conducted consistently throughout. The methodology employed was identical to that developed for the first trial campaign.

The analysis involved the following steps:

(1) Analysis of the video footage was performed using Adobe Premiere Pro.
(2) The footage from each camera for a trial was synchronised and a time stamp superimposed, with the clock starting from when the start whistle was heard.
(3) Checks were undertaken to ensure that the starting conditions (e.g. crowd densities) were correct for each trial; i.e., that they matched the specified experimental condition.
(4) Using one or more of the camera views (for cross-referencing) the trial video data was analysed. The data being extracted included initial densities, flow at exit, flow at bollards, density at bollards, gap usage and bollard avoidance.

Each type of data collected is now described.

3.1 DENSITY MEASUREMENTS:

Population densities were measured in the holding area before the start of the trial and at 5 second intervals at the BA line.

3.1.1 TS1, TS2 and TS3: INITIAL DENSITIES IN HOLDING AREA

The initial densities were critical as they represented a controlled variable in the experimental condition. For TS1/TS2 trials two 5m^2 areas were marked out in red over the video near the front and rear of the queuing participants (see Figure 19). The population within these areas at the start of each trial was then counted to ensure that the levels were as expected. Care had to be taken when counting someone within an area as the camera perspective had to be considered. In Figure 19, the trial condition required 4 p/m^2 starting density and there are 20 people in each area.

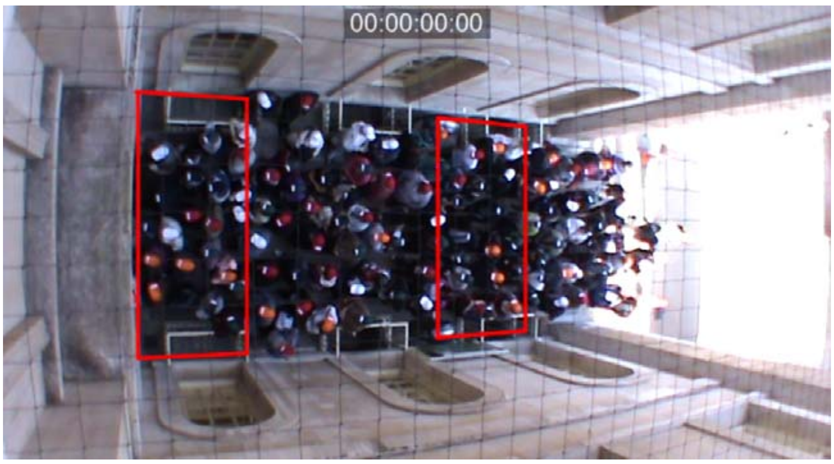


Figure 19: TS1/TS2 example footage from initial density analysis.

For the TS3 trial series, there were two different queuing areas depending on the width of the setup. When the effective width of the exit was 3.5m, the areas marked out are 7m^2 and there should be 28 people in the each of the areas, see Figure 20a. When the exit was 4.5m wide the areas marked out are 9m^2 and there should contain 36 people, see Figure 20b.

a) Starting density check for 3.5m exit width	b) Starting density check for 4.5m exit width

Figure 20: Example footage from initial density analysis for TS3 trials.

3.1.2 TS1: GENERAL DENSITIES AT BOLLARD ARRAY LOCATION

The area around the BA line was divided into three sections, a large central region (B: 6.77m^2 without bollards present) and two smaller outer regions (A and C: 2.26m^2 without bollards present). Region B equates to gaps 2-4 described in the following section, while A equates to gap 1 and C equates to gap 5. Lines were overlaid on the video footage, defining the areas at ground level, using the floor tiles as a guide (see Figure 21 and Figure 22).

a) Camera 1a, 1m BA

b) Camera 2, 1m BA

c) Camera 1a, 1.5m BA

d) Camera 2, 1.5m BA

e) Camera 1a, 2m BA f) Camera 2, 2m BA

Figure 21: Example footage from density analysis at 1m, 1.5m and 2m.

The depth of each region was 1.88m and covers a region of space both in front and behind the BA. When bollards were present within an area the total area of the bollards or part of bollards was subtracted to give the available area for participants to occupy. This became $6.65m^2$ for region B with bollard present and $2.22m^2$ for regions A and C. The density within these areas was measured at 5 second intervals. This was measured in order to establish whether the densities at the BA were significantly different from those in the exit area. This analysis was conducted for the 1m, 1.5m and 2m BA stand-off positions. It was also done for 3m and 6m in the trials when the bollard array was not present.

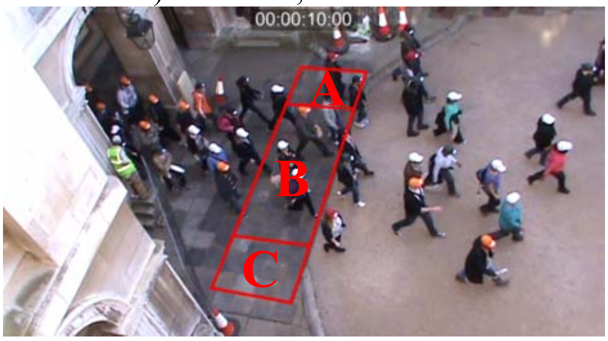
a) Camera 1a, 1m No BA b) Camera 2, 1m No BA

c) Camera 1a, 1.5m No BA d) Camera 2, 1.5m No BA

e) Camera 1a, 2m No BA

f) Camera 2, 2m No BA

g) Camera 1a, 3m No BA



h) Camera 2, 3m No BA

No Image
Distance out of camera view

i) Camera 1a, 6m No BA

j) Camera 2, 6m No BA

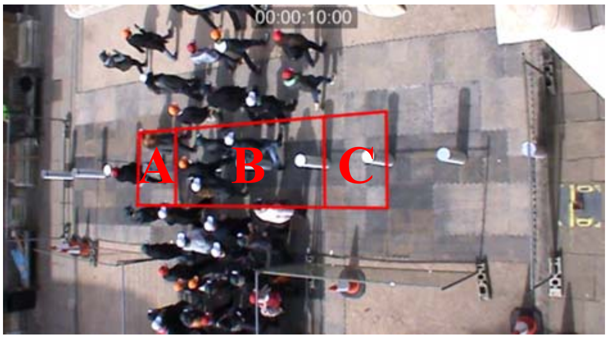
Figure 22: Example footage from density analysis at 1m, 1.5m, 2m, 3m and 6m (No BA).

At each time interval the number of people, within each area was counted. A person was counted if it was judged that at least half of their body footprint was within the marked region. Two camera views were required to reliably determine exactly where a person was located: Camera 1a and Camera 2. When a person was close to a boundary, careful consideration of the perspective of the camera angle was required. Examples of this analysis are shown in Figure 21 and Figure 22 for each distance of bollard. It should be noted that when the bollard array was only 1m or 1.5m distance from the exit, only the central region B can be compared when using these trials as regions A and C lie mostly outside the barriers, see Figure 22 (a-d). The density around the bollard for the 0m trials was assumed to be that of the starting conditions.

3.1.3 TS3: GENERAL DENSITIES AT BOLLARD LOCATION

Densities at the BA location were also calculated for the TS3 trials using the same method as described above. The area around the BA line was divided into three sections, a large central region (B: 6.77m^2 without bollards present) and two smaller outer regions (A and C: 2.26m^2 without bollards present). Region B equates to gaps 4-6 described in the following section, while A equates to gap 3 and C equates to gap 7. Lines were overlaid on the video footage, defining the areas at ground level, using the floor tiles as a guide (see Figure 23 and Figure 24). The density of people using the extreme gaps was not measured as this was generally zero or very low.

a) Camera 2a, 1m BA



b) Camera 2a, 2m BA

c) Camera 2a, 3m BA

Figure 23: Example footage from density analysis of 3.5m exit trials at 1m, 2m and 3m

The depth of each region was 1.88m and covers a region of space both in front and behind the BA. When bollards were present within an area the total area of the bollards or part of bollards was subtracted to give the available area for participants to occupy. This became 6.65m^2 for region B when bollards were present and 2.22m^2 for regions A and C. The density within these areas was measured at 5 second intervals. This analysis was conducted for the 1m, 2m and 3m BA stand-off positions for both the 3.5m and 4.5m exit width trials. It was also done for 1m, 2m and 3m distances in the 4.5m exit with trials when the bollard array was not present.

a) Camera 2a, 1m BA

b) Camera 2a, 1m No BA

c) Camera 2a, 2m BA

d) Camera 2a, 2m No BA

e) Camera 2a, 3m BA

f) Camera 2a, 3m No BA

Figure 24: Example footage from density analysis of 4.5m exit trials at 1m, 2m and 3m

At each time interval the number of people, within each region was counted. A person was counted if it was judged that at least half of their body footprint was within the marked region. Only Camera 2a was used to determine where a person was located as it provided the best view to judge when the participants were within the regions. When a person was close to a boundary, careful consideration of the perspective of the camera angle was required. Figure 23 and Figure 24 show an example of this analysis.

3.2 TS1 and TS3: GAP USAGE AT BOLLARD ARRAY LOCATION

The number of people using each gap during the TS1/TS3 trials over the entire trial period was counted in order to measure how the population spread out during the trials. For TS1 the gaps available were numbered 1 to 5 from left to right within the BA and with gap number 3 being the central gap, see Figure 25.

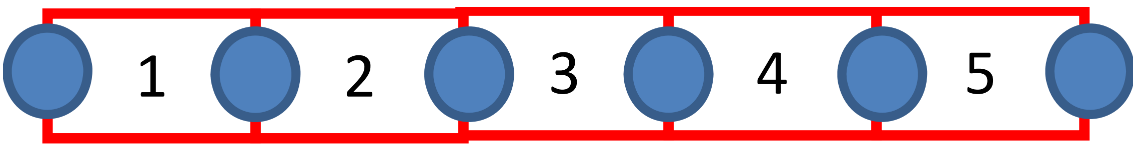


Figure 25: Numbering of the gaps within the BA.

For TS3 the gaps were numbered 1 to 9 with 5 being the central gap, see Figure 26. The examination of the use of these gaps is referred to throughout the discussion as gap analysis.

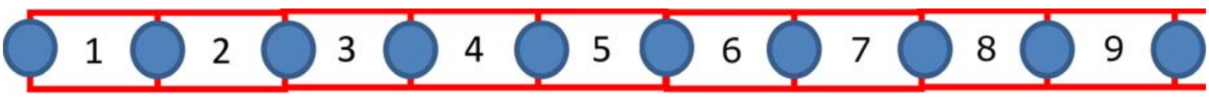


Figure 26: Numbering of the gaps within the BA.

The gap analysis was also conducted when the BA was not present for the two additional trial series that were done by overlaying lines where the BA would have been. This was done at 1m, 1.5m, 2m, 3m and 6m distance for the TS1 NoBA additional trial and at 1m, 2m, 3m for TS3 4.5m wide exit NoBA additional trials. Example footage of how this measurement was made can be seen in Figure 27.

a) TS1 2m NoBA	b) TS3 2m NoBA

Figure 27: Example footage of gap analysis measurement at BA location when BA was not present.

3.3 FLOW MEASUREMENTS

In TS1, TS2 and TS3, flow measurements were conducted at the exit point and at the BA position for the 1m, 1.5m, 2m and 3m bollard array trials and at each of these distances for the no bollard array trials. These were conducted at five second intervals to ensure that sufficient data was collected to characterise the performance of the participants.

3.3.1 EXIT FLOWS

To measure the flow at the exit, a red line was superimposed on the video footage along the start line at ground level. This line passed through where the bollard would be at 0m distance and was used whether or not the BA was present (see Figure 28). The number of people that passed the superimposed red line within each 5 second period was counted. A person was judged as having passed the line if at least half of their body footprint had crossed the red line during the time interval.

a) Camera 1a: 0m BA b) Camera 1a: No BA

c) Camera 2a: 1m BA d) Camera 2a: No BA

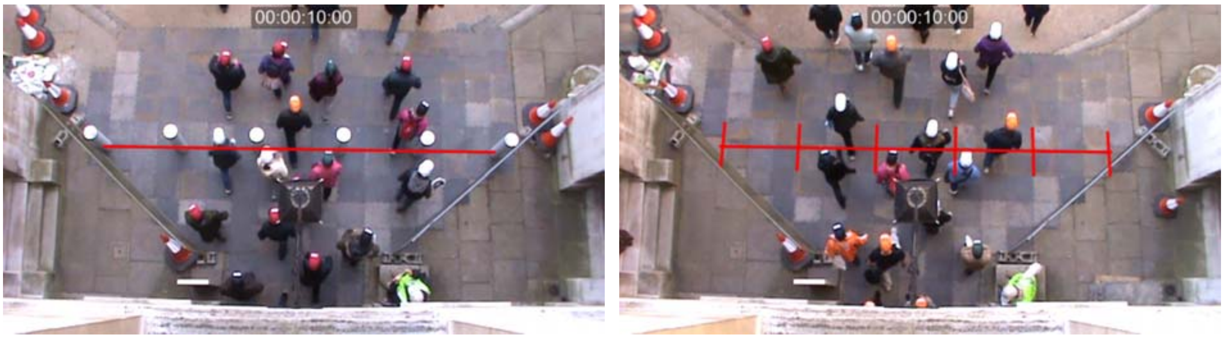
Figure 28: Example footage from exit flow analysis.

3.3.2 BA FLOWS

The flow was measured at the 1m, 1.5m, 2m stand-off positions for the TS1 trials (see Figure 29) and at 1m, 2m and 3m for the TS3 trials (see Figure 30). A line was superimposed on the video footage at ground height and along the line of the BA for each of the bollard trials and also at each of these distances for the respective no bollard trials. The number of people that had passed the superimposed red line within each 5 second period was counted.

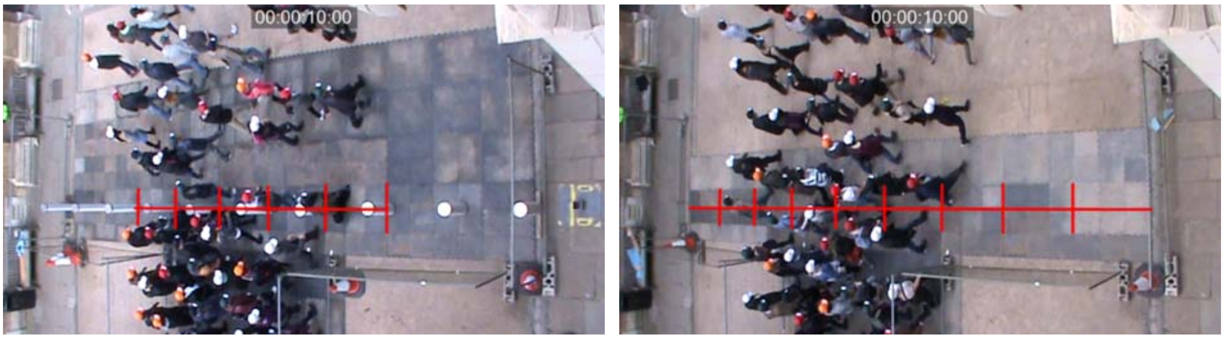
a) Camera 1a: 1m BA b) Camera 1a: 1m No BA

c) Camera 1a: 1.5m BA d) Camera 1a: 1.5m No BA

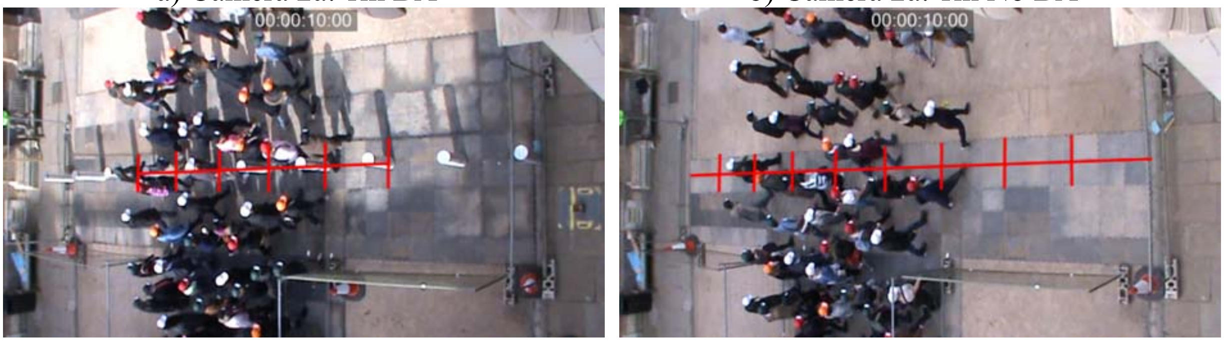


e) Camera 1a: 2m BA f) Camera 1a: 2m No BA

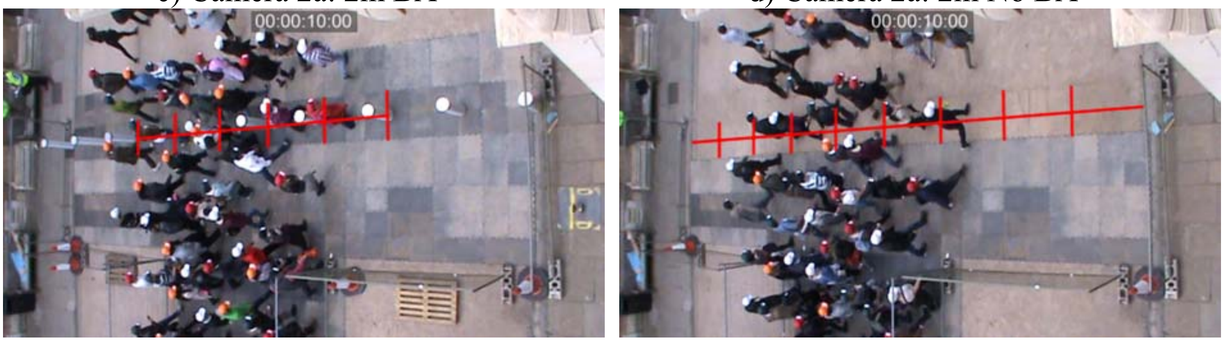
Figure 29: Example footage from TS1 flow analysis at 1m, 1.5m and 2m.



a) Camera 2a: 1m BA b) Camera 2a: 1m No BA



c) Camera 2a: 2m BA d) Camera 2a: 2m No BA



e) Camera 2a: 3m BA f) Camera 2a: 3m No BA

Figure 30: Example footage from TS3 flow analysis at 1m, 2m and 3m.

A person was counted if at least half of their body footprint had crossed the red line during the time interval. When using Camera 2a careful consideration of the perspective of the camera angle was required.

3.4 BOLLARD COLLISION AVOIDANCE

The number of participants that took a diversionary action at the BA due to the presence of a bollard was measured. This is defined as persons who are within two steps of a bollard and who take diversionary measures to avoid colliding with the bollard. This may be changing their direction of movement, taking a side step or twisting their body in order to avoid coming into contact with the bollard.

The bollards were numbered as shown in Figure 31 and Figure 32 and at each bollard the number of participants that avoided outwards (away from the centre) or inwards (towards the centre) were counted. It was also noted if the participant made contact with the bollard whilst trying to avoid it. This does not include those who deliberately tapped the bollard as they passed it.

Figure 31: Numbering of bollards used in avoidance analysis for TS1 trials.

Figure 32: Numbering of bollards used in avoidance analysis for TS3 trials.

This measurement was made by viewing the video footage from the camera that gave the best view of the bollards and the actions the participants were taking to avoid the bollards (Camera 1a for TS1 & TS2 trials and Camera 3 for TS3 trials). The video was played through with the analyst focussing their attention first on one side and then on the other side of each bollard. The analyst counted the avoidance actions taken by each participant as they passed the bollard in question. The number of contacts with the bollard were also counted. Thus the video was played through twice for each bollard in the trial series.

Due to the subjective nature of this measurement, three raters performed the analysis and the results were compared to ensure that the trends of “in to out” avoidance actions at each bollard were in agreement. The counts at each bollard in each direction for the three data sets were then averaged to produce the overall score.

Three types of avoidance were defined:

- Sidestep: Where the participant makes a sideways step within two steps of the bollard, see Figure 33.
- Turn: Where the participant changes direction within two steps of the bollard, see Figure 34.
- Body Swerve: Where the participant moves their body at the last moment to avoid the bollard, see Figure 35.

Examples of each of these bollard avoidance actions can be seen in Figure 33 to Figure 35.

a) b) c)

Figure 33: Example of “Sidestep”.

a) b) c)

Figure 34: Example of “Turn”.

a) b) c)

Figure 35: Example of “Body Swerve”.

3.5 ANALYTICAL PROCESS

The processing and analysis of the video footage involved the performance of several steps. Firstly, the video footage from each camera for each trial was identified. Then the footage for each trial was imported into Adobe Premiere Pro where it was edited; therefore, only relevant portions of the video were retained for analysis. Each clip was then time stamped, using the whistle blown to start each trial as time zero and finally synchronised within Premier Pro to ensure that the views were appropriately represented. Once synchronised, the peak flow period was identified; i.e., the period where steady-state flow conditions were established.

Given the peak flow period available for each trial, it was necessary to establish the appropriate time interval for data capture. This needed to be small enough to ensure a sufficient data-set within the time available, but large enough such that differences in the trial between the time periods could be determined on the video footage; e.g., the analyst could determine that participants had moved from one location to another. At these points in time, the analyst established the initial density, flow at the exit, flow at the BA, Gap usage, BA density analysis and bollard collision avoidance for data from each trial day, as described in Section 3.2. Once data-sets had been collected, spot checks were undertaken involving redoing the data analysis to ensure consistency between the data collected.

While the data gathered involved unambiguous measurements, (i.e. Counting people in a defined location or noting a time when a person passed a defined point) it was important to check that the analysts were making self-consistent measurements and that the different analysts were consistent between each other. Furthermore, it was essential to check that the measurements were consistent with those made in the first trial campaign. This was done by the analyst from the first trial campaign first training two new analysts in how the measurements should be made and then while the analysts collected the data, spot checking that the analysis was consistent.

To check the flow measurements were consistent, for each trial series a repeat run was chosen and a 10 second time interval was picked and the times noted when each person passed the line. This was compared with the analyst's measurements and checked that they were within 1-2 frames i.e. the equivalent of a 10th of a second accuracy.

To check the density counts, a run from each trial series was selected and the density count measures at 5, 15, 25, 35 seconds. These counts were checked that they agreed with the analysts.

4 RESULTS

In these sections the results produced during the TS1, TS2 and TS3 experimental trials are presented. All the exit and BA flow graphs for all the trials conducted during the second trial campaign can be found in ANNEX I: RESULTS.

4.1 Terminology

During the following description a number of terms are used for brevity. These are:

- ppm – people per minute.
- BA – bollard array.
- BA Line – Location at which the BA might be situated, whether the BA is present or not.
- BA Flow – Flow measured at the BA Line.
- Exit Flow – Flow measured at the line where the arch ends in TS1.
- Peak time periods – set of time periods including steady state flow conditions and excluding other conditions where the flow was initially building up or was in decline. This meant that flow during time periods which was significantly lower than the following time periods was cut (initial time periods) and flows that were significantly lower than flow in the preceding time periods (last time periods) were cut. This meant that the first one or two time periods and the last one or two periods were usually excluded from the peak flow determinations.

During the discussion of the results, an abbreviated description of the scenario conditions is used, for brevity and clarity. This abbreviation takes the following form:

[Trial Series]_[Stand-Off distance/NoBA]_[Trial Repeat Number]

The sections of this abbreviated form can then take the following values:

[TS1; TS2; TS3]_[SD1; SD2; SD3; NoBA]_[1; 2; 3]

This abbreviated form is used throughout – as a label and in the text – in order to improve the flow of the results discussion.

4.2 TS1: EXIT FLOW TRIALS

The TS1 trials involved the 2.4m wide exit with stand-off distances of 1m, 1.5m and 2m. A trial with NoBA was also conducted.

4.2.1 No BOLLARD ARRAY

The three bonus trials conducted on day 1 consisted of three trials without BA (see Table 2). These trials were conducted at initial densities of 4 p/m^2 and so could be compared with the NoBA trials conducted during the first trial campaign in 2013. Examples of the participant movement during these trials can be seen in Figure 18. Presented in Table 9 are the exit flows for each of the TS1 NoBA trials for the 4 p/m^2 initial density presented in 5 second time intervals during the peak period. Also presented is the average peak period flow. The flow curves for the NoBA conditions during the peak period are shown in Figure 36.

Table 9: Exit flow during peak period measured in 5 sec time intervals for the 4p/m^2 trials with NoBA.

Trial Type	Peak period flow (ppm)						Overall Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
TS1_NoBA_1	324	288	312	216	252	216	268
TS1_NoBA_2	384	312	276	264	204	240	280
TS1_NoBA_3	372	348	288	252	252	204	286
Average (NoBA)	360	316	292	244	236	220	278

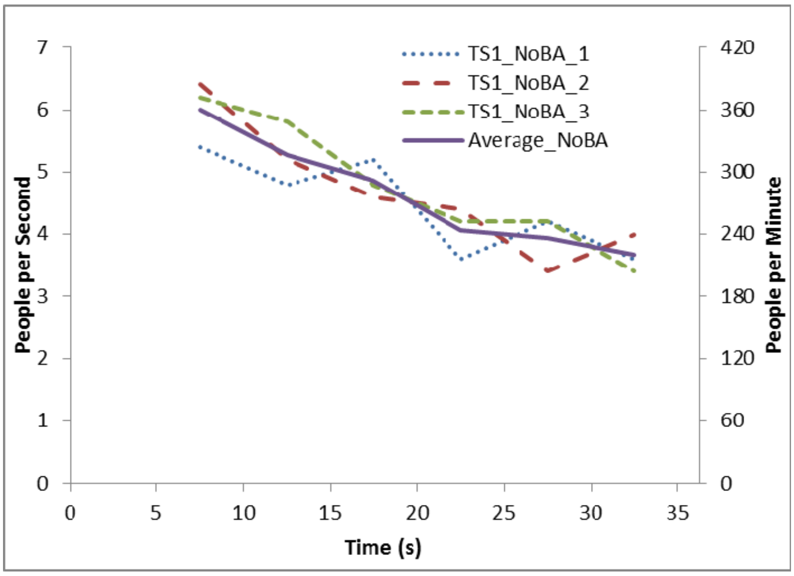


Figure 36: TS1 - Peak exit flow measured in 5 sec intervals for the three NoBA 4 p/m^2 trials and the average flow curve.

It is clear from Figure 36 and Table 9 that there is a gradual decline in exit flow during the peak period in all three repeat trials. On average the exit flow declines by 39% from its maximum value during the first time interval during the peak period to the last time interval during the peak period. This decline in exit flow is thought to be due to participant fatigue as explained in Section 2.3.4. These trials were the last of 24 trials and were completed at around 16:00 of day 1, some 8 hours after the start of the day. Given the potential impact of fatigue, it would be expected that these trials would produce slower average flow results than those for the first trial campaign conducted in 2013.

Presented in Table 10 and Figure 37 are the average peak flows for the NoBA trials from 2013 and 2014. It is apparent that the peak exit flows are both qualitatively and quantitatively different. As can be seen in Figure 37, the 2014 NoBA trials produce higher flows initially and then reduce to the same levels as in the 2013 NoBA trials. From Table 10 we note that the average NoBA exit flow in the 2014 trials are some 13% faster than those for the 2013 trials.

Rather than being slower than the 2013 trials due to the possible impact of fatigue, the 2014 trials are faster. The non-uniformity and drop off in the exit flow in the 2014 trials is likely to result from the impact of fatigue. This can also be observed in the 2013 trials although to a lesser extent – the drop off in performance in 2013 being 22%. While the 2013 trials were also performed at the end of the day, the day was much shorter involving fewer trials.

Table 10: Comparison of 2013 and 2014 peak exit flows measured in 5 sec time intervals for the $4p/m^2$ trials with NoBA.

	Peak period flow (ppm)						Overall Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
2013 Average (ppm)	278	247	242	259	226	216	246
2014 Average (ppm)	360	316	292	244	236	220	278

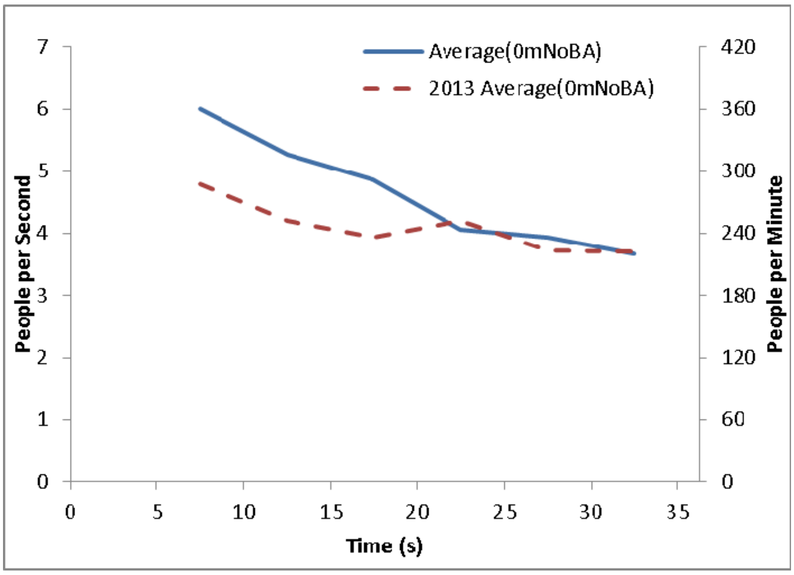


Figure 37: Average peak exit flow at 5 second intervals for the 2013 and 2014 NoBA trials.

The average exit flow in the 2014 NoBA trials is 13% greater than the average exit flow in the 2013 NoBA trials. This difference could be a result of the significantly different weather conditions experienced during the two trial series (see Section 2.3.4). During the 2013 trials, the maximum day time temperature was around 9°C with light snow while during the 2014 trials, the maximum day time temperature was a sunny 19°C. Associated with the difference in temperature, the overall environmental conditions between the two sets of trials were also different. The environmental conditions in 2013 could be described as cold, wet, icy and snowy whereas in 2014 the environmental conditions were warm and dry. These differences in environmental conditions could also have impacted walking speeds and hence flows. However, it is noted that the walking surfaces in 2013 were gritted and not slippery. Indeed, it was noted that none of the participants slipped or lost footing during the trials and none of the participants complained about the nature of the walking surfaces. It may also be possible that had the NoBA trials been conducted earlier in the day, the difference between the 2013 and 2014 trials may have been greater.

As the initial population densities in both the 2013 and 2014 trials was the same (4 p/m^2), the greater unit flows achieved in 2014 must be due to greater average travel speed achieved in 2014. Furthermore, while the population demographics of the 2013 and 2014 are comparable, there were a greater proportion of females and older participants in the 2014 trials. These differences in demographics should have resulted in a slightly slower average travel speed in 2014. The observed improvement in performance is therefore all the more interesting and possibly due to the differences in weather conditions, which had an overall greater positive impact than the negative differences brought about by both demographics and fatigue which should have resulted in slower flows in 2014 than in 2013.

These results suggest that exit flows and average travel speeds in colder conditions are likely to be lower than those in more moderate conditions. This is an important observation and should be considered when making provision for emergency exit capacity and evacuation times. For the exit width used in these trials (2.4m), the unit flow in 2013 is 1.71 p/m/s while in 2014 it is 1.93 p/m/s. Both values are considerably larger than the UK standard design standard of 1.33 p/m/s. Perhaps of greater significance is the greater average travel speeds achieved.

As the participants were travelling faster in the 2014 trials, they must spread out further than they did in the 2013 trials. This is necessary as the higher speeds can only be achieved with a lower density crowd. Thus we would expect to see the gap usage increase towards the outer edges in the 2014 trials compared to the 2013 trials. Presented in Figure 38 and Figure 39 are the gap usage at the 3m and 6m lines for the NoBA cases. The gap usage is determined by counting the number of people that pass through the space where the gaps would be had there been a BA present. As can be seen from the figures the usage of the central gap is reduced while the usage of the outer gaps increases in the 2014 trials compared to the 2013 trials. This observation is consistent with the greater average travel speeds achieved in the 2014 trials compared to the 2013 trials.

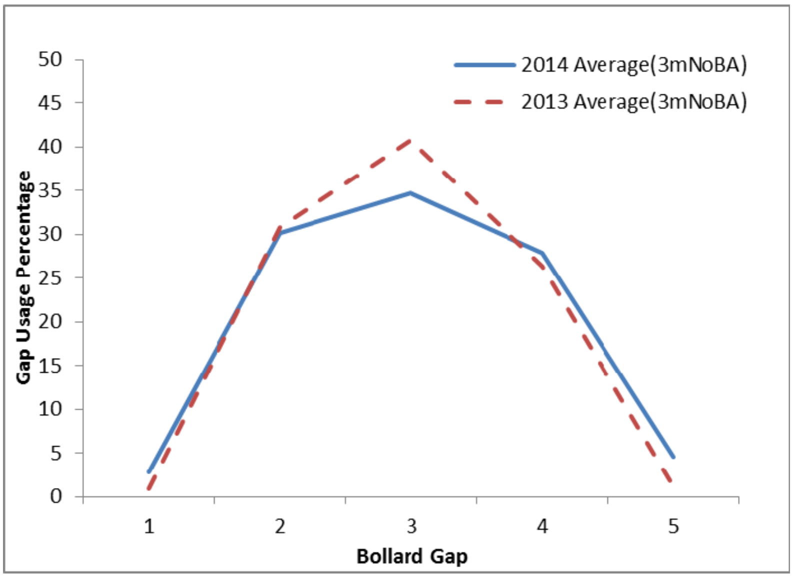


Figure 38: Comparison of gap usage between the 2013 and 2014 trials – 3m line NoBA.

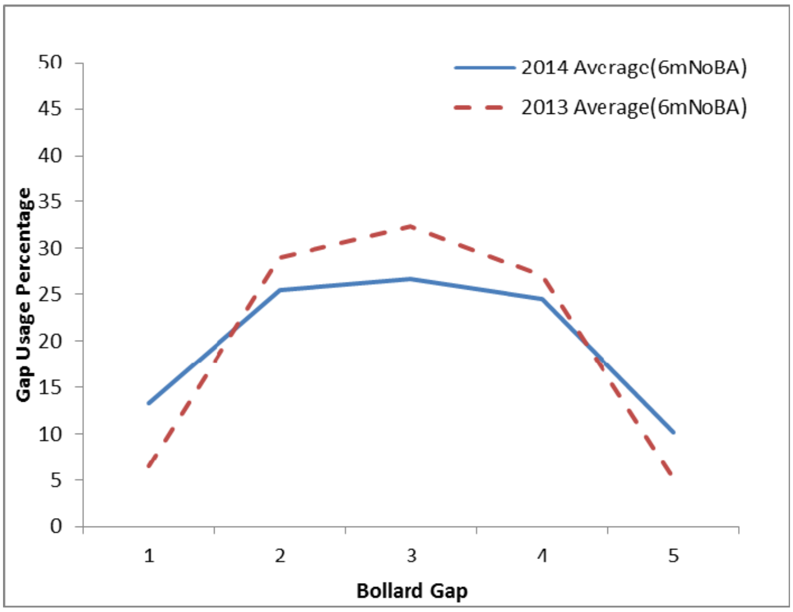


Figure 39: Comparison of gap usage between the 2013 and 2014 trials – 6m line NoBA.

If this observation is valid in general, then it would be expected that all the flows in the 2014 trials were greater than those in the equivalent 2013 trials, not simply the NoBA flow cases. The average exit flow for the 3m and 6m BA cases from the 2013 trials is 247 ppm while the average for the 1m, 1.5m and 2m BA cases from 2014 is 270 ppm (see Section 4.2.2.1). Thus the 2014 average exit flow with bollards is some 9.3% greater than the 2013 average exit flow with bollards. As expected, all the exit flows from the 2014 trials are some 10% greater than the corresponding average exit flows from the 2013 trials. These differences in exit flows between the 2013 and 2014 conditions will make direct comparison between the trials from 2013 and 2014 difficult.

Key findings:

- Exit flows in the 2014 trials are some 13% faster than the corresponding flows in 2013 and the BA flows are some 9.3% faster than the equivalent 2013 trials.
- The faster flows result in the population spreading out further, making greater usage of the outer regions.
- Faster flows are thought to be due to the better weather conditions in 2014.
- Exit flows and travel speeds may be impacted by environmental conditions with a 10% improvement in performance achieved by improving weather conditions from cold, with light snow to moderate and dry.
- Fatigue may have influenced the NoBA trial results, and hence the measured NoBA flows may underestimate the actual flows.
- The effect of weather on the population travel speed and flows may have been greater had it not been for the effects of fatigue and the larger proportion of females and elderly people in the 2014 trials compared to the 2013 trials.

4.2.2 1m, 1.5m and 2m BOLLARD ARRAY

In the following sections, the trials for the 1m, 1.5m and 2m stand-off distance with BA are discussed and compared with the trials without BA. Typical flow situations at the BA for the three cases are shown in Figure 40.

a) 1m BA

b) 1.5m BA

b) 2m BA

Figure 40: Overview of configuration for BA at 1m, 1.5m and 2m stand-off distance.

4.2.2.1 EXIT FLOW

The peak exit flows for the three BA stand-off distances are presented in Figure 41 to Figure 43 and Table 11 to Table 13. These results are more uniform during the peak periods than the corresponding NoBA trials (see Figure 36). This supports the view that the drop-off in performance observed in the NoBA trials may have been caused by fatigue as these BA trials were the first in the day.

Table 11: Peak exit flow measured in 5 second intervals for the three 1m BA trials and the average.

1m BA Trials	Peak period flow (ppm) Time interval (sec)							Overall Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS1_SD1_1	300.0	300.0	252.0	276.0	264.0	228.0	264.0	269
TS1_SD1_2	324.0	300.0	336.0	276.0	240.0	252.0	264.0	284
TS1_SD1_3	336.0	264.0	300.0	252.0	264.0	264.0	264.0	278
Average (PPM)	320.0	288.0	296.0	268.0	256.0	248.0	264.0	**277**

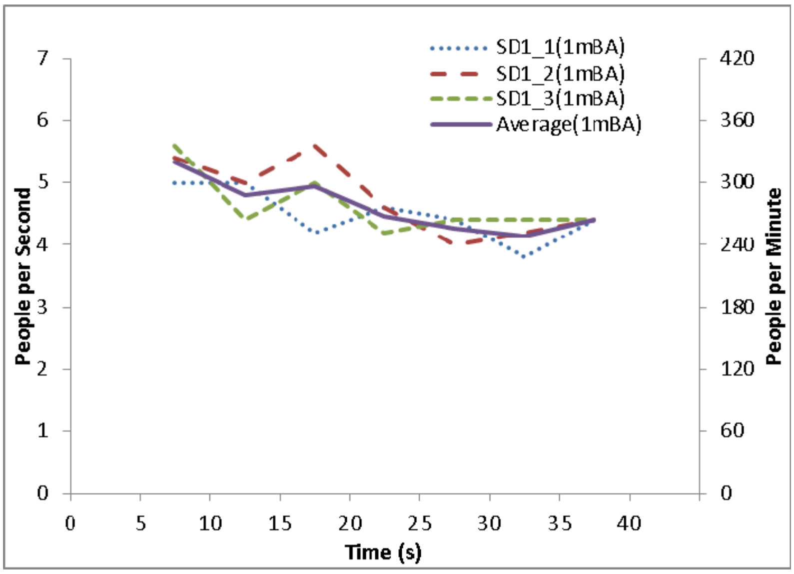


Figure 41: Peak exit flow measured in 5 second intervals for the three 1m BA trials and the average exit flow curve.

Table 12: Peak exit flow measured in 5 second intervals for the three 1.5m BA trials and the average.

1.5m BA Trials	Peak period flow (ppm) Time interval (sec)							Overall Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS1_SD2_1	312.0	288.0	264.0	288.0	216.0	252.0	276.0	271
TS1_SD2_2	312.0	264.0	264.0	264.0	276.0	252.0	252.0	269
TS1_SD2_3	288.0	228.0	276.0	264.0	264.0	240.0	240.0	257
Average (PPM)	304.0	260.0	268.0	272.0	252.0	248.0	256.0	**266**

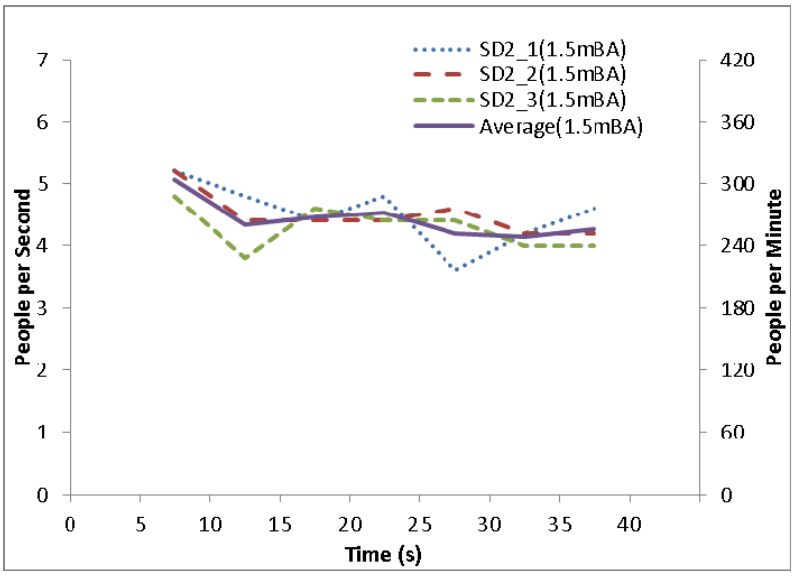


Figure 42: Peak exit flow measured in 5 second intervals for the three 1.5m BA trials and the average exit flow curve.

Table 13: Peak exit flow in 5 second intervals for the three 2m BA trials and the average.

2m BA Trials	Peak period flow (ppm) Time interval (sec)							Overall Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS1_SD3_1	348.0	276.0	216.0	252.0	288.0	264.0	228.0	267
TS1_SD3_2	276.0	264.0	300.0	264.0	240.0	264.0	252.0	266
TS1_SD3_3	348.0	252.0	288.0	240.0	252.0	264.0	240.0	269
Average (PPM)	324.0	264.0	268.0	252.0	260.0	264.0	240.0	**267**

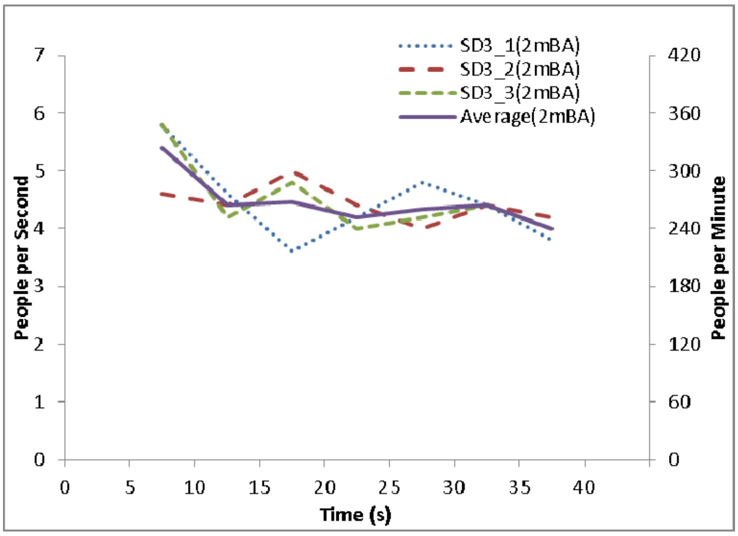


Figure 43: Peak exit flow in 5 second intervals for the three 2m BA trials and the average exit flow curve.

Presented in Figure 44 is a comparison of the average peak exit flows for the 1m, 1.5m and 2m BA together with the average NoBA average peak exit flow for 2013 and 2014. All the average exit flow curves with BA are above the 2013 NoBA average exit flow curve. This again confirms that the 2014 trial produced faster flows and faster average travel speeds.

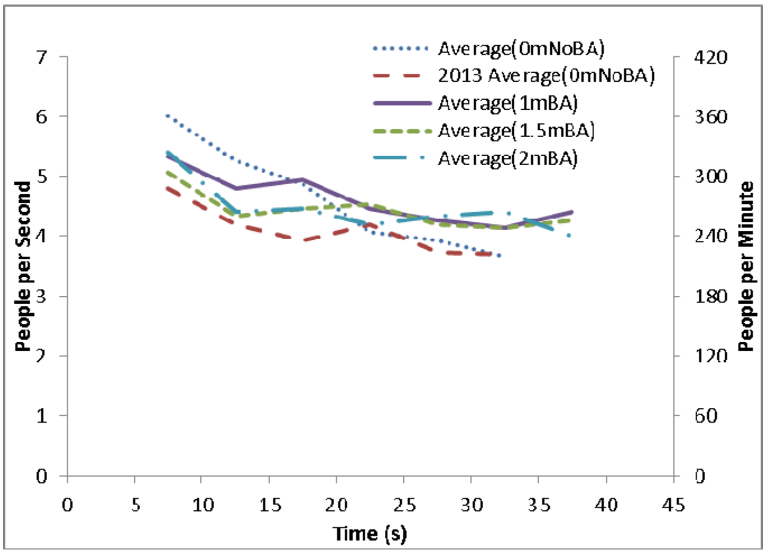


Figure 44: Average Peak exit flow in 5 second intervals for the NoBA (2013 and 2014), 1m, 1.5m and 2.0m BA trials.

The 1.5m and 2.0m stand-off distance produce similar average flows at the exit, while the 1.0m stand-off produces somewhat higher exit flows (see Figure 44). For the first half of the flow period, all the exit flows with BA are slightly smaller than the NoBA exit flows (see Figure 44). However, half way through the measurement period, the NoBA average flows dips under the exit flows for the cases with BA (see Figure 44). The under-performance with BA in the first part of the exit flow is partially compensated by the over-performance with BA in the second part of the flow. However, the dip in the NoBA flow in the second part of the exit flow could be the result of fatigue.

For a given BA condition the average exit flow over the peak period is determined. Each BA condition is run three times, producing three average peak exit flows. The average and range of the average exit flow are presented in Figure 45 and Table 14.

The average exit flow with BA is always less than that without BA. The reduction in exit flow varies from 0.3% to 4.3%. The range in average exit flow for the three BA stand-off distances all overlap with the range in average exit flow for the NoBA. However, the average exit flows for the 1.5m and 2m BA stand-off falls just outside the range of the NoBA case. The BA at 1.5m produces the greatest reduction in exit flow at 4.3%. The 1.5m BA stand-off case also produces a low minimum average exit flow. If the NoBA trials were not impacted by the effects of fatigue, it is possible that the difference between the NoBA and BA cases may have been greater.

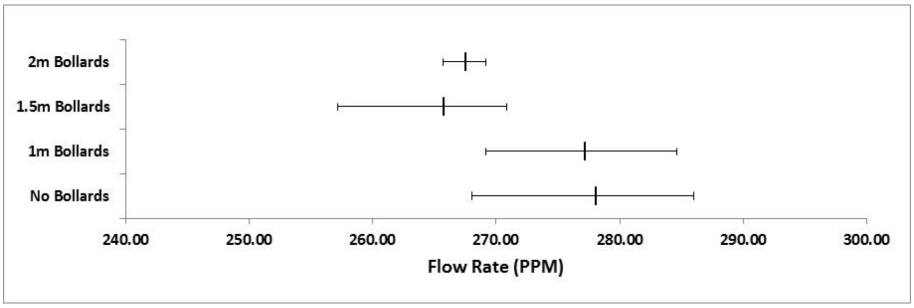


Figure 45: Average and range of average peak exit flows for the NoBA and the 1m, 1.5m and 2m BA trials.

Table 14: Average Exit Flow for peak period.

BA Condition	Average Exit Flow (ppm)	Comparison BA Vs NoBA
NoBA	278.0 [268.0 – 286.0]	-
BA_1m	277.1 [269.1 – 284.6]	-0.3%
BA_1.5m	265.7 [257.1 – 270.9]	-4.3%
BA_2m	267.4 [265.7 – 269.1]	-3.9%

Clearly the 1.5m BA case stands out as having the greatest impact on exit flows of the three cases examined. It was noted (see Section 2.3.4) that the 1.5m BA setup was not ideal given that a smaller expanse of BA was employed at 1.5m than would have been the case had all the available space been utilised. Indeed, the expanse of BA at 1.5m stand-off was identical to that at 1m stand-off. It was suggested that the reduction in effective width at the 1.5m BA due to the blocking of space would impact the flow at the BA and this would have an adverse effect on the exit flow. Presented in Table 15 are the average peak flows at the BA line with and without BA.

Table 15: Average peak BA Flow with and without BA.

BA Condition	Flow at BA line without BA (ppm)	Flow at BA line with BA (ppm)	Difference %
1.0m	277	278	+0.4
1.5m	277	267	-4%
2.0m	278	271	-2%

We note that at a distance of 1.5m, the flow at the BA line with BA is 4% lower than the corresponding flow without BA. This is twice the reduction observed at 2m and more than 10 times the difference observed at 1m. Thus the flow at the BA is adversely affected by the excessive reduction in effective width which in turn has an impact on the exit flow which is greater than would have been expected simply for the BA at 1.5m stand-off. For this reason it is suggested that the 1.5m BA stand-off results should be excluded from the analysis.

Presented in Table 16 are the normalised average exit peak flows determined across the 2013 and 2014 trials. Due to the differences in conditions between the 2013 and 2014 trials the flow at the exits was normalised using the NoBA flows appropriate for the data-set. So the NoBA normalised exit flow is always 1.0 and the exit flows for the BA trials in 2013 are normalised with the NoBA exit flow from 2013 and the BA trials for 2014 are normalised with the NoBA exit flow from 2014.

These results suggest that when the BA is placed closer than 3m from the exit it has a greater effect then when placed greater than 3m. However, when the BA is as close as 1m from the exit, the effect is again small. It must be noted that the maximum impact on exit flow at 3.9% for the BA at 2m stand-off is quite small. While the 1.5m BA results are included in the table, they should be discounted from the analysis due to the issues with the trial set-up.

Table 16: Summary normalised average peak flows produced at the exit.

BA Condition	Normalised Exit Flow (BA/NoBA)	Comparison BA Vs NoBA
NoBA	1.000	-
1.0m BA	0.996	-0.3%
1.5m BA	0.957	-4.3%
2.0m BA	0.960	-3.9%
3.0m BA (2013)	0.993	-0.6%
6.0m BA (2013)	1.006	+0.6%

Key findings:

- All the average peak exit flows with BA are less than the corresponding NoBA average peak exit flows.
- The reduction in exit flow varies from 0.3% to 4.0%.
- The least reduction in exit flow occurs for the smallest stand-off distance 1m while the greatest observed reduction in exit flow occurs for the middle stand-off distance 2.0m.
- The range in average exit flows for the three BA stand-off distances all overlap with the range in average exit flows for the NoBA.
- The 1.5m, and to a lesser extent the 2.0m trials were affected by the experimental setup which negatively affected the flow at the BA which then influenced the exit flow.
    - The 1.5m BA more significantly reduced the free exit width than intended.
    - The approach to the outer gaps in the 2m BA were constrained by the barriers which may have affected the exit flow at the BA and hence at the exit.
- Assuming that the 1.5m BA results are discarded, a stand-off distance of between 1m and 3m produces the greatest reduction in exit flow.
    - The greatest observed reduction in exit flow is 4%.
    - This is observed to occur when the BA is placed at 2m from the exit.

4.2.2.2 GAP USAGE

As the population move further from the exit they spread out using more of the available space (see Table 17, Table 18 and Figure 46). This is clearly noted in the NoBA trials (see Table 17 and Figure 46). As can be seen, the usage of the central three gaps decreases with increasing distance of the participants from the exit as more of them utilise the outer gaps. Furthermore, as already noted in Section 4.2, the crowd in the 2014 trials tend to spread out more than they did in 2013 (central gap usage is less in 2014 compared to 2013) due to their greater average travel speed (due to the colder weather conditions in 2013).

Table 17: TS1: Gap usage based on 2014 results (NoBA).

	% Gap Use						
Distance from exit	**1**	**2**	**3**	**4**	**5**	**Central Gaps**	**Central Gap (2013)**
6m	13.3	25.4	26.6	24.5	10.2	76.5	88.4
3m	2.8	30.1	34.7	27.9	4.5	92.7	98.0
2m	0.4	29.2	40.8	28.2	1.4	98.2	-
1m	-	24.6	48.7	26.7	-	100	-

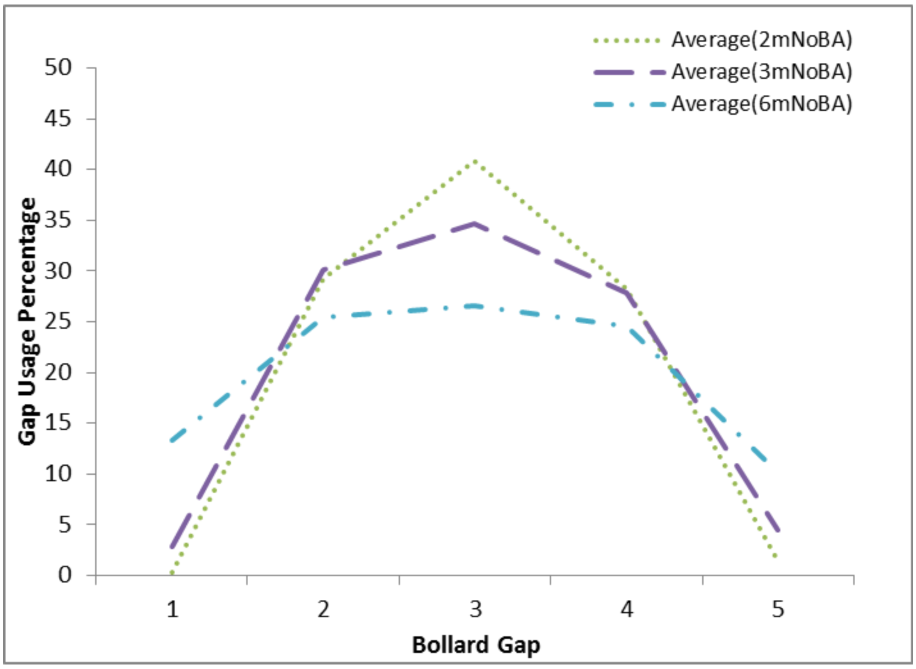


Figure 46: Gap usage with distance from the exit for the NoBA trials.

It is also noted that the BA acts as a divergent lens causing the population to spread out further with a BA present than when there is no BA present (see Table 18). This is a similar result to that noted in the 2013 trials [3].

Finally, due to the differences in the BA setup between the 2013 and 2014 trials, it is not possible to use the TS1 results to investigate the relationship between the BA expanse and the exit width. This will be investigated using TS3 data.

Table 18: Gap usage at 1m and 2m stand-off distance with and without BA.

	% Gap Use					
Distance from exit	**1**	**2**	**3**	**4**	**5**	**Central Gap(s)**
2m NoBA	0.4	29.2	40.8	28.2	1.4	98.2
2m BA	1.8	27.2	41.0	27.6	2.5	95.8
1m No BA	-	24.6	48.7	26.7	-	48.7
1m BA	-	26.4	47.5	26.2	-	47.5

Key findings:

- The flow spreads out as it moves further from the exit.
  - This is consistent with the 2013 trials; however, it is noted that the spread is greater in the 2014 trials due to the greater flows resulting from the greater walking speeds.
- The BA acts as a divergent lens causing the population to spread out further than would be the case without the BA.
  - This observation is consistent with 2013.

4.2.3 2.4m Exit, 4 P/M^2 FLOW DENSITY RESULT SUMMARY

The 2013 and 2014 trials have shown that as a crowd of initial density 4 p/m^2 exits from a 2.4m exit they disperse the further they are from the exit. If a BA is positioned perpendicular to their direction of movement, the BA acts as a divergent lens dispersing the crowd more than would be the case had the BA not been present.

In the case of the 2.4m wide exit with initial crowd density of 4 p/m^2, a BA with stand-off distance of 1m to 6m has little impact on the exit flow, assuming there is sufficient expanse of BA so as not to restrict the dispersion of the flow. The maximum observed degradation in exit flow is 4% which occurred at a stand-off distance of 2m. Stand-off distances of 1m (2014 trials) and 3m (2013 trials) were observed to have negligible impact on exit flows. As stand-off distances of 1m, 2m, 3m and 6m were examined, it is possible that the critical stand-off distance which causes the greatest degradation in exit performance could be located anywhere between 1m and 3m from the exit.

The 2014 trials produced average peak exit flows which were 13% faster than the 2013 trials. The main difference between the trials was the environmental conditions, with the 2013 conditions being colder than that in 2014. This result suggests that individual travel speeds and exit flows may be affected by modest changes in the environmental conditions. The possibility of reduced exit flows and individual travel speeds resulting from colder conditions should be taken into consideration when designing evacuation systems.

4.3 TS2: ENCUMBRANCE FLOW TRIALS

The encumbrance trials (TS2) were conducted on the same day as the TS1 and were conducted at the same location – under the arch in the Queen Anne Courtyard. The trials consisted of the 4p/m^2 initial population density with 40% encumbrance levels passing through the 2.4m exit with a bollard placed at 0m stand-off (three trials) and NoBA (three trials). These six trials were then repeated with 60% encumbrance levels (see Table 2). The results produced in the TS2 trials are discussed in this section. Depicted in Figure 47 are typical scenes from TS2.

a) Getting ready to start, 40% encumbrance with 0m BA.

b) 60 % encumbrance with NoBA.

c) 40% encumbrance with 0m BA.

d) 60% encumbrance with 0m BA.

Figure 47: TS2 trials, with BA set at 0m.

4.3.1 NoBA, 0%, 40% and 60% ENCUMBRANCE LEVELS

This section compares the exit flow conditions of the NoBA trials conducted at 4p/m^2 with 0%, 40% and 60% encumbrance. The results for the 0% NoBA have been discussed in Section 4.2.1 and are presented in Figure 36 and Table 9. The results for the 40% level of encumbrance NoBA are presented in Table 19 and Figure 48 while the results of the 60% encumbrance NoBA are presented in Table 20 and Figure 49. The data in Table 9, Table 19 and Table 20 are used to calculate the overall average peak flow in persons per minute at the exit for the various levels of encumbrance with NoBA.

Table 19: Exit flow during peak period in 5 sec time intervals for the 40% encumbrance trials with NoBA.

40% encumbrance trials with NoBA	Peak period flow (ppm)							Overall Average (ppm)
	Time interval (sec)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS2_NoBA_1(40%)	288.0	264.0	192.0	252.0	228.0	264.0	276.0	252
TS2_NoBA_2(40%)	288.0	264.0	228.0	264.0	240.0	252.0	252.0	255
TS2_NoBA_3(40%)	300.0	264.0	204.0	240.0	264.0	240.0	216.0	247
Average(40%,NoBA)	292.0	264.0	208.0	252.0	244.0	252.0	248.0	**251**

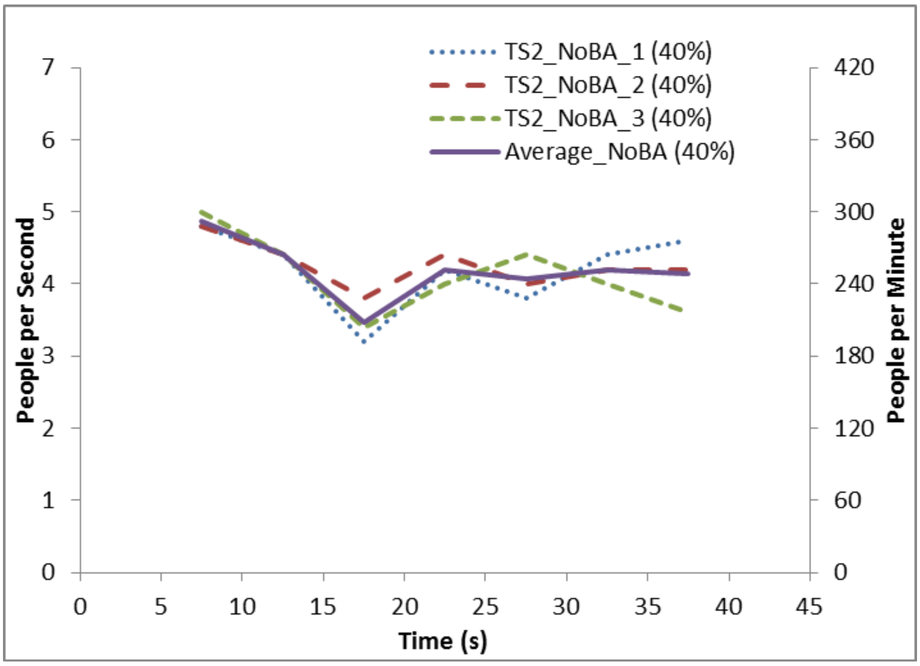


Figure 48: Peak exit flow in 5 second intervals for the three NoBA trials with 40% encumbrance and the average exit flow curve.

Table 20: Exit flow during peak period in 5 sec time intervals for 60% encumbrance trials with NoBA.

60% encumbrance trials with NoBA	Peak period flow (ppm)							Overall Average (ppm)
	Time interval (sec)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS2_NoBA_1(60%)	228.0	180.0	240.0	240.0	228.0	228.0	240.0	226
TS2_NoBA_2(60%)	276.0	252.0	216.0	240.0	240.0	216.0	264.0	243
TS2_NoBA_3(60%)	288.0	192.0	264.0	204.0	228.0	216.0	228.0	231
Average(60%,NoBA)	264.0	208.0	240.0	228.0	232.0	220.0	244.0	**234**

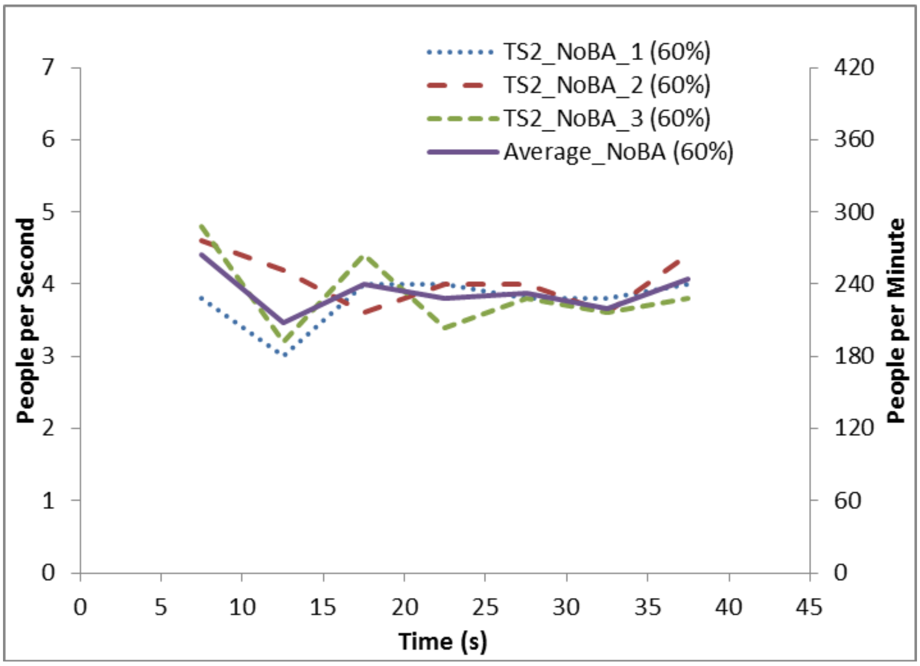


Figure 49: Peak exit flow in 5 second intervals for the three NoBA trials with 60% encumbrance and the average exit flow curve.

As can be seen from Figure 48 and Figure 49 the flow over the peak period for both the 40% and 60% encumbrance levels are all fairly uniform with good levels of consistency between the repeat trials. Presented in Table 21 are the average peak flows in each 5 sec interval (averaged over the three repeat trials) and the average overall peak exit flow (derived from the overall average of each trial).

The overall average peak exit flow with 0% encumbrance is 278 ppm (varies by -3.6% to +2.9%), 40% encumbrance 251 ppm (varies by -2.1% to +1.4%) and for the 60% encumbrance 234 ppm (varies by -3.2% to 4%).

As the amount of encumbrance increases, the overall average exit peak flow decreases as can be clearly seen in Figure 50. For the NoBA trials the decrease in average exit flow for each level of encumbrance is greater than the natural variation in the average exit flows and so is significant.

Table 21: Average Exit flow during peak period in 5 sec time intervals encumbrance trials with NoBA.

Encumbrance levels	Average Peak period flow (ppm)							Overall Average (ppm)	% Diff
	Time interval (sec)								
	5-10	10-15	15-20	20-25	25-30	30-35	35-40		
0%	360	316	292	244	236	220	--	278 [268 – 286]	--
40%	292	264	208	252	244	252	248	251 [246 – 255]	9.6
60%	264	208	240	228	232	220	244	234 [226 – 243]	15.9

When approximately 40% of the participants are encumbered the average exit flow decreases by 10% and when approximately 60% of the participants are encumbered the average exit flow decreases by 16% compared to the case with 0% encumbrance (see Table 21). Increasing the level of encumbrance from 40% to 60% results in a 7% decrease in the exit flow. Furthermore, the natural variation in the NoBA case with 60% encumbrance (-3.2% to +4.0%) is greater than the variation in the case with 40% encumbrance (-2.1% to +1.4%).

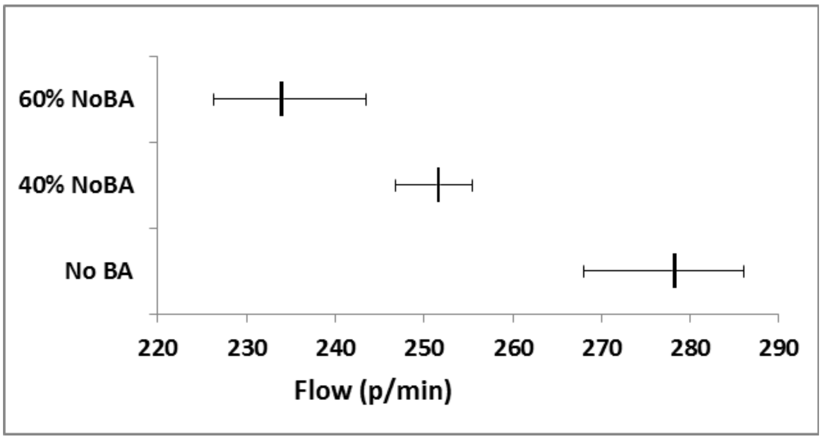


Figure 50: Average and range of overall peak exit flow for the NoBA with 0%, 40% and 60% encumbrance levels.

Presented in Figure 51 is the average peak exit flow measured in 5 sec intervals for the 0%, 40% and 60% encumbrance levels. As can be seen, the average flow in the second part of the peak flow period drops of sharply for the 0% encumbrance level.

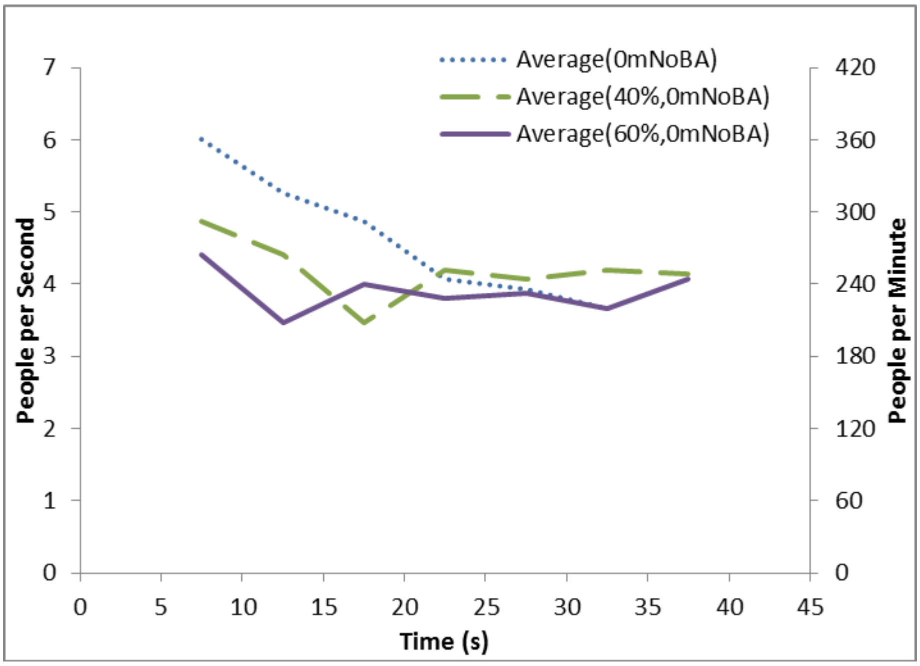


Figure 51: Average peak exit flows for the NoBA trials with 0%, 40% and 60% encumbrance.

It has already been suggested that this is the result of fatigue which impacted the NoBA 0% encumbrance trials which were the last to be performed on day 1 of the second trial campaign. Had this effect not been present, it is likely that the impact of the encumbrance described above would have been even more pronounced.

Key findings:

- The flow remains fairly uniform with the varying degrees of encumbrance without the BA present.
- As the level of encumbrance increases, the average peak exit flow decreases without the BA present.
- Compared to the case where the participants have no encumbrance, the exit flow decreases by 10% when approximately 40% of the participants are encumbered and 16% when 60% are encumbered.
- Increasing the level of encumbrance from 40% to 60% results in a 7% decrease in the exit flow.
- The natural variation in the average exit flow increases as the level of encumbrance increases from 40% to 60%.
- The impact of encumbrance may be greater had fatigue not impacted the NoBA 0% luggage trials.
- The impact of encumbrance on exit flow is appreciably greater than the impact of the BA at any of the stand-off distances measured.

4.3.2 0m BA, 40% and 60% ENCUMBRANCE LEVELS

This section compares the exit flow conditions of the BA trials conducted at $4p/m^2$ with 40% and 60% encumbrance. The results for the 40% level of encumbrance 0m BA are presented in Table 22 and Figure 52 while the results of the 60% encumbrance 0m BA are presented in Table 23 and Figure 53. The data in Table 22 and Table 23 are used to calculate the overall average peak flow in persons per minute at the exit for the various levels of encumbrance with 0m BA.

Table 22: Exit flow during peak period in 5 sec time intervals for 40% encumbrance trials with 0m BA.

40% encumbrance trials with 0m BA	Peak period flow (ppm)							Overall Average (ppm)
	Time interval (sec)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS2_0m_1(40%)	276.0	264.0	264.0	264.0	252.0	216.0	252.0	255
TS2_0m_2(40%)	252.0	252.0	252.0	216.0	276.0	240.0	252.0	248
TS2_0m_3(40%)	264.0	264.0	240.0	276.0	216.0	264.0	264.0	255
Average(40%,0mBA)	264.0	260.0	252.0	252.0	248.0	240.0	256.0	**253**

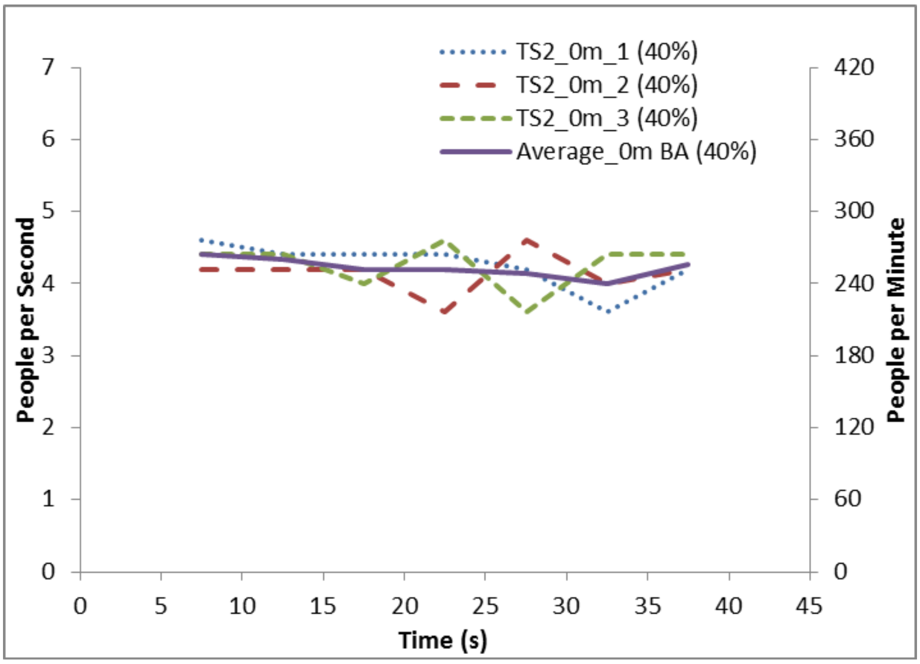


Figure 52: Peak exit flow in 5 second intervals for the three 0m BA trials with 40% encumbrance and the average exit flow curve.

Table 23: Exit flow during peak period in 5 sec time intervals for 60% encumbrance trials with 0m BA.

60% encumbrance trials with 0m BA	Peak period flow (ppm) Time interval (sec)							Overall Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
TS2_0m_1(60%)	252.0	240.0	204.0	204.0	228.0	240.0	252.0	231
TS2_0m_2(60%)	312.0	192.0	204.0	204.0	240.0	240.0	228.0	231
TS2_0m_3(60%)	288.0	180.0	192.0	204.0	204.0	228.0	216.0	216
Average(60%,0mBA)	284.0	204.0	200.0	204.0	224.0	236.0	232.0	**226**

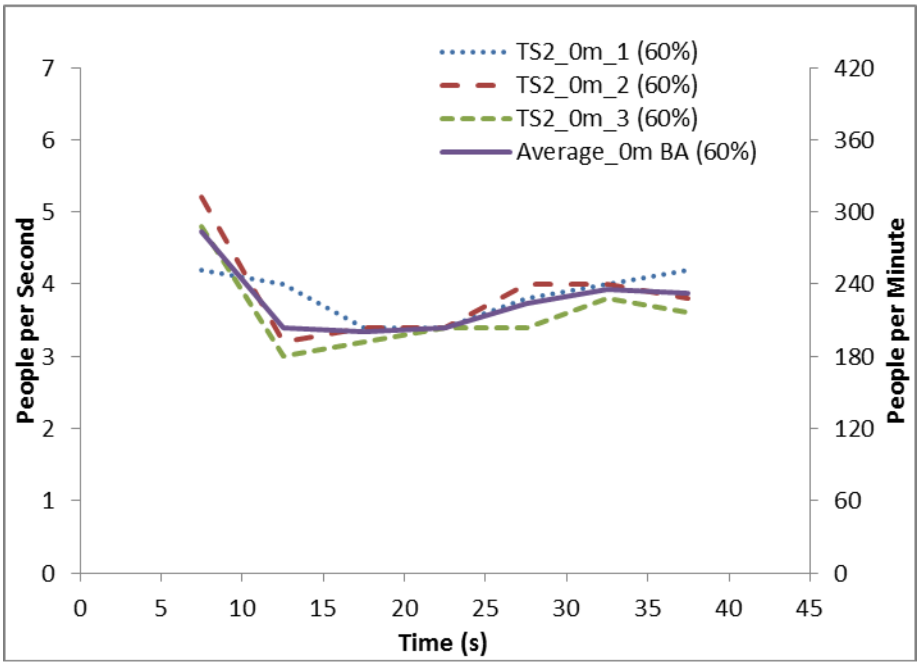


Figure 53: Peak exit flow in 5 second intervals for the three 0m BA trials with 60% encumbrance and the average exit flow curve.

As can be seen from Figure 52 and Figure 53 the flow over the peak period for both the 40% and 60% encumbrance levels are all fairly uniform with good levels of consistency between the repeat trials. Presented in Table 24 are the average peak flows in each 5 sec interval (averaged over the three repeat trials) and the average overall peak exit flow (derived from the overall average of each trial). The overall average peak exit flow with 0% encumbrance and NoBA is 278 ppm (varies by -3.6% to +2.9%), 40% encumbrance with 0m BA 253 ppm (varies by -1.6% to +0.7%) and for the 60% encumbrance with 0m BA 227 ppm (varies by -4.7% to +1.9%).

As the amount of encumbrance increases, the overall average exit peak flow decreases as can be clearly seen in Figure 54. For the 0m BA trials the decrease in average exit flow for each level of encumbrance is greater than the natural variation in the average exit flows and so is significant.

Table 24: Average Exit flow during peak period in 5 sec time intervals encumbrance trials with and without BA.

Encumbrance level	Average Peak period flow (ppm)							Overall Average (ppm)	% Diff
	Time interval (sec)								
	5-10	10-15	15-20	20-25	25-30	30-35	35-40		
NoBA 0%	360	316	292	244	236	220	--	278 [268 – 286]	--
0m BA 40%	264	260	252	252	248	240	256	253 [249 – 255]	9.0
0m BA 60%	284	204	200	204	224	236	232	227 [216 – 231]	18.4

These observations are similar to those observed without a BA placed at 0m. Increasing the level of encumbrance from 40% to 60% results in a 10.4% decrease in the exit flow (see

Figure 54 and Figure 55). This is greater than the corresponding decrease noted in the NoBA case (i.e. 7%). Thus the degradation in performance as the level of encumbrance is increased is more significant when the 0m BA is present than when it is not present.

When approximately 40% of the participants with are encumbered with the 0m BA the average exit flow decreases by 9% and when approximately 60% of the participants are encumbered with the 0m BA the average exit flow decreases by 18% compared to the case with 0% encumbrance (see Table 24Table 21). Increasing the level of encumbrance from 40% to 60% with 0m BA results in a 10% decrease in the exit flow. Furthermore, the natural variation in the NoBA case with 60% encumbrance (-4.7% to +1.9%) is greater than the variation in the case with 40% encumbrance (-1.6% to +0.7%).

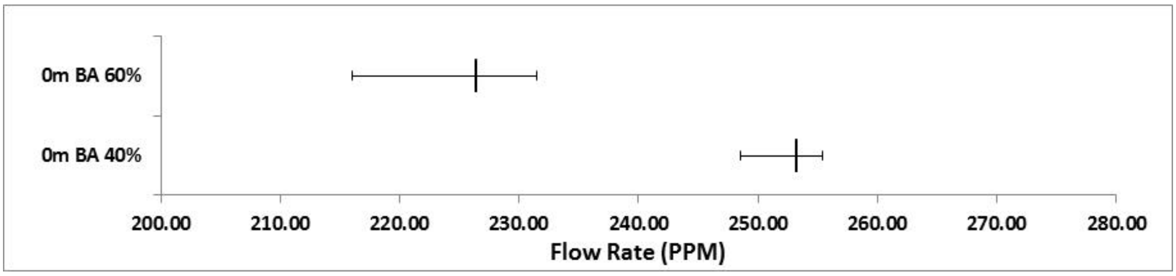


Figure 54: Average and range of peak exit flow for the 0m BA with 40% and 60% encumbrance trials.

Presented in Figure 55 is the average peak exit flow measured in 5 sec intervals for the 40% and 60% encumbrance levels. As can be seen, the average flow produced by the 60% encumbrance level with 0m BA is less than the corresponding flow produced by the 40% encumbrance levels virtually throughout the peak period.

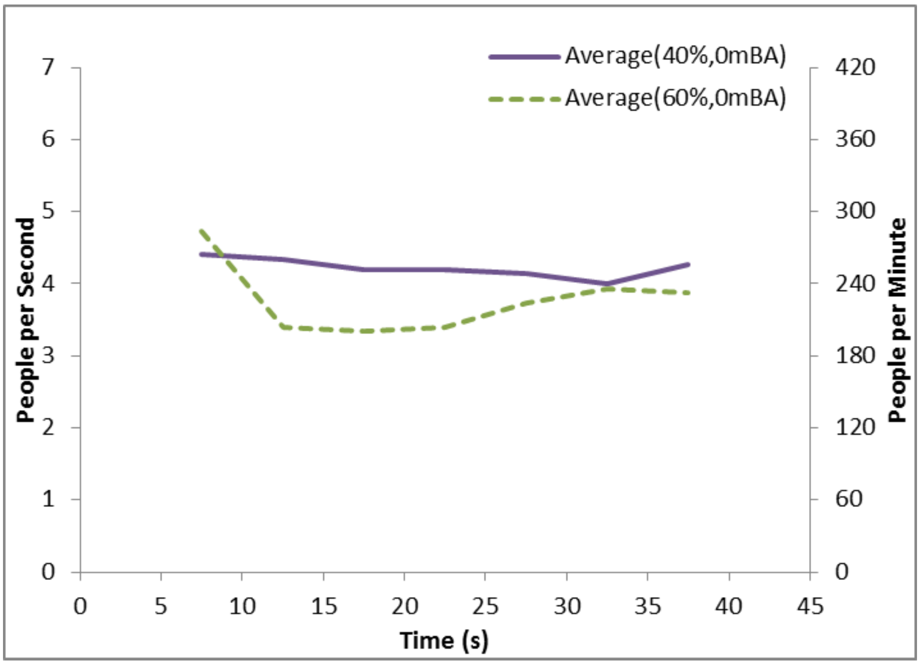


Figure 55: Average peak exit flows for the 0m BA trials with 40% and 60% encumbrance.

Key findings:

- The flow remains fairly uniform with the varying degrees of encumbrance with the 0m BA present. This is similar to the NoBA case.
- As the level of encumbrance increases, the average peak exit flow decreases with 0m BA present. This is similar to the NoBA case.
- Increasing the level of encumbrance from 40% to 60% results in a 10.4% decrease in the exit flow. This is greater than the corresponding decrease in the NoBA cases.
  - The degradation in performance due to increasing levels of encumbrance is more significant with the 0m BA present then in the NoBA case.
- The natural variation in the average exit flow increases as the level of encumbrance increases from 40% to 60%.
- **While the impact of encumbrance on exit flow is appreciably greater than the impact of the BA at any on the stand-off distances measured, the impact of encumbrance plus the 0m BA represents the greatest degradation in peak exit flow, being some 18% less than the flow with 0% encumbrance and NoBA.**

4.3.3 COMPARING ENCUMBERED CASES WITH AND WITHOUT 0m BA

This section compares the exit flow conditions for the 40% and 60% encumbered trials with and without BA. The results for the 40% level of encumbrance with and without the 0m BA are presented Figure 56 while the results of the 60% encumbrance with and without 0m BA are presented in Figure 57. The flows with the 0m BA appear to be more uniform over the peak flow period, in particular for the 40% encumbrance level.

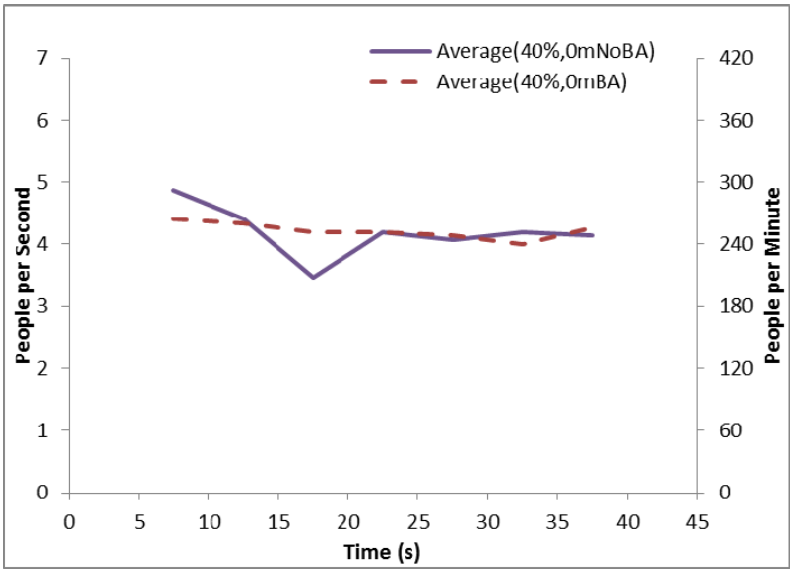


Figure 56: Average peak exit flows for the 40% encumbrance case with NoBA and 0m BA

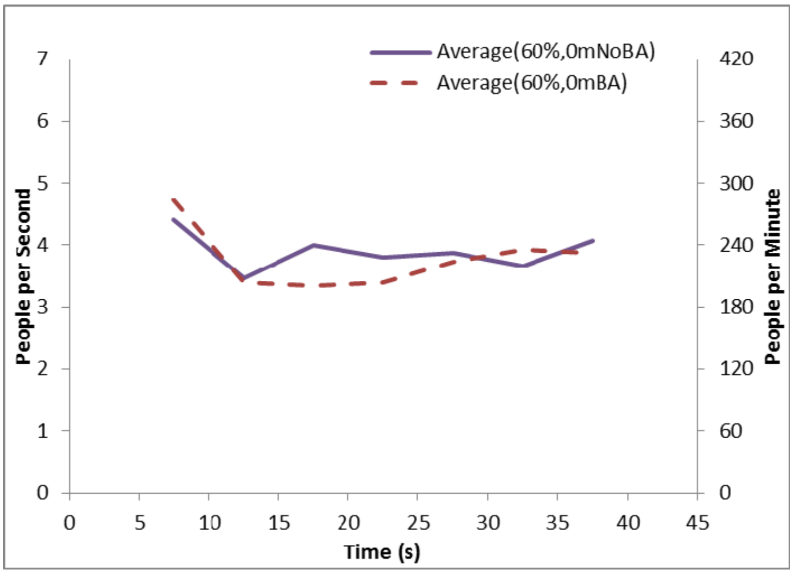


Figure 57: Average peak exit flows for the 60% encumbrance case with NoBA and 0m BA

From Table 21 and Table 24 we note that with the 40% encumbrance level, the average exit flow INCREASES by 0.7% while with the 60% encumbrance the average exit flow DECREASES by 3.0% with the introduction of the BA at 0m.

Figure 58 and Figure 59 show the average and range in peak exit flow for the cases with 40% and 60% encumbrance with and without 0m BA. For the 40% encumbrance levels (see Figure 58) the difference between the average peak exit flows for the NoBA and the 0m BA is less than the spread in the trial results for each case. There is a larger difference between the average peak exit flows for the 60% encumbrance levels (see Figure 59) with and without the 0m BA. While the average exit flow for the 0m BA 60% encumbrance case falls within the natural variation of the NoBA case, the NoBA average falls outside the natural range of the 0m BA 60% encumbrance case.

As the level of encumbrance increases the presence of the BA at 0m has a greater impact on the exit flow.

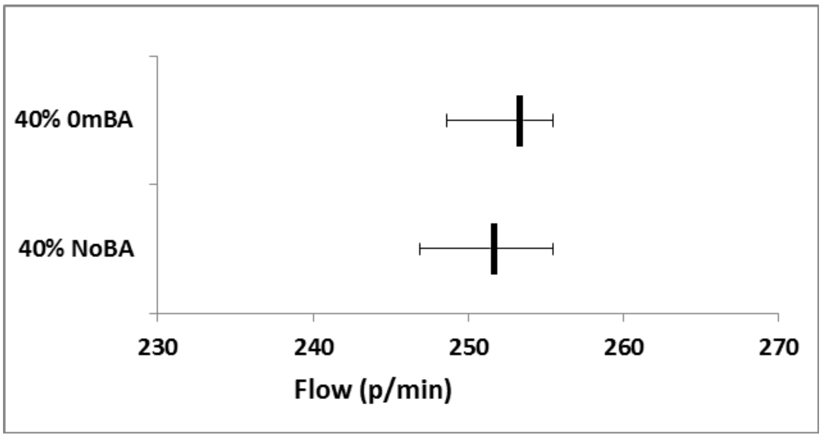


Figure 58: Average and range of peak exit flow for the 0m BA and NoBA with 40% encumbrance trials.

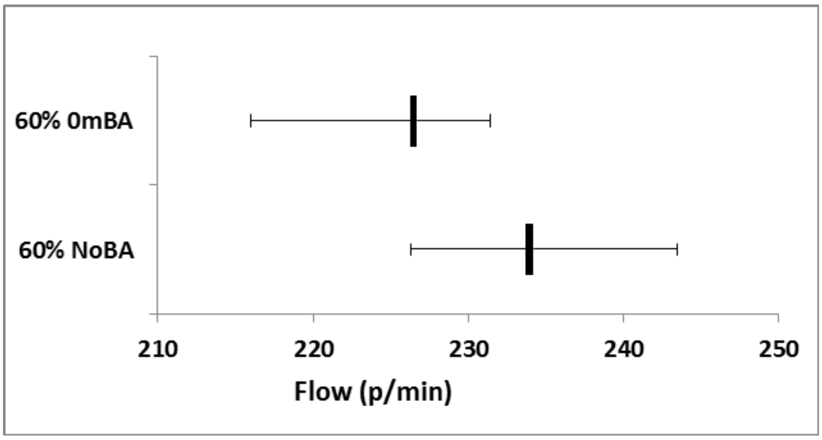


Figure 59: Average and range of peak exit flow for the 0m BA and NoBA with 60% encumbrance trials.

Key findings:

- For moderate to low levels of encumbrance (less than 40% of the population is encumbered) the presence of the BA at 0m has little impact on the exit flow.
- For high levels of encumbrance (60% or greater) the presence of the BA at 0m can reduce the exit flow by 3.0%.
- However, increasing levels of encumbrance have a greater impact on exit flow than simply the presence of the BA at 0m.

4.3.4 DISCUSSION OF UNIT FLOW WITH 0m BA AND ENCUMBRANCE

The 0m BA case produced greater flows than expected given the reduction in exit width associated with positioning of the bollard. The presence of a bollard in the exit leads to a 9.4% reduction in the available exit width; i.e. 2.4m available width without bollards and 2.175m of available width with bollards. As a result, we would expect the flow to be 9.4% lower with the bollard present. However, it is measured to be 0.7% higher with 40% encumbrance and only 3% lower with 60% encumbrance. As with the 2013 trials this difference can be explained by considering the unit flow for the exit [3].

Table 25: Summary average peak flows (p/min) and unit flows (p/m/s) with encumbrance for the NoBA and 0m BA trials.

Encumbrance level	NoBA	BA	% Difference (BA – NoBA)
0% (2013)	247.1 (1.72)	244.6 (1.87)	-1.0 (+8.7)
0% (2014)	278.0 (1.93)	- -	- -
40%	251.4 (1.75)	253.1 (1.94)	+0.7 (+10.9)
60%	233.7 (1.62)	226.7 (1.74)	-3.0 (+7.4)
% Difference (60% - 40%)	-7.0 (-7.4)	-10.4 (-10.3)	

A fundamental measure of the flow capacity of an exit is the unit flow. This measures the flow per unit exit width. While the flow of an exit is dependent on the width of the exit, the unit flow for an exit is a fundamental property of the exit. According to UK Building Regulations [4], the unit flow for a standard exit (no door leaf) is 1.33 people/m/sec. For safety reasons, this number is conservative, with unit flow values as high as 2.00 people/m/sec reported in the literature [5].

Using the available free exit width, the average unit flow for the exit without bollard at 40% encumbrance is 1.75 p/m/sec while that for the exit with the bollard is 1.94 p/m/sec. Thus we note that with the bollard present, the unit flow for the exit is 10.9% higher than without the BA present (see Table 25). The improvement in unit flow is likely due to the reduction of conflicts between pedestrians at the exit resulting from the presence of the bollard. The bollard acts as a barrier, preventing lateral conflicts from occurring between pedestrians at the exit. This results in a more ordered flow through the exit which generates a higher than expected exit flow. Thus, the 9.4% reduction in flow produced by the reduction in effective width of the exit due to the presence of the bollard is compensated for by the 10.9% improvement in unit flow achieved by the ordered exit flow generated by the presence of the bollard resulting in a net increase in the overall flow.

This is similar to the effect of the bollard alone – without the impact of encumbrance. Using the data from the 2013 trials we note that the presence of the bollard in the entrance only resulted in a net reduction in exit flow of 1% due to the 8.7% increase in the unit flow. Thus introducing low to moderate amount of encumbrance does not amplify the negative impact of the bollard at 0m.

The average unit flow for the exit without bollard at 60% encumbrance is 1.62 p/m/sec while that for the exit with the bollard is 1.74 p/m/sec. Thus we note that with the bollard present, the unit flow for the exit is 7.4% higher than without the BA present (see Table 25). The improvement in unit flow with 60% encumbrance is not as great as was achieved with 40% encumbrance. Thus as the level of encumbrance increases to high levels, this tends to disrupt the free movement of the pedestrians increasing the number of conflicts at the exit and thus counteracts the impact of the bollard.

In contrast to the impact of the bollard, which tends to calm the flow leading to greater unit flows, the presence of pedestrians with increasing levels of encumbrance tends to disrupt the flow reducing the unit flow. This is noted for the NoBA and the 0m BA case. In the case of NoBA, when the level of encumbrance is increased from 0% to 40%, the unit flow decreases by 9.3% and when the level of encumbrance is increased from 0% to 60% the unit flow is decreased by 16.1%.

In the case of the 0m BA, when the level of encumbrance is increased from 40% to 60%, the unit flow decreases by 10.3%. This is a larger reduction in unit flow than the corresponding case with NoBA which results in a 7.4% reduction.

Key findings:

- For moderate levels of encumbrance (40%) the presence of a 0m BA has little impact on the exit flow. This result is consistent with the findings of the 2013 trials (which showed a 1% reduction in flow for the 0m bollard case).

- For high levels of encumbrance (60%) the presence of a 0m BA reduces the exit flow by 3% compared to the NoBA case. This is three times larger than observed in the 2013 trials without encumbrance.
- While the presence of the bollard tends to calm the flow reducing conflicts resulting in greater unit flows, the presence of pedestrians with increasing levels of encumbrance tends to disrupt the flow, increasing conflicts and reducing the unit flow.
- The negative effect of pedestrians with encumbrance counteracts the positive effect of the bollard placed in the exit resulting in a net reduction in exit flow.
- In the case of no bollards, increasing the encumbrance level from 40% to 60% results in a 7% decrease in the exit flow.
- In the case of the 0m bollard, increasing the encumbrance level from 40% to 60% results in an 11% decrease in the exit flow.
- Increasing the level of encumbrance from moderate to high levels has a greater impact on exit flow when a bollard is present then if the exit is unobstructed.
- A high level of encumbrance has a negative effect on exit flow irrespective of whether a bollard is present in the exit or not. However, the effect is enhanced if a bollard is present in the exit.

4.3.5 0m BA WITH ENCUMBRANCE RESULT SUMMARY

For high exit crowd densities (4 p/m^2) passing through a 2.4m wide exit, the presence of an encumbered crowd has a greater impact on the exit flow then the impact of the BA.

Compared to the exit flow without a BA and without encumbrance:

- The introduction of a moderate amount of encumbrance (40%) reduces the flow at the exit by: **10%**
- The introduction of a high amount of encumbrance (60%) reduces the flow at the exit by: **16%**

Thus introducing encumbrance has a large negative impact on the flow at the exit. Both of these values are greater than any reduction in exit flow produced by a BA placed from 0m to 6m from an exit.

Compared to the exit flow without a BA and 40% encumbrance:

- The introduction of a BA ***increases*** the flow at the exit by **0.7%**
- Increasing the encumbrance to 60% ***reduces*** the flow at the exit by **7.0%**

Thus at moderate levels of encumbrance introducing a BA in the exit has negligible impact on the exit flow. However, increasing the level of encumbrance from moderate (40%) to high (60%) without the introduction of a BA has a large negative effect on exit flow which is 10X the impact of the BA on flow at the exit.

Compared to the exit flow without a BA and 60% encumbrance:

- The introduction of a BA ***reduces*** the flow at the exit by: **3%**

Thus at high levels of encumbrance (60%), introducing a BA in the exit has little impact on the exit flow, the maximum degradation in exit flow being 3%. However, this is four times the impact of introducing the BA at low levels of encumbrance (40%).

Compared to the exit flow with a BA and 40% encumbrance:

- Increasing the encumbrance to 60% ***reduces*** the flow at the exit by: **10%**

Thus with a BA in the exit, increasing the encumbrance from moderate (40%) to high (60%) decreases the flow at the exit by 50% more than if no bollard array was present.

Compared to the exit flow without a BA and 0% encumbrance:

- The introduction of a BA and 60% encumbrance ***reduces*** the flow at the exit by: **18%**

Thus introducing high levels of encumbrance (60%) AND a BA in the exit will reduce the exit flow by almost one fifth.

Thus encumbered flows, as may be expected at rail, underground and airport terminals, will achieve lower flows through exits than unencumbered flows. The degree of exit flow degradation increases with the level of crowd encumbrance. If 60% of the crowd is encumbered the exit flow will decrease by 16% compared to its unencumbered value.

If a bollard is positioned within the exit and the flow is encumbered no appreciable degradation occurs for moderate levels of encumbrance (40%) compared to a similarly encumbered flow without a bollard present. Even at high levels of encumbrance (60%) the degradation in exit flow is modest, decreasing by 3% compared to the flow achieved without a bollard in the exit.

However, it is worth noting that flows with high levels of encumbrance (60%) and a bollard positioned in the exit with experience a large degradation in flow compared to the unencumbered flow without a bollard. The degradation in flow is as much as 18% or almost one fifth of its unencumbered no bollard value.

4.4 TS3: EXTRA EXIT WIDTH TRIALS

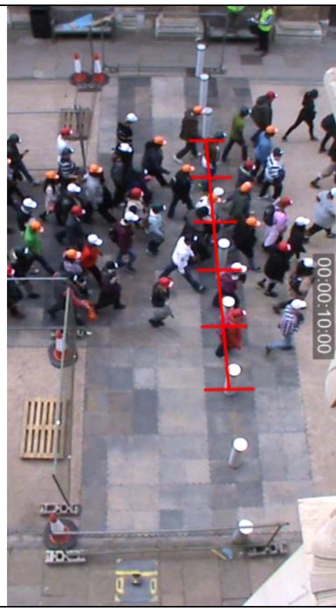
The extra width encumbrance trials (TS3) were conducted on the second day of the trial campaign. The trials were conducted in the centre of the Queen Anne Courtyard (see Section 2.3 for a full description of the experimental setup). TS3 presented the participants with 10 bollards (with approximately 13m between the outer surfaces of the outer bollards in the array), providing 10.8m of effective space through which to move. Two exit widths were used, 3.5m and 4.5m and in each trial the initial population density was $4p/m^2$. The trial setup can be seen in Figure 5. As can be seen the space between the exit and the BA was not constrained by diagonal barriers and so the participants had full access to the BA. This is more similar to the setup in first trial campaign (2013) than the day 1 trials of the second trial campaign.

A total of 21 trials were run, three stand-off distances were explored, 1m, 2m and 3m, two exit widths were considered 3.5m and 4.5m and each trial was run three times. In addition, three trials were run for the 4.5m exit without BA (see Table 3). The results produced in the TS3 trials are discussed in this section. Depicted in Figure 60 are typical scenes from TS3.

a) 4.5m exit width NoBA.

b) 4.5m exit 1m BA.

c) 4.5m exit 2m BA.



d) 4.5m exit 3m BA.

Figure 60: TS3 trials.

4.4.1 4.5m EXIT NoBA TRIALS

The three trials conducted at the end if day 2 consisted of three trials without BA and the 4.5m exit width (see Table 3). These trials were conducted at initial densities of 4 p/m^2 and so could be compared with the NoBA trials conducted on day 1 with the 2.4m exit width. Examples of the participant movement during the 4.5m wide NoBA trials can be seen in Figure 60a. Presented in Table 26 are the exit flows for each of the TS3 4.5m exit NoBA trials for the 4 p/m^2 initial density presented in 5 second time periods during the peak period.

Also presented is the overall average peak period flow. The flow curves for the 4.5m exit with NoBA conditions during the peak period are shown in Figure 61.

Table 26: Exit flow during peak period in 5 sec time intervals for the 4.5m wide exit with NoBA.

4.5m wide NoBA trials	Peak period flow (ppm) Time interval (sec)				Overall Average (ppm)
	5-10	**10-15**	**15-20**	**20-25**	
TS3_NoBA_4.5m_1	552.0	492.0	528.0	468.0	510
TS3_NoBA_4.5m_2	576.0	552.0	528.0	468.0	531
TS3_NoBA_4.5m_3	552.0	564.0	456.0	492.0	516
Average(4.5mExit, NoBA)	560.0	536.0	504.0	476.0	519

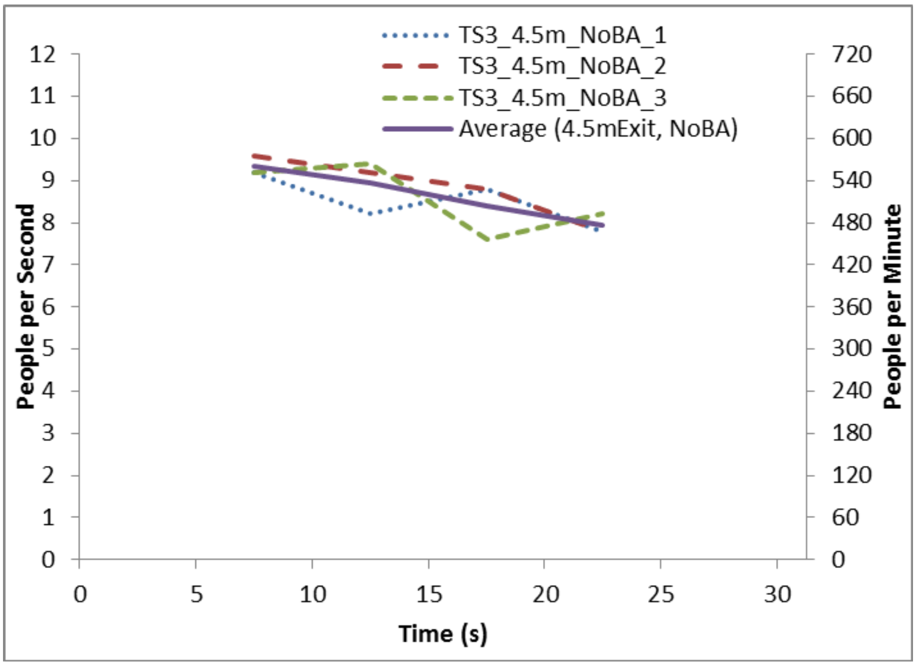


Figure 61: Average peak exit flow at 5 second intervals for the 4.5m NoBA trials.

As can be seen from Table 26 and Figure 61 the flow across the three repeats is fairly uniform and consistent. There is a slight degradation in performance with the average exit flow declining by 15% from its maximum value during the first time interval during the peak period to the last time interval during the peak period. This is less than half the decline in performance noted for the day 1 NoBA trials which were also conducted at the end of the day. However, the decline in exit flow is again thought to be due to participant fatigue as explained in Section 2.3.4.

Presented in Table 27 are average unit exit flows for TS3 4.5m exit NoBA trial and the 2.4m exit NoBA trial presented in 5 second time periods during the peak period. Also presented are the overall average peak period unit flows. The average exit flow curves for the 4.5m exit with NoBA and 2.4m NoBA conditions during the peak period are shown in Figure 62.

Table 27: Exit unit flow during peak period in 5 sec time intervals for the 4p/m^2 trials with NoBA - 2014.

NoBA Average across three trials for each of the 2.4m and 4.5m exits	Peak period unit flow (p/m/min)						Overall Average (p/m/min)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
2.4m exit	150.0	131.7	121.7	101.7	98.3	91.7	115.8
4.5m exit	124.4	119.1	112.0	105.8	--	--	115.3

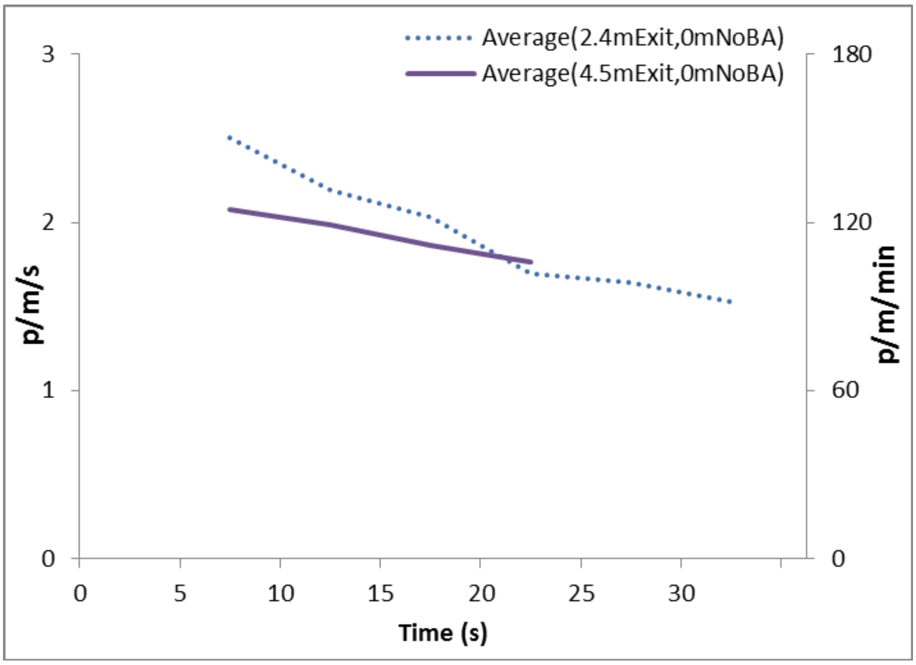


Figure 62: Average peak exit unit flow at 5 second intervals for the 4.5m and 2.4m NoBA trials.

Figure 63 shows the average and range in peak unit exit flow for the 2.4m and 4.5m exit width cases with NoBA. As can be seen the difference between the average peak unit exit flows for the 2.4m and 4.5m exit widths is less than the spread in the trial results for each case.

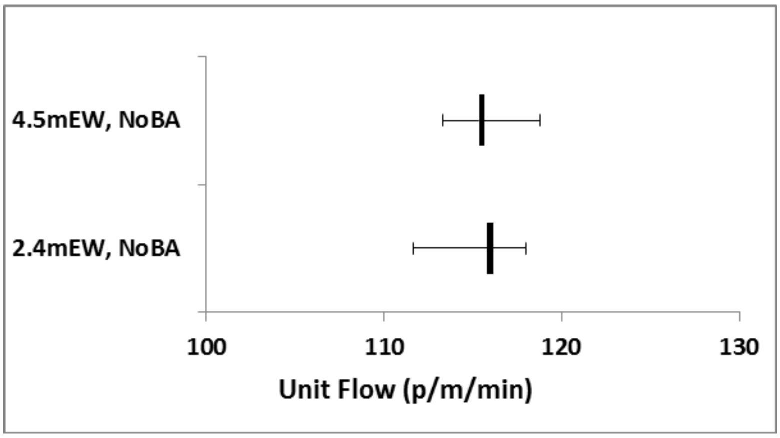


Figure 63: Average and range of peak exit unit flow for the 2.4m and 4.5m exit width cases with NoBA.

As can be seen from Table 27 the average exit unit flow during the peak period for both the 2.4m exit and the 4.5m exit are identical. This is as expected with the unit flows generated by exits under identical conditions being theoretically constant irrespective of the exit width. Thus it is not necessary to undertake the NoBA trial for the 3.5m exit as it would theoretically generate the same unit flow. It is noted from Figure 62 that the flows in both exits suffer from the impact of fatigue, with the 2.4m exit suffering a greater degradation over a longer period.

Key findings:

- Peak exit flow for the 4.5m NoBA is almost uniform.
- Unit flow during peak for the 4.5m exit is 115.3 p/m/min which is almost identical to the 115.8 p/m/min produced by the 2.4m exit.

4.4.2 EXIT FLOWS FOR THE 3.5m and 4.5m WIDE EXITS WITH 1m, 2m and 3m BA

This section compares the exit flow conditions of the 1m, 2m and 3m BA stand-off distances for the 3.5m and 4.5m wide exits. The results for all the cases can be found in ANNEX I: RESULTS. In this section a representative sample and summary of the results are presented in order to facilitate the analysis and discussion.

The results for the 3.5m exit width with 1m BA are presented in Table 28 and Figure 64 while the results for the 4.5m exit width with 1m BA are presented in Table 29 and Figure 65. The data in Table 28 and Table 29 are used to calculate the overall average peak flow in persons per minute at the exit for the two exit widths with 1m BA.

Table 28: Exit flow during peak period in 5 sec time intervals for the 3.5m wide exit with 1m BA.

3.5m wide, 1m BA trials	Peak period flow (p/min)						Overall Average (p/m/min)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
TS3_3.5m_1mBA_1	432.0	444.0	372.0	420.0	432.0	396.0	416
TS3_3.5m_1mBA_2	408.0	408.0	408.0	420.0	396.0	372.0	402
TS3_3.5m_1mBA_3	420.0	396.0	360.0	384.0	396.0		391
Average(3.5mExit,1mBA)	420.0	416.0	380.0	408.0	408.0	384.0	**403**

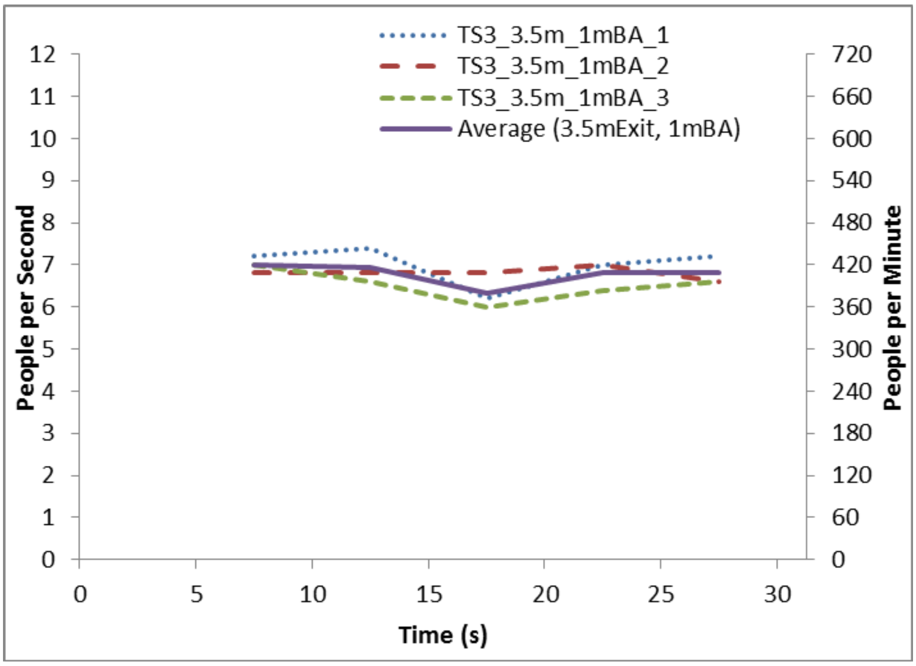


Figure 64: Average peak exit flow at 5 second intervals for the 3.5m exit width, 1m BA trials.

Table 29: Exit flow during peak period measured in 5 sec time intervals for the 4.5m wide exit with 1m BA.

4.5m wide, 1m BA trials	Peak period flow (p/min)					Overall Average (p/m/min)
	Time interval (sec)					
	5-10	10-15	15-20	20-25	25-30	
TS3_4.5m_1mBA_1	504.0	444.0	504.0	468.0	456.0	475
TS3_4.5m_1mBA_2	516.0	492.0	492.0	432.0	468.0	480
TS3_4.5m_1mBA_3	504.0	480.0	492.0	432.0	432.0	468
Average(4.5mExit,1mBA)	508.0	472.0	496.0	444.0	452.0	**474**

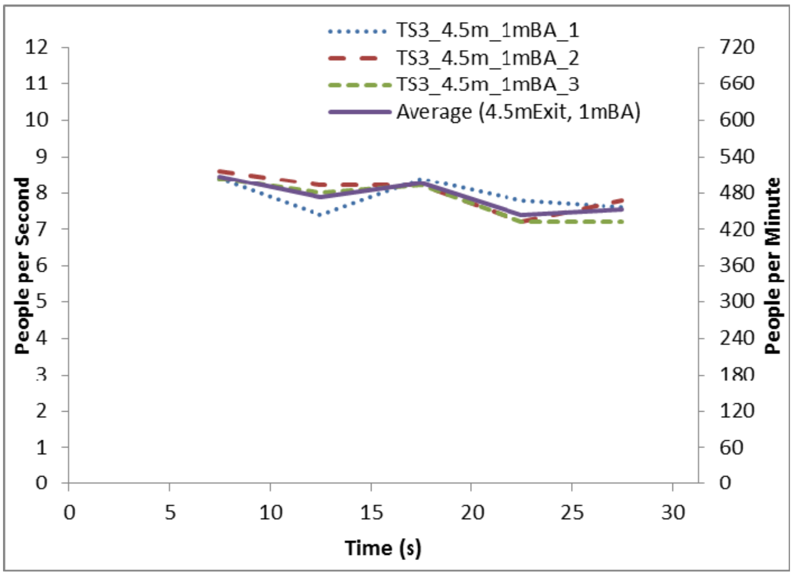


Figure 65: Average peak exit flow at 5 second intervals for the 4.5m exit width, 1m BA trials.

As can be seen from Figure 64 and Figure 65 the flow over the peak period for both the 3.5m and 4.5m exits with 1m BA are all fairly uniform with good levels of consistency between the repeat trials. This is also true for the other BA stand-off distances (see ANNEX I: RESULTS). Given the similarity in the peak flow condition, the results for each exit width and stand-off distance are averaged over the three repeat trials to produce a single curve for each condition. The flows are then converted to unit flows (by dividing by the exit width) in each 5 sec time period and the average unit flows are plotted as shown in Figure 66 for the 3.5m exit and Figure 67 for the 4.5m exit. The average unit flows for each condition in each 5 sec time period are shown in Table 30 along with the overall average unit flow. Data for the 2.4m exit, derived from Table 9 (NoBA), Table 11 (1m BA) and Table 13 (2m BA) is presented for completeness.

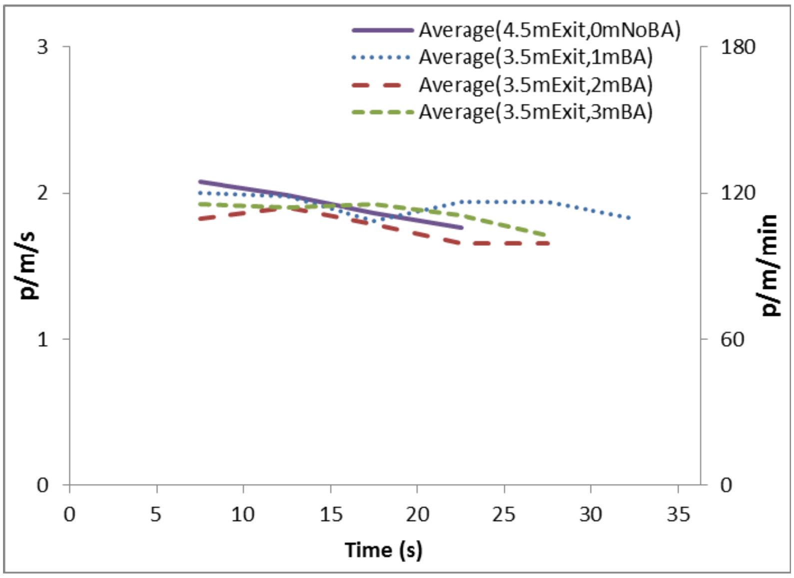


Figure 66: Average peak exit unit flow at 5 second intervals for the 3.5m exit width, 1m, 2m, 3m and 4.5 m exit width NoBA trials.

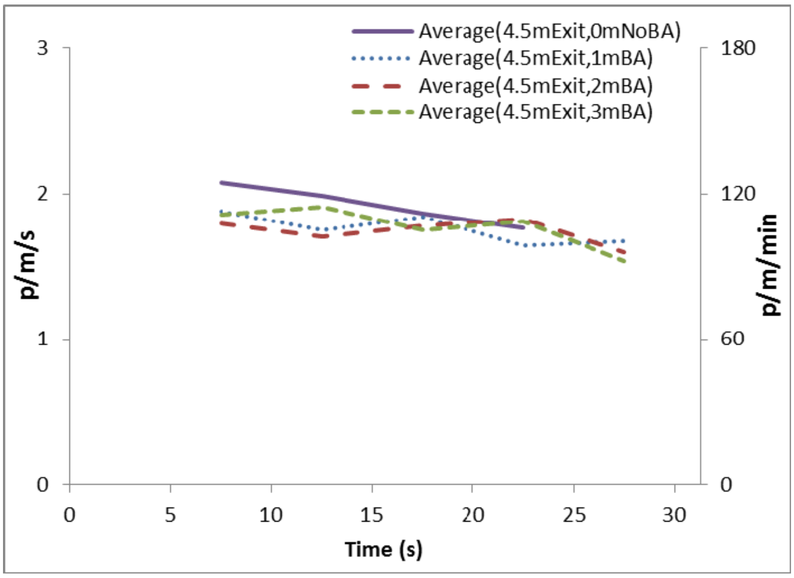


Figure 67: Average peak exit unit flow at 5 second intervals for the 4.5m exit width, 1m, 2m, 3m and NoBA trials.

Table 30: Exit unit flow during peak period measured in 5 sec time intervals for the $4p/m^2$ trials for the 2.4m, 3.5m and 4.5m exits with NoBA, 1m BA, 2m BA and 3m BA.

Exit and BA condition	Average peak period unit flow (p/m/min)							Overall Average (p/m/min)
	Time interval (sec)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
3.5/4.5m exit, NoBA	124.4	119.1	112.0	105.8	--	--	--	115.3 (113.3 -118.0)
2.4m exit, NoBA	150.0	131.7	121.7	101.7	98.3	91.7	--	115.8 (111.7 – 119.2)
2.4m exit, 1m BA	133.3	120.0	123.3	111.7	106.7	103.3	110.0	115.5 (112.1 – 118.6)
2.4m exit, 2m BA	135.0	110.0	111.7	105.0	108.3	110.0	100.0	111.4 (110.7 – 112.1)
3.5m exit 1m BA	120.0	118.9	108.6	116.6	116.6	109.7	--	115.2 (111.8 – 118.9)
3.5m exit 2m BA	109.7	114.3	107.4	99.4	99.4	--	--	106.1 (104.3 – 109.0)
3.5m exit 3m BA	115.4	114.3	115.4	110.9	102.9	--	--	111.8 (110.4 – 112.5)
4.5m exit 1m BA	112.9	104.9	110.2	98.7	100.4	--	--	105.4 (104.0 – 106.7)
4.5m exit 2m BA	107.6	102.2	106.7	109.3	96.0	--	--	105.1 (103.5 – 107.3)
4.5m exit 3m BA	111.1	114.7	104.9	108.4	92.0	--	--	107.5 (105.6 – 110.7)

From Table 30, Figure 66 and Figure 67 it is clear that for a given exit width, the exit unit flows for all the BA stand-off distances are all similar but produce a degraded exit unit flow compared to the NoBA case. The greatest reduction in exit unit flow is 9% which occurs for the 2m stand-off in the 4.5m exit case.

Figure 68, Figure 69 and Figure 70 shows the average and range in peak unit exit flow for the 2.4m, 3.5m and 4.5m exit width cases with the various BA cases. As can be seen, in each case the 2m BA stands out as producing the lowest exit unit flow (note that 1.5m BA case for the 2.4m exit is unreliable due to experiment setup – see earlier discussion).

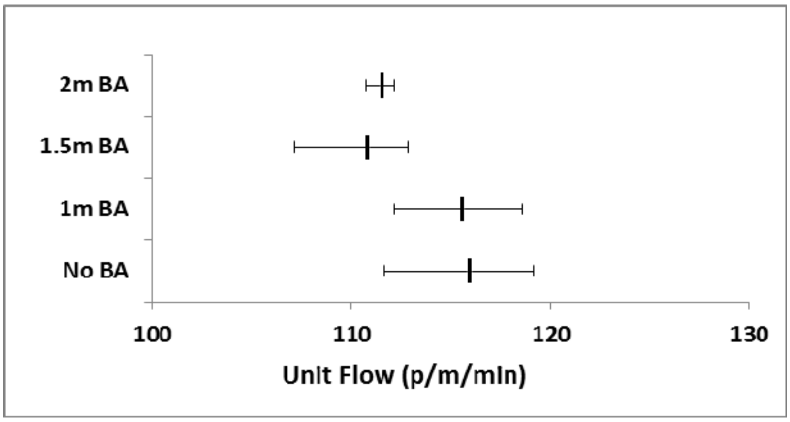


Figure 68: Average and range of peak exit unit flow for the 2.4m exit width cases with NoBA, 1m BA, 1.5m BA and 2m BA.

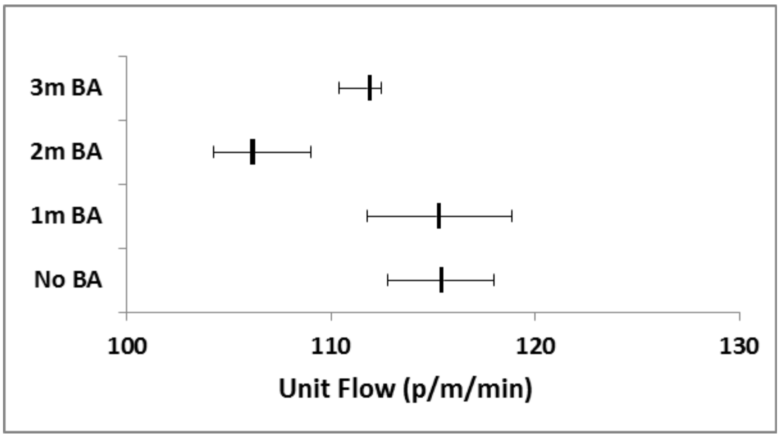


Figure 69: Average and range of peak exit unit flow for the 3.5m exit width cases with NoBA, 1m BA, 2m BA and 3m BA.

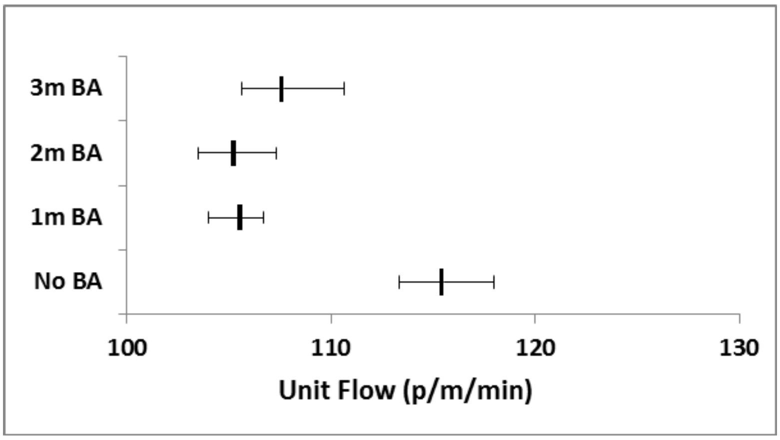


Figure 70: Average and range of peak exit unit flow for the 4.5m exit width cases with NoBA, 1m BA, 2m BA and 3m BA.

Key findings:

- Flows produced for the 3.5m and 4.5m exit widths with BA stand-off 1m, 2m and 3m are consistent and produce uniform flows during the peak period.
- For both the 3.5m and 4.5m exit configuration the 2m BA stand-off produces the greatest reduction in exit unit flow. This is a similar observation that noted in TS1 where the 2m BA produced the greatest reduction in exit flow.
    - The maximum reduction in exit unit flow was 9% which occurred for the largest exit.

4.4.3 GAP USAGE AND DENSITY AT THE BA FOR THE 3.5m and 4.5m WIDE EXITS WITH 1m, 2m and 3m BA AND NoBA

This section compares the gap usage and densities measured at the BA or the BA line (for the NoBA case) for the 1m, 2m and 3m BA stand-off distances for the 3.5m and 4.5m wide exits. The detailed density results for all the cases can be found in ANNEX I: RESULTS. In this section a summary of the results are presented in order to facilitate the analysis and discussion.

It was noted in the day 1 trials and the trials from the first trial campaign that as the crowd leaves the exit they diffuse into the surrounding space, reducing the population density and enabling the individuals within the crowd to walk at their desired faster pace. This is also confirmed by the day 2 trials. Presented in Table 31 is the gap usage for the NoBA at 1m, 2m, 3m, BA at 1m, 2m and 3m from the 4.5m exit.

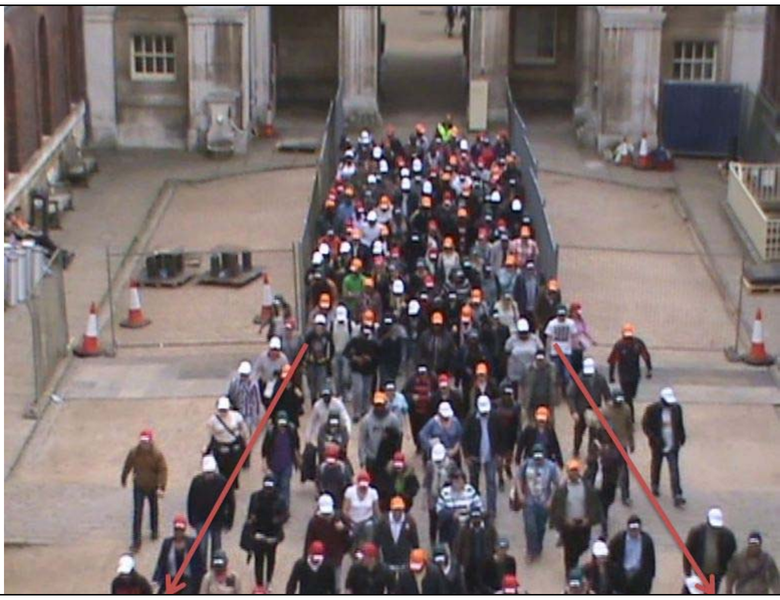
For the NoBA case the central gap usage (gaps 4, 5 and 6) decreases with increased distance from the exit. As the distance to the exit increases, more people are using the outer spaces and more of the outer spaces are being used, thus the further from the exit the greater the diffusion. This effect is shown in Figure 71a, which shows the diffusion of the crowd with increasing distance from the exit for the NoBA 4.5m wide exit case.

Table 31:TS3- Gap usage (%) for the 4.5m exit for the NoBA, 1m BA, 2m BA and 3m BA trials.

Trials	Gap Use (%)									
	1	2	3	4	5	6	7	8	9	Central Gaps (4,5,6)
1m NoBA	0	0	11.1	26.1	28.1	28.6	6.1	0	0	82.8
1m BA	0	0	11.1	24.9	29.8	25.1	9.1	0	0	79.8
2m NoBA	0	0.1	14.1	25.7	26.8	23.3	10.0	0	0	75.8
2m BA	0	0.1	12.8	24.0	28.8	22.6	11.3	0.4	0	75.4
3m NoBA	0	1.0	14.3	23.6	25.8	23.0	12.1	0.1	0	72.4
3m BA	0	1.1	14.5	22.3	27.7	20.5	13.1	0.7	0	70.5

This is also true in the BA cases, however it is noted that the BA tends to diffuse the crowd further; i.e. with BA, there is a decrease in the central gap usage and an increase in the usage of the outer gaps (see Table 31 and Figure 71b). Thus as noted in the first trial campaign, the

BA acts as a divergent lens increasing the diffusion of the crowd compared to the situation without the BA (compare Figure 71a with Figure 71b).



(a) 4.5m exit, NoBA

(b) 4.5m exit, 1m BA

(c) 3.5m exit, 1m BA

Figure 71:TS3 – Diffusion in the exiting crowd for the (a) NoBA with 4.5m exit, (b) 1m BA with 4.5m exit and (c) 1m BA with 3.5m exit.

The density was measured in three regions, the central group of 3 gaps and the outer gaps to the left and right and immediately adjacent to the central three gaps (see Sections 3.1.2 and 3.1.3). Combining the two measures provides the density over the central 3 gaps and the central 5 gaps. Presented in Table 32 are the averages of these two measures for the 3.5m and 4.5m wide exits. It should be recalled that the density measures are only approximate. In particular, if more than half a person was determined to be within the measurement region they were counted as a whole person, otherwise they were ignored. The density in the central three gaps is always larger than the density in the central five gaps. This is because the density in the outer gaps is quite low with fewer people using these gaps than the central three gaps.

Table 32: Average peak crowd density for the 3.5m and 4.5m exits with and without BA at 1m, 2m and 3m stand-off.

Stand-off	NoBA 4.5m Exit		4.5m Exit		3.5m Exit		2.4m Exit
	Density Central 5 gaps p/m^2	Density Central 3 gaps p/m^2	Density Central 5 gaps p/m^2	Density Central 3 gaps p/m^2	Density Central 5 gaps p/m^2	Density Central 3 gaps p/m^2	Density Central 3 gaps p/m^2
1m	0.91	1.24	0.88	1.14	0.75	1.19	0.97
2m	0.92	1.17	1.04	1.25	0.67	0.91	0.88
3m	0.94	1.12	0.82	0.95	0.66	0.81	--

For the 4.5m exit with NoBA it is clear that the density over the central 5 gaps remains fairly constant from 1m to 3m from the exit. However, the central gap density consistently decreases as the distance from the exit increases. This is consistent with the observation that the central gap usage decreased with increasing distance from the exit and indicates the general diffusion away from the high density centre regions.

For the 4.5m exit with BA we note that the density over the central 5 gaps is generally less than density in the case with NoBA. This is also true for the central 3 gaps. This is also consistent with the gap analysis which showed that more people tend to use the outer gaps with the BA present than without. Thus the densities at the BA measured in the central regions are generally less with the BA present and confirms that the BA acts as a divergent lens pushing the population towards the outer regions to a greater extent than when no BA is present. It is also clear that as the distance from the exit increases, the density generally decreases indicating that the outward diffusion increases with distance from the exit.

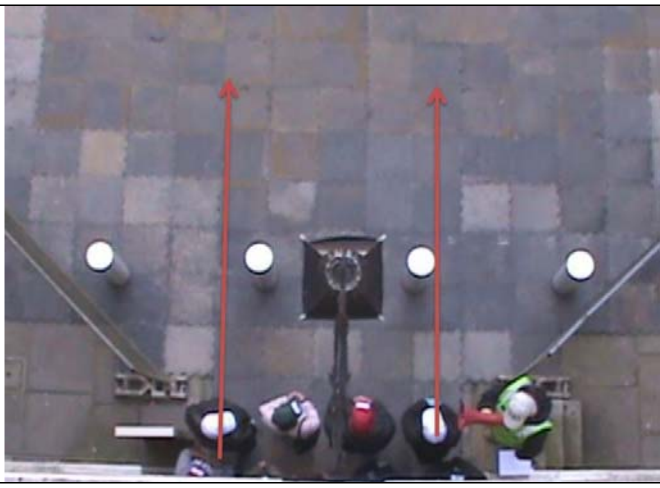
However, it is noted in the case with BA that at 2m from the exit the density is ***LARGER*** than at 1m and it is larger than the case with NoBA i.e. opposite the noted trends. If we consider the gap analysis at 2m from the exit, the degree of diffusion in both the NoBA and BA cases is almost identical (see Table 32). Thus the crowd is more concentrated towards the centre with the 2m BA than it should be. As can be seen in Table 32, the percentage difference between the NoBA and BA central gap usage is 3.6% at 1m and 2.6% at 3m however it is only 0.5% at 2m. This lack of additional diffusion at the 2m line results in the increase in density noted at the BA line.

For the 3.5m wide exit with BA (and the 2.4m wide exit) it is noted that the central densities decrease with increasing distance from the exit which indicates increased diffusion as the crowd moves further away from the exit. As there is no NoBA case for the 3.5m wide exit we cannot confirm that the crowd is dispersed to a greater extent with the BA present.

However, it is also noted that the densities in the 3.5m exit case are generally smaller than those for the 4.5m exit case, both for the central five gaps and the central three gaps. The densities in the 2.4m exit case over the central three gaps are also smaller than those for the 3.5m exit. This can be explained by the number of people positioned across the exit opening. For the wider exit there are more people available to pass through the same number of gaps (size opening) in the BA. This can clearly be seen in Figure 72 which shows the different exit sizes with the crowds ready to exit relative to the BA. For the 1m stand-off, with the 2.4m exit there are four people directly opposite the central three gaps (see Figure 72a), while for the 3.5m exit there are eight people opposite the central three gaps (see Figure 72b) and for the 4.5m exit there are 11 people opposite the central gaps (see Figure 72c). Thus as the exit width increases from 2.4m to 4.5m there are more and more people attempting to utilise the three central gaps and hence the central density increases.

If we now extend the exit width beyond 4.5m this brings into consideration two additional gaps on the periphery. So as the exit width increases beyond 4.5m the additional people will utilise the two additional gaps and so the central density will not increase further. As the width increases from 4.5m to 7.4m (the extent of the BA with 6 bollards and 5 gaps) the density of the outer regions are expected to increase to a maximum value and then remain almost constant as the exit width was increased from 7.4m to 10.2m (the extent of the BA with 8 bollards and 7 gaps). **This concept was not tested as the largest exit width used was 4.5m. It may be advisable to test larger exit openings to confirm this prediction.**

The one exception to the increasing BA density with exit width occurs at 1m from the exit. At 1m from the exit, the density measured over the central three gaps is ***less*** for the 4.5m exit than the 3.5m exit. This is thought to be due to the outer occupants of the 4.5m exit being aligned directly with the outer bollards of the central three gaps. When faced with the bollard directly in front of them, the participants will swerve either inwards towards the higher density region or outwards towards the lower density region. It is suggested that the participants swerve outward and so decrease the density of the inner region but increasing the density of the outer region. Thus the density measured over the five central gaps for the 4.5m exit is greater than that for the 3.5m exit while the density measured over the three central gaps is smaller for the 4.5m exit compared to the 3.5m exit.



(a) 2.4m exit with 1m BA.

(b) 3.5m exit with 1m BA.

(c) 4.5m exit with 1m BA.

Figure 72: Bollard arrangement for the 2.4m, 3.5m and 4.5m wide exits.

Key findings:

- The crowd diffuses outwards and the degree of diffusion increases with distance from the exit. As a result the density of the central regions decreases with increasing distance from the exit.

- The degree of diffusion is greater when the BA is present, the BA acting as a divergent lens. As a result, the density in the central regions with BA is less than that for the NoBA case.

- Gap usage for the 4.5m exit with 2m BA appears to be less diffused than expected, with a concentration of participants towards the central gaps. In this case the central density is ***greater*** than in the NoBA case.

- The central densities at the BA increase with exit width.

  - The increase in central densities with exit width is due to the positioning of the BA relative to the exit. As the exit width increases from 2.4m to 4.5m the number of gaps within the exit opening is always three while the number of people attempting to utilise these gaps increases with exit width. If the exit widths were to increase beyond 4.5m the central densities are not expected to increase further as two additional gaps become available.

- One exception to the increasing BA density with exit width occurs at 1m from the exit. At 1m from the exit, the density measured over the central three gaps is ***less*** for the 4.5m exit than the 3.5m exit. This is thought to be due to the orientation of the BA relative to the exit, with the outer occupants of the 4.5m exit being aligned directly with the outer bollards. When faced with the bollard directly in front of them, it is suggested that participants will swerve outwards towards the lower density region thus decreasing the density of the inner region.

- The positioning of the BA relative to the exit is critical in order to achieve the minimum disruption to the flow.

4.4.4 FLOW AT THE BA

This section compares the flow at the BA or the BA line (for the NoBA case) for the 1m, 2m and 3m BA stand-off distances for the 3.5m and 4.5m wide exits (see Table 33). The detailed flow results for all the cases can be found in ANNEX I: RESULTS. In this section a summary of the results are presented in order to facilitate the analysis and discussion.

As the flow at the BA or BA line was not confined by bounding walls and the flow did not expand to occupy the entire available width at any stand-off distance, it is difficult to estimate a unit flow as the flow width must be determined at each of the stand-off distances. The unit flow is determined by estimating the effective width used by the flow. For the NoBA case this is approximately the equivalent to 5 (7.35m), 5 (7.35m) and 6 (8.775m) gaps at 1m, 2m and 3m stand-off respectively, for the 4.5m exit with BA, 5 (6m), 6 (7.2m) and 7 (8.4m) gaps at 1m, 2m and 3m stand-off respectively, and for the 3.5m exit with BA, 5 (6m), 5 (6m) and 6 (7.2m) gaps at 1m, 2m and 3m stand-off respectively. However, these distances are only approximate and so the unit flows at the BA and BA line are considered unreliable and so are not presented.

Taken across the entire BA, the decrease in effective width at the BA line is approximately 18% (due to the presence of the bollards), while the decrease in the flow for the 4.5m exit NoBA and BA cases is around 7% (see Table 33). While this is lower than what may have been expected, it is unlikely to be due to an improvement in the unit flow at the BA line. This is because the flow density at the BA line is quite low and hence not all the space is being utilised. The flow at the BA line for the NoBA and BA 4.5m exit are fairly constant irrespective of stand-off distance (see Table 33). However, for the 3.5m exit the flow with a 2m stand-off is some 9% lower than at the 1m stand-off and 7% lower than the 3m stand-off (see Table 33).

Table 33: Average peak flow at the BA or BA line for the 3.5m and 4.5m exits with and without BA at 1m, 2m and 3m stand-off.

Stand-off	4.5m Exit			3.5m Exit
	NoBA Flow p/min	BA Flow p/min	% difference	BA Flow p/min
1m	517	485	6.2	404
2m	529	489	7.6	369
3m	523	486	7.1	398

Thus the flows at the BA are lower than that for the NoBA case, but not as low as would be expected due to the reduction in free width due to the presence of the BA. The 4.5m exit with BA produces a consistent set of flows at the BA stand-off distances. For the 3.5m exit, the flow at the 1m and 3m stand-off distances appear consistent however, the flow at the 2m appears to be lower than expected.

Key findings:

- The flow at the BA lines for the 1m, 2m and 3m stand-off with and without BA appear fairly constant across all the cases – flow does not appear to diminish with increase distance from the exit. However, the flow at 2m from the exit for the 3.5m exit width appears to be lower than expected.

- The flow at the BA for the 4.5m exit at all stand-off distances is 7% lower than the case for NoBA. However, this difference is less than the 18% that would be expected from the reduction in exit width at the BA line. The lower than expected reduction in BA flow is thought to be due to the low densities experienced at the BA.

4.4.5 COLLISION AVOIDANCE ANALYSIS AT THE BA

This section investigates the number of participants that had to take a diversionary action at the BA due to the presence of a bollard. This is defined as persons who are within two steps of a bollard and who take diversionary measures to avoid colliding with the bollard. This may be changing their direction of movement, taking a side step or twisting their body in order to avoid coming into contact with the bollard.

Note that the diversionary actions being measured are effectively last minute changes in direction. It does not include those participants who modified their direction of travel to take into the presence of the BA at a greater distance from the BA.

In addition, it is noted whether the person took a diversion which directed them towards the centre of the exit or away from the centre of the exit. Furthermore, the number of people who have come into contact with the bollard are also noted. This does not include those who deliberately tapped the bollard as they passed it. Those who came into contact with the bollard are included in the number that took diversionary actions. The detailed results can be found in ANNEX I: RESULTS. In this section a summary of the results are presented in order to facilitate analysis and discussion. The numbering of the bollards is presented in Figure 73 and Figure 74.

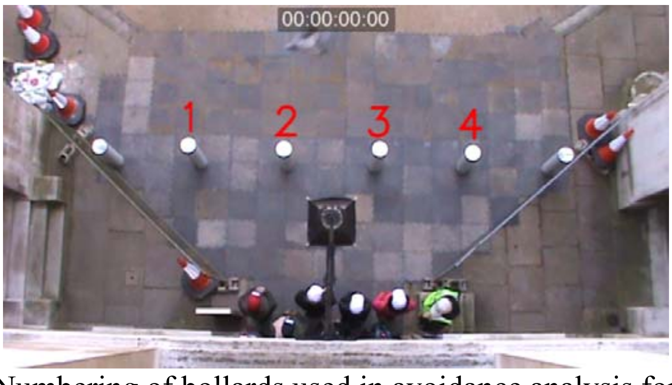


Figure 73: Numbering of bollards used in avoidance analysis for TS1 trials.

Figure 74: Numbering of bollards used in avoidance analysis for TS3 trials.

Presented in Table 34 are the average number of avoidance actions for bollards 1 and 4 and the total number of avoidance actions for bollards 1 to 4 for the 2.4m exit. Presented in Presented in Table 35 are the average number of avoidance actions for bollards 3 and 6 and the total number of avoidance actions for bollards 3 to 6. The avoidance actions are broken down into 'Out' and 'In' which indicate an avoidance movement that meant the person deviated their path away from the centre line (Out) or towards the centre line (In). Also shown are the number of bollard hits and the total number of avoidance actions, irrespective of whether they were 'Out' or 'In' movements.

Table 34: Average avoidance actions and physical contacts with the BA for the 2.4m exit with 1m and 2m BA.

Configuration	**Bollards 1 and 4**			**Total Bollards 1-4**			**Total Out/In**
	Out	**In**	**Hit**	**Out**	**In**	**Hit**	
2.4m exit 1m BA	0.0	0.0	0.0	24.0	11.2	4.4	35.2
2.4m exit 2m BA	5.8	1.0	0.6	22.1	11.8	3.1	33.9

Table 35: Average avoidance actions and physical contacts with the BA for the 3.5m and 4.5m exits with 1m, 2m and 3m BA.

Configuration	**Bollards 3 and 6**			**Total Bollards 3-6**			**Total Out/In**
	Out	**In**	**Hit**	**Out**	**In**	**Hit**	
3.5m exit 1m BA	8.3	0.8	0.8	35.8	18.6	4.9	54.3
3.5m exit 2m BA	30.2	1.9	1.1	57.1	17.4	4.1	**74.6**
3.5m exit 3m BA	21.8	3.0	0.6	44.2	14.7	1.8	58.9
4.5m exit 1m BA	**46.4**	6.4	1.9	66.8	26.4	4.6	**93.2**
4.5m exit 2m BA	**39.8**	4.6	1.3	63.7	22.1	5.0	**85.8**
4.5m exit 3m BA	19.1	6.0	0.6	40.0	20.1	3.1	60.1

We note that the total number of avoidance actions is highest for the 4.5m exit 1m BA, 4.5m exit 2m BA and 3.5m exit 2m BA, with the total number of avoiding actions being in the 90's, 80's and 70's respectively. These exit bollard configurations also have a high number of collisions. The next highest is the 4.5m exit with 3m BA with the total number of avoiding actions in the 60's followed by the 3.5m exit with 3m BA, with the total number of avoiding actions in the high 50's. The least number of avoiding actions occurs for the 3.5m exit with 1m BA, with the number of avoiding actions being in the 50's. This corresponds to the order of the degradation in exit performance of the BA cases compared to the NoBA case (see Table 36). For the 2.4m wide exit, the total number of avoiding actions for the 2.4m exit with

1m BA is almost the same as that for the 2m BA. This inconsistent result is thought to be due to the pinching effect of the side barriers, as described in Section 2.3.4, and so is a result of the slightly different configuration in the 2.4m exit trials.

When taking an avoiding action the individual's forward motion is generally reduced as they must travel a greater distance to the side reducing their forward progress. In addition the individual taking the avoiding action impedes not only the person directly behind them but also those off to the side into which they are moving into. Thus a larger number of people behind them are impacted than if they simply slowed their forward progress. This in turn may impact the overall exit flow. Thus the configurations which have a high number of avoiding actions may also have a lower exit flow.

The direction of the avoiding action will also have an impact on the central gap density. Consider the outer bollards i.e. 3 and 6. If the individual takes an inner avoiding action they will move into the inner gap thereby slightly increasing the gap density of the central three gaps. If the individual takes an outer avoiding action, they will move into the outer gap thereby slightly decreasing the density of the central three gaps. The impact of last minute avoidance behaviour on the BA density is small compared to the overall movement of people but may have an impact on the BA density.

For the outer bollards (bollards 3 and 6) the number of outward avoiding actions greatly outnumbers the inward avoiding actions across all the configurations. Thus when confronted with one of the outer bollards, the vast majority of the participants swing to the outer lower density regions.

The 4.5m exit 1m BA, with 46.4 outer avoiding actions has the highest number of outer avoiding actions at bollard locations 3 and 6, 16.5% greater than the next largest. This relatively high number of outward avoiding actions may have contributed to the slight decrease in the density of the inner region compared to the 3.5m exit with 1m BA. It is also worth noting that the 3.5m exit with 1m BA had the smallest number of avoiding actions overall and also the smallest number of avoiding actions for the outer bollards, an order of magnitude less than that for the 4.5m exit with 1m BA. Thus the impact of bollard avoiding actions on the BA density for the 3.5m exit with 1m BA is expected to be small.

With 39.8 outer avoiding actions, the 4.5m exit 2m BA has the second largest number of avoiding actions at bollard locations 3 and 6. However, this does not explain why the density in the central region for this case is greater than that of the NoBA case. It is suggested that the higher density in this case is due to other factors associated with BA positioning relative to the exit.

Key findings:

- The 4.5m exit 1m and 2m BA and the 3.5m exit 2m BA, have the highest number of last minute BA avoiding actions. The next highest is the 4.5m exit with 3m BA and the 3.5m exit with 3m BA, while the least number of avoiding actions occurs for the 3.5m exit with 1m BA.

- When taking an avoiding action the individuals forward motion is generally reduced impeding those directly behind them and also those into which path they are moving.

BA/Exit configurations which produce a high number of avoiding actions will also incur a lower exit flow.

- Whether the avoiding action takes the person inward towards the centre of the exit or outward towards the boundary will impact the centre density at the BA. The impact of last minute avoidance behaviour on the BA density is small compared to the overall movement of people but may have an impact on the BA density.
- For the outer bollards (bollards 3 and 6) the number of outward avoiding actions greatly outnumbers the inward avoiding actions across all the configurations. Thus when confronted with one of the outer bollards, the vast majority of the participants swing to the outer lower density regions.
- The 4.5m exit 1m BA has the highest number of outer avoiding actions at bollard locations 3 and 6, 16.5% greater than the next largest. This relatively high number of outward avoiding actions may have contributed to the slight decrease in the density of the inner region compared to the 3.5m exit with 1m BA.

4.4.6 DISCUSSION OF EXIT UNIT FLOW IN EXTRA WIDTH TRIALS

The extra width trials have produced a complex set of results. For the 3.5m and 4.5m wide exits the reduction in unit flow at the exit compared to the NoBA case is generally greater than the natural variation within each case (see Figure 69 and Figure 70). However, this was not the case for the 2.4m exit with 1m BA stand-off (see Figure 68). In order to filter out the width of the exit from consideration it is informative to consider the exit unit flow, this is the flow per unit width of available exit width. Presented in Table 36 is a summary of the unit flows for various exit widths and stand-off distances.

Table 36: Average peak exit unit flow achieved for the 2.4m, 3.5m and 4.5m exits with and without BA at 1m, 2m and 3m stand-off.

	NoBA	1m BA		2m BA		3m BA	
	UF (p/m/min)	UF (p/m/min)	% diff	UF (p/m/min)	% diff	UF (p/m/min)	% diff
2.4m exit	**115.8** (111.7 – 119.2)	**115.5** (112.1 – 118.6)	-0.3	**111.4** (110.7 – 112.1)	-3.8	**102.3*** (98.6 – 108.3)	-0.6*
3.5m exit	**115.3+** (113.3 -118.0)	**115.2** (111.8 – 118.9)	-0.1	**106.1** (104.3 – 109.0)	-8.0	**111.8** (110.4 – 112.5)	-3.0
4.5m exit	**115.3** (113.3 -118.0)	**105.4** (104.0 – 106.7)	-9.0	**105.1** (103.5 – 107.3)	-9.0	**107.5** (105.6 – 110.7)	-6.8
Average	**115.6x**	**112.0**	-3.1	**107.5**	-7.0	**109.7**** (111.5)+*	-5.1 (-3.5)+*

*Based on 2013 results (NoBA produced mean peak exit unit flow of 102.9 p/m/min with a range of 100.8 to 105.0 p/m/min)

+Based on the 2014 4.5m exit width with NoBA.

xAverage excludes 3.5m result.

**Average excludes 2.4m width exit result.

+*Average based on scaled up 2013 trial result. NoBA 2014/NoBA 2013 = 115.8/102.9 = 1.13. Applying this factor to the 3m BA result 1.13 * 102.3 = 115.1 p/m/min

For exits ranging in widths from 2.4m to 4.5m and for BA with a stand-off distance from 1m to 3m for high density exit flows (up to $4p/m^2$), and assuming there is no restriction on the BA width available, several trends can be identified:

- ***Generally as the exit width increases from 2.4m to 4.5m, the greater the impact of the BA on the unit exit flow for all stand-off distances.*** For the 1m stand-off the degradation in unit flow increases from 0.3% for the 2.4m exit to 9% for the 4.5m exit; for the 2m stand-off the degradation increases from 3.8% for the 2.4m exit to 9% for the 4.5m exit while for the 3m stand-off the degradation increases from 0.6% for the 2.4m exit to 6.8% for the 4.5m exit. This increase in edit flow degradation with exit width is concerning as it suggests the wider the exit the greater the impact of the BA on exit flow.

- ***The maximum impact on peak exit unit flow observed was a degradation of 9% which occurred for the widest exit configuration (4.5m) and with a 2m stand-off.*** The degradation in unit exit flow ranged from 0.1% to 9%.

- ***The maximum impact on peak exit unit flow occurs with a stand-off distance of 2m across all the exit widths examined.*** Generally, the closer and further away the BA is located, the smaller the impact on the unit exit flow. In reality the critical BA location could be anywhere from 1m to 3m. For the 2.4m wide exit, the maximum impact on exit flow occurred for a stand-off distance of 1.5m however, these results are considered less reliable than the other results due to the nature of the setup of the 1.5m BA trials.

- ***The 4.5m exit with a BA stand-off distance of 1m experiences a degradation in unit exit flow equal to the maximum degradation (observed at 2m stand-off).*** This observation is unique to the 4.5m exit width and does not occur for the other exits.

- ***Averaged across the three exit widths, the greatest impact on exit unit flow is a 7% reduction in unit exit flow which occurs for a 2m stand-off.*** The average results display the same trends as the individual exits, with the 2m stand-off producing the maximum degradation in unit exit flow, with smaller and larger stand-offs producing a smaller degree of exit flow degradation.

These observations can be explained through an understanding of the flow dynamics and the interactions with the BA.

4.4.6.1 **Degradation of performance with increased exit width:**

It has been noted that the density in the central regions of the BA increases with exit width (see Table 32). This increase in central densities results in greater conflicts between pedestrians as they compete to utilise the three central gaps in the BA. However, this trend is thought to only apply to the range of exits examined in this study i.e. 2.4m to 4.5m wide exits with BA arranged such that there is a gap at the symmetry line of the exit. Increasing the exit width beyond 4.5m will not result in more pedestrians vying for the central three gaps and so the overall degradation in performance is not likely to increase further, assuming that there is sufficient space to the sides to allow the crowd to diffuse. If correct, the maximum impact on exit flow may be a degradation of around 10%. This is an important conclusion as it suggests that the impact of the BA on exit flows is capped and will not continue to increase as the exit width increases. **This hypothesis should be tested by running an additional trial with an exit width greater than 4.5m using a BA similar to that in TS3.**

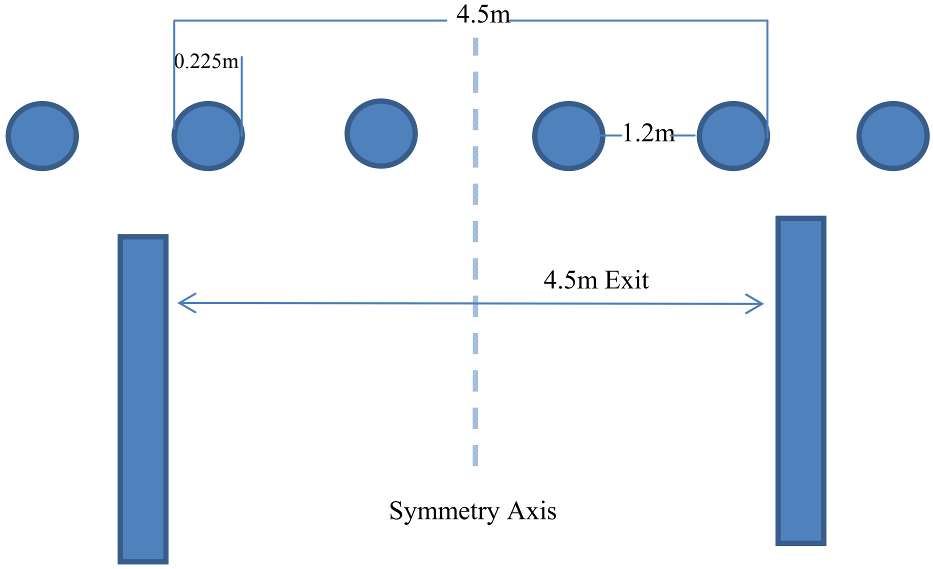
4.4.6.2 **Degradation of performance for the 4.5m exit with 1m stand-off:**

The 1m stand-off distance for the 4.5m wide exit produced uncharacteristically large degradation in performance at the exit. This can be explained by the arrangement of the BA for this exit width. For both the 2.4m and 3.5m wide exits there were only 2 bollards positioned directly in the opening of the exit (see Figure 72a and b). For the 4.5m wide exit there were 4 bollards positioned within the exit opening (see Figure 72c). Furthermore, for the 4.5m exit, the first and fourth bollards were aligned with the inside edges of the exit opening which meant that as soon as participants exited the geometry they were confronted with a bollard directly in their path and so had to take diversionary actions (see Figure 72c). In contrast, in the 2.4m and 3.5m wide exit cases, the participants could maintain a straight path immediately on exiting the geometry for the first 1m.

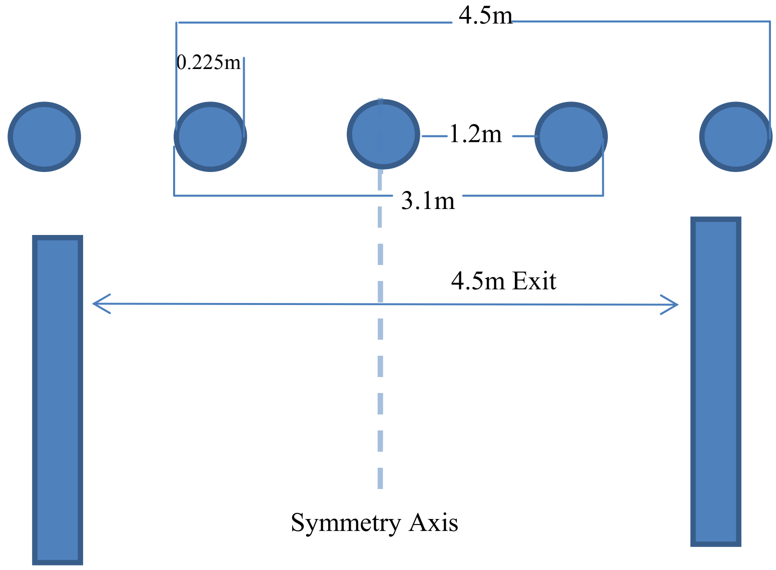
This is confirmed by the large number of last minute bollard avoidance actions observed for the outer bollards (bollards 3 and 6) in the 1m BA 4.5m wide exit (see Table 35) case. Not only was the number of avoidance actions for the outer bollards the largest observed, this configuration also achieved the maximum overall number of avoidance actions. Being forced to take these avoidance actions disrupts the flow just behind the BA line which impacts back onto the exit flow resulting in a degraded performance compared with the NoBA flow. It is also noted that it is not simply a matter of the number of bollards within the expanse of the exit width, as the 4.5m exit with 3m stand-off had the same number of bollards within the exit opening expanse but experienced fewer avoidance actions and produced a smaller degradation in exit performance.

This suggests that for BA's positioned close to an exit (within around 1m stand-off distance) if possible, the BA should be positioned such that the minimum number of bollards fall within the exit opening. Furthermore, the BA configuration should avoid positioned bollards in line with the inside edge of the exit.

Presented in Figure 75 is a poor arrangement (see Figure 75a) and the preferred arrangement (see Figure 75b) of bollards for a 4.5m wide exit with 1m stand-off. The poor arrangement (see Figure 75a) was the configuration used in the TS3 trials. The arrangement in Figure 75b is preferred as it uses the minimum number of bollards within the exit opening and bollards are not placed in line with the inside edge of the exit. ***However it must be emphasised that BA configurations such as that shown in Figure 75b, in which a bollard is placed on the symmetry axis of the exit have not been tested and so it is not clear what impact this may have on the exit flow. It is suggested that this configuration should be tested in another series of trials.***



(a) Poor arrangement of BA for 4.5m exit.



(b) Preferred arrangement of BA for 4.5m exit.

Figure 75: Poor arrangement (a) and preferred arrangement (b) of BA for a 4.5m exit with 1m stand-off.

If correct, this suggests that for a BA placed close to an exit:

- For the 2.4m exit the impact of the BA on the exit flow would be ***reduced*** if a single bollard, placed on the symmetry axis of the exit was positioned across the exit opening, rather than the two used in the trials.
- For the 4.5m exit, the impact of the BA on the exit flow would be ***reduced*** if three bollards were positioned across the exit opening, with one bollard on the exit symmetry axis rather than the four bollards used in the trials.

- For the 3.5m exit, the impact of the BA on the exit flow would be ***increased*** if three bollards were positioned across the exit opening, with one bollard on the exit symmetry axis rather than the two bollards used in the trials.

4.4.6.3 The maximum degradation of performance occurs for the 2m stand-off for all exit widths:

It has been noted that as the crowd leaves the exit they diffuse into the surrounding space, reducing the population density and enabling the individuals within the crowd to walk at their desired faster pace. The BA acts as a divergent lens increasing this diffusion (see Section 4.4.3).

However, at 2m from the exit the degree of diffusion in both the NoBA and BA cases is almost identical (see Table 31). Thus the crowd is more concentrated towards the centre with the 2m BA then it should be. This lack of additional diffusion at the 2m line also results in an increase in central density at the BA line (see Table 32). This increase in density may result in increased conflicts slowing down the movement of the crowd resulting in the enhanced degradation in the exit flow. However, the increase in central densities was not observed for the 2.4m and 3.5m wide exits.

It was also noted that the number of last minute bollard avoidance actions is a maximum for the 2m BA for the 3.5m and 4.5m exit widths (see Table 35). This high number of last minute bollard avoidance actions disrupts the flow behind the person taking the avoidance action which impacts back onto the exit flow resulting in the reduced exit flow noted in these cases compared to the NoBA cases. The correlation between the level of last minute bollard avoidance actions and the degradation in exit performance is confirmed by comparing the number of bollard avoidance actions (see Table 35) with the degradation in exit performance (see Table 36). This is presented in Table 37. As can be seen, the minimum degradation in performance equates to the minimum in avoidance actions and the maximum degradation in exit performance correlates to the maximum avoidance actions incurred. The second largest and second lowest degradations also correspond to the second largest and second lowest number of avoidance actions.

Table 37: Average peak exit unit flow achieved for the 3.5m and 4.5m exits with and without BA at 1m, 2m and 3m stand-off and the number of bollard avoidance actions*.

	1m BA			2m BA			3m BA		
	UF (p/m/min)	% diff	# avoid actions	UF (p/m/min)	% diff	# avoid actions	UF (p/m/min)	% diff	# avoid actions
3.5m exit	**115.2**	-0.1	**54.3**	**106.1**	-8.0	**74.6**	**111.8**	-3.0	58.9
4.5m exit	**105.4**	-9.0	**93.2**	**105.1**	-9.0	**85.8**	**107.5**	-6.8	**60.1**

*Note the 2.4m exit results are not included in this table due to the difference in experimental setup created by the side barriers.

It is suggested that the 2m location of the BA is such that it does not allow sufficient time for the crowd to adjust their path so that they can take earlier avoidance measures and as such have to make a last minute avoiding action. The 3m location of the BA allows sufficient time for more of the population to take earlier avoiding measures and hence the exit flow is disrupted to a smaller extent.

However, as already noted, the critical stand-off distance could be located between 1m and 3m from the exit. **To more precisely identify the critical stand-off distance requires further trials.**

It is suggested that if the crowd were aware of the presence of the BA they may be able to take avoiding actions before reaching the BA and hence reduce the disruption to the flow at the BA line. This could be achieved by for example making the BA stand out more by increasing their height so that they could be seen over the heads of the crowd. By introducing taller bollards this may reduce the number of last minute avoiding actions and hence decrease the reduction on exit flow. However, the increase in bollard height may also make it more difficult for people to manoeuvre around the bollard. This hypothesis could be tested in a series of trials similar to those in TS3.

4.4.7 EXPANSE OF BA REQUIRED TO ACCOMMODATE DIFFUSION OF CROWD

During these trials the entire population had the same objective: moving to a location positioned directly beyond the BA. Therefore, any dispersion of participants across the width of the BA was due to issues of local route availability (due to crowd density issues) and local navigation rather than longer term route selection based on varying objectives. Furthermore, the extent of BA usage will also be dependent on the width of the exit flow.

It has been observed in both the first and second trial campaign that as the crowd leaves the exit they diffuse into the surrounding space, reducing the population density and enabling the individuals within the crowd to walk at their desired faster pace (see Section 4.4.3). This effect is shown in Figure 71a, which shows the diffusion of the crowd with increasing distance from the exit for the NoBA 4.5m wide exit case.

In order to accommodate this nature expansion of the exit flow it is important that sufficient BA is available at the various stand-off distances. If a smaller expanse of BA is available then would be required for the exit width and stand-off distance, then the flow would be constrained, increasing the flow density, reducing travel speeds and eventually negatively impacting on the exit flow.

In the first trial campaign it was suggested that for a given exit width, the BA should be at least 50% wider than the exit at a 3m stand-off distance, and so:

BA Width /Exit Width > 1.5m at 3m. (1)

However, this was based only on a single exit width and a single stand-off distance. In the second trial campaign three exit widths are examined (2.4m, 3.5m and 4.5m) with a range of stand-off distances (1m, 2m and 3m). The expanse of BA required to accommodate at least 90% of the exit flow was determined from the gap analysis. Given the width of the BA required to accommodate the flow (measured in metres) a simple correlation such as that shown above was sought. Unfortunately, the relationship or something similar could not be determined.

Rather than find a correlation based on the length of the BA required, the analysis was repeated based on the number of gaps required. The number of gaps required to accommodate at least 90% of the exit flow is presented in Table 39 for all the trials conducted in the second trial campaign.

Using this data a multi-dimensional regression analysis was performed to determine the nature of the surface that would best fit the given data points. The independent variables are the Exit Width and the Stand-off distance and the dependent variable is the number of Bollard Array Gaps that are required. Given that the number of BA gaps (B_g) is determined, this can be converted to the width (in metre) of the BA (B_w) using the relationship:

$$B_w = B_g * 1.200 + (B_g + 1) * 0.225 \qquad (2)$$

Table 38: TS1 and TS3 Gap Usage.

	% Gap Use										
Distance from exit and exit width	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Central Gap(s)**	**90% Gap usage**
3m BA 4.5m	0	1.1	14.5	**22.3**	**27.7**	**20.5**	13.1	0.7	0	70.5	3-6, 85% 3-7, 98%
3m BA 3.5m	0	0.3	12.1	**23.2**	**30.2**	**22.4**	11.7	0.2	0	75.8	3-6, 88% 3-7, 99%
2m BA 4.5m	0	0.1	12.8	**24.0**	**28.8**	**22.6**	11.3	0.4	0	75.4	3-6, 88% 3-7, 99%
2m BA 3.5m	0	0	8.8	**24.5**	**34.9**	**25.0**	6.0	0	0	84.4	4-7, 90%
2m BA 2.4m	-	-	1.8	**27.2**	**41.0**	**27.6**	2.5	-	-	95.8	4-6, 96%
1m BA 4.5m	0	0	11.1	**24.9**	**29.8**	**25.1**	9.1	0	0	79.8	3-6, 91%
1m BA 3.5m	0	0	1.9	**29.4**	**37.3**	**29.7**	1.7	0	0	96.4	3-5, 96%
1m BA 2.4m	-	-	-	26.4	**47.5**	26.2	-	-	-	47.5	

Based on this analysis, the following regression surface was determined:

$$B_g = 0.6026 + 0.5994 * E_w + 0.5782 * S_d + 0.0225 * E_w * S_d \qquad (3)$$

Where:

- B_g — Minimum number of gaps in bollard array required to accommodate 90% of participants,
- E_w — Width of exit,
- S_d — Stand-off distance of bollard array.

The corresponding width (in metre) of the bollard array (B_w) can be calculated using Equation (2), where B_g is a rounded integer obtained from Equation (3). Equation (3) fits the data with a resnorm = 0.667. While this is not a very good fit, the value returned by Equation (3) is always rounded to the appropriate integer value of gaps and so the relationship always returns the correct value for the given experimental data points (see Table 39).

Depicted in Figure 76 to Figure 78 are the curve fits for given stand-off distance of 1m, 2m and 3m respectively. The curves fits provide the number of BA gaps as a function of the Exit Width for a given stand-off distance.

Table 39: Experimental results and fit function prediction of the minimum number of gaps in bollard array.

E_w (m)	S_d (m)	Exp. results		Equation (3) prediction		
		B_g	B_w (m)	B_g	B_g(rounded)	B_w (m)
4.5	1.0	4	5.9	3.98	4	5.9
3.5	1.0	3	4.5	3.36	3	4.5
2.4	1.0	3	4.5	2.67	3	4.5
4.5	2.0	5	7.4	4.66	5	7.4
3.5	2.0	4	5.9	4.01	4	5.9
2.4	2.0	3	4.5	3.31	3	4.5
4.5	3.0	5	7.4	5.34	5	7.4
3.5	3.0	5	7.4	4.67	5	7.4

The curve fit presented in Equation (3) should ideally be used only for the range of data from which it is derived. This means that it ideally should only be used for exit widths from 2.4m up to 4.5m and stand-off distances from 1m to 3m. However, presented in Table 40 are a range of predicted BA gaps and BA widths for exit widths of 2m and 6m and stand-off distances of 1m to 6m. As can be seen in Table 40 the predicted number of BA gaps appears to be consistent with the experimentally derived data even though the exit widths and the stand-off distances are outside the range of the experimental data.

Table 40: Extrapolation of fit function (E_w= 2m, 6m; S_d=1m~6m).

E_w (m)	S_d (m)	Equation (3) prediction		
		B_g	B_g(rounded)	B_w (m)
6.0	1.0	4.91	5	7.4
6.0	2.0	5.63	6	8.8
6.0	3.0	6.34	6	8.8
6.0	4.0	7.05	7	10.2
6.0	5.0	7.77	8	11.6
6.0	6.0	8.48	8	11.6
2.0	1.0	2.42	2	3.1
2.0	2.0	3.05	3	4.5
2.0	3.0	3.67	4	5.9
2.0	4.0	4.29	4	5.9
2.0	5.0	4.92	5	7.4
2.0	6.0	5.54	6	8.8

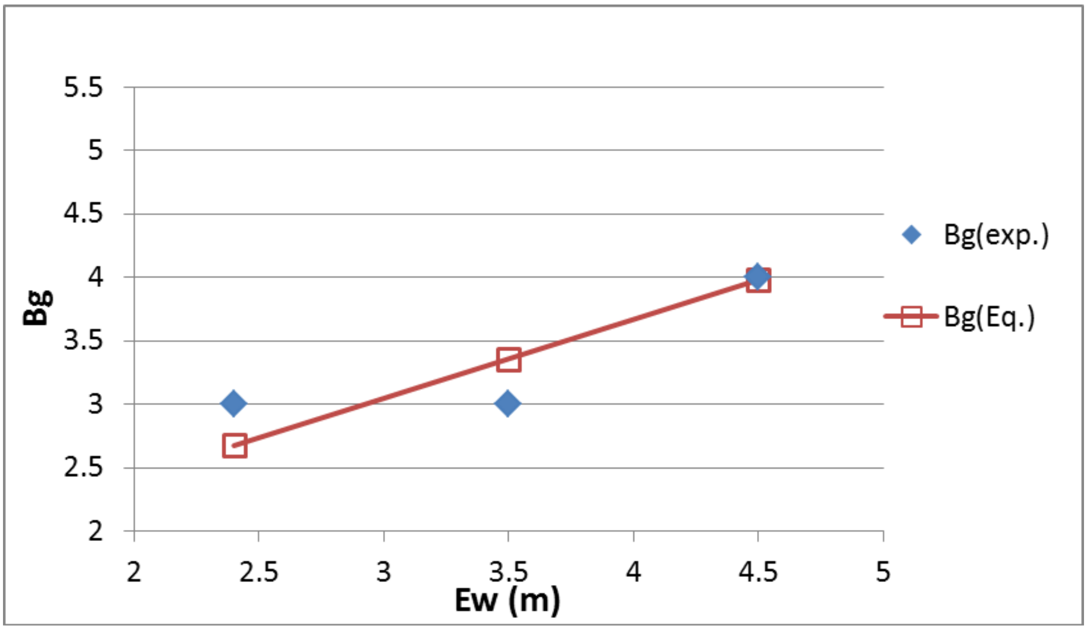


Figure 76: Experimental results and fit function prediction of the minimum number of gaps in bollard array (Sd=1m).

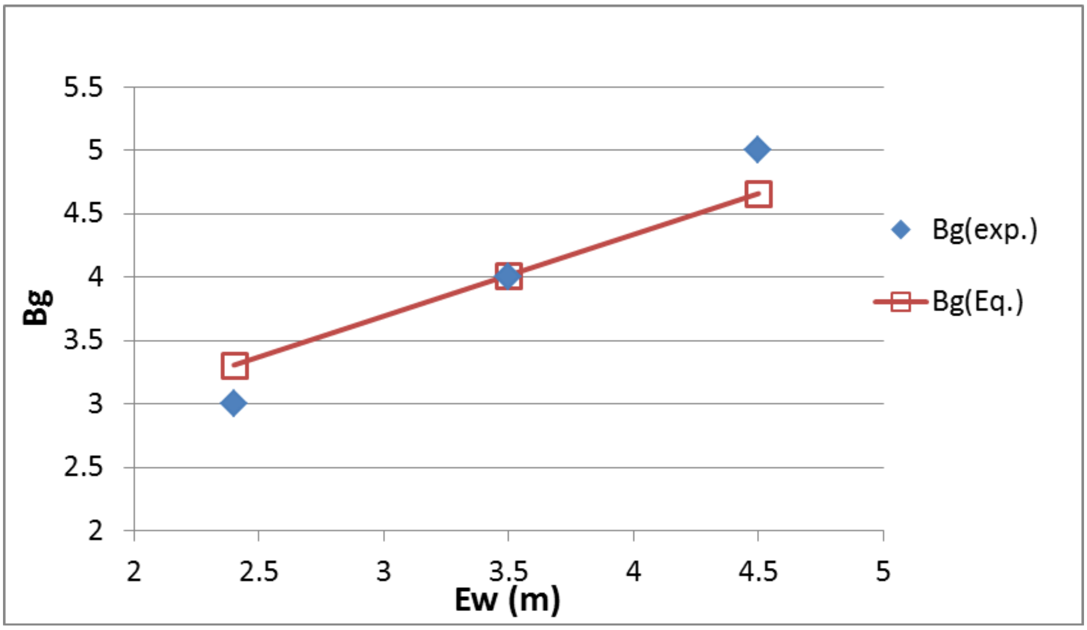


Figure 77: Experimental results and fit function prediction of the minimum number of gaps in bollard array (Sd=2m).

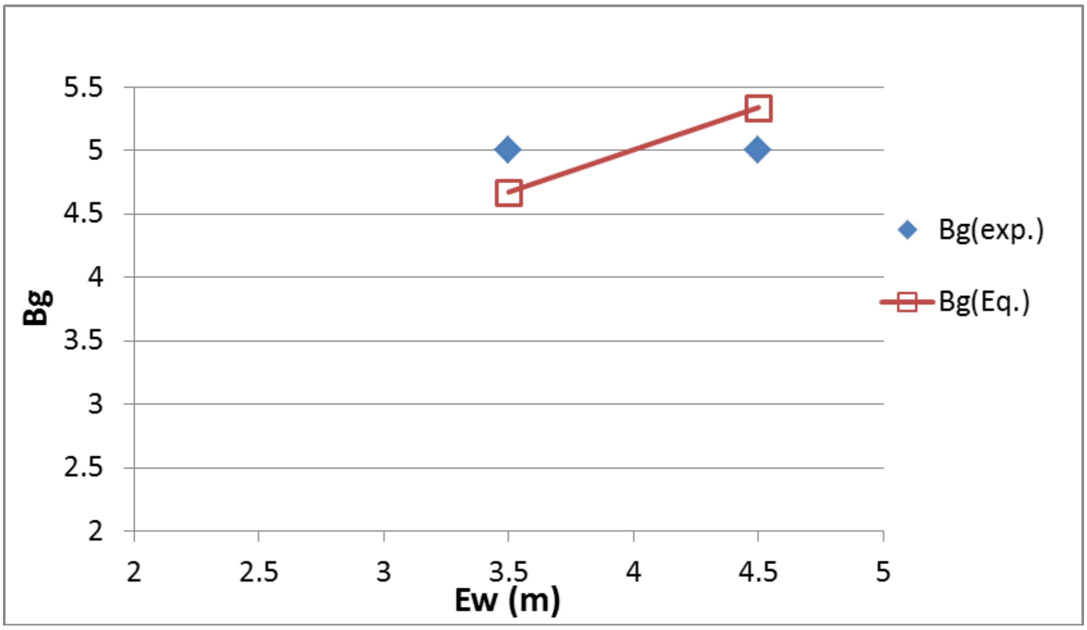


Figure 78: Experimental results and fit function prediction of the minimum number of gaps in bollard array (Sd=3m).

Key findings:

- A correlation exists to determine the minimum expanse of BA required minimising the impact of the BA on the exit flow. The correlation, which links exit width and stand-off distance to required BA expanse is:

$$B_g = 0.6026 + 0.5994 * E_w + 0.5782 * S_d + 0.0225 * E_w * S_d \qquad (3)$$

Where:

  - B_g — Minimum number of gaps (rounded to the nearest integer value) in bollard array required to accommodate 90% of participants;
  - E_w — Width of exit,
  - S_d — Stand-off distance of bollard array.

  - This relationship can be used to determine the minimum expanse of BA required for a given exit width and stand-off distance in order that the exit flow is not constrained; i.e. the BA does not constrain the natural expansion of the exit flow as it leaves the exit and comes into contact with the BA.
  - The correlation is based on experimental data concerning BA gap usage for the three exit widths (2.4m, 3.5m and 4.5m) and the three stand-off distances (1m, 2m and 3m) examined, for BA configurations where a bollard is NOT placed on the symmetry axis of the exit.

5 CONCLUSIONS

The aim of this project was to design, conduct and analyse a series of pedestrian flow trials to explore the impact of Hostile Vehicle Mitigation Measures (i.e. a Bollard Array, BA) upon pedestrian flows of simulated evacuation conditions. This report reflects the performance of these trials and the subsequent analysis of the data produced.

The trials were designed to explore two specific issues namely, the relationship between exit width, stand-off distance (from 1m to 3m) and exit flow and the impact of a bollard at 0m stand-off on exit flows with participants carrying luggage. These trials were all conducted with initial population densities of 4 p/m^2 as results from the first trial campaign (2013) confirmed that the impact of the BA was greater for higher density flows.

In total 45 individual trials involving 441 participants were conducted over the weekend of the 29th and 30th March 2014. The trials were conducted, as with the first trial campaign, on University of Greenwich grounds, in the Queen Anne Courtyard. Three sets of trials were conducted:

- TS1 was intended to further investigate the relationship between the BA stand-off distance and exit flow. With the 2.4m wide exit three stand-off distances were investigated, 1m, 1.5m and 2m.
- TS2 was intended to examine the impact of encumbrance upon the egress flow produced given the presence of the BA at 0m. These trials used the 2.4m wide exit. Three levels of encumbrance were investigated, one in which 0% of the population was encumbered and ones in which 40% and 60% of the population were encumbered.
- TS3 was intended to examine the relationship between exit width, BA stand-off distance and the flow generated by varying the stand-off and exit widths. Two exit widths were considered, 3.5m and 4.5m and three stand-off distances were investigated, 1m, 2m and 3m.

The findings from the trials reflect the complexity of the impact of the BA upon performance. The key findings are listed below.

General Findings:

- ***Exit flows and travel speeds may be strongly affected by modest changes in ambient environmental conditions (see Section 4.2).*** The 2014 trials produced average peak exit flows which were 13% faster and BA flows which were 9% faster than measured flows in the 2013 trials. The main difference between the trials was the weather conditions, with the 2013 conditions being colder (maximum day temperature 9^{o}C with light snow on occasion) than that in 2014 (maximum day temperature 19^{o}C with sunny conditions). This result suggests that individual travel speeds and exit flows may be affected by modest changes in the environmental conditions.
    - *The possibility of reduced exit flows and individual travel speeds resulting from colder conditions should be taken into consideration when designing evacuation systems. When using multi-agent evacuation modelling tools, it*

may be necessary to reduce individual travel speeds when simulating evacuation scenarios in cold environments.

- ***High crowd density (4 p/m^2) exit flows are strongly affected by the presence of a moderate to high number of pedestrians encumbered with luggage (see Section 4.3.1).*** For the 2.4m wide exit, the introduction of a moderate (40% of the crowd) level of encumbrance reduces the exit flow by 10%, while the introduction of a high (60% of the crowd) level of encumbrance reduces the exit flow by 16%. Both values of degraded exit flow are greater than any reduction in exit flow produced by a BA with stand-off distance from 0m to 6m.
    - *The possibility of reduced exit flows and individual travel speeds resulting from pedestrians carrying baggage should be taken into consideration when designing evacuation systems, especially for rail and airport applications. When using multi-agent evacuation modelling tools, it may be necessary to reduce individual travel speeds when simulating evacuation scenarios in which it is likely that occupants are carrying luggage, even if it is not possible to directly represent the luggage within the evacuation simulation environment.*

- ***As a high crowd density (4 p/m^2) flow exits from an opening, it diffuses outwards into the surrounding space and the degree of diffusion increases with distance from the exit (see Section 4.4.3).*** As a result the density of the central regions of the flow decreases with increasing distance from the exit. The diffusion of the flow is thought to be due to individuals in the high density flow moving to the outer lower density regions of the flow enabling individuals within the crowd to walk at their desired stride length and hence travel speed.
    - *It is essential to ensure that sufficient space is available outside the exit to allow the crowd to diffuse into. If this space is constrained it is likely to impact back on the exit flow reducing the flow.*

- ***The degree of diffusion is greater when a BA is present, the BA acting as a divergent lens (see Section 4.4.3).*** As a result, the density in the central regions with BA is less than that for the case without BA.
    - *When a BA is placed outside an exit, sufficient space must be provided beyond the exit to cater for the enhanced diffusion caused by the BA.*

- ***The unit exit flow for the 2.4m wide exit and the 4.5m wide exit without BA were identical (see Section 4.4.1).*** This confirms that unit flows for similar types of exits are the same regardless of exit width. The unit flow derived from these trials for a free exit was 1.93 p/m/s. This is some 45% greater than the unit flow recommended in the UK Building Codes (1.33 p/m/s).
    - *The concept of the constancy of exit unit flow is confirmed for exits from 2.4m to 4.5m in width. Furthermore, the unit flow measured in these trials is some 45% greater than that recommended in the UK Building Code indicating the conservatory nature of the code.*

Stand-Off Distance:

- ***Generally as the exit width increases from 2.4m to 4.5m, the greater the impact of the BA on the unit exit flow for 1m, 2m and 3m stand-off distances (see Section 4.4.6).*** However, this trend is thought to only apply to the range of exits widths examined in this study i.e. 2.4m to 4.5m with BA arranged such that there is a gap in the BA at the symmetry line of the exit.
    - For exit widths of 2.4m to 4.5m each row of exiting people are competing to access the central three gaps in the BA. As the exit width is increased from 2.4m, there are more people competing for the three central BA gaps and hence the density in the central regions of the BA increases. This increase in central densities results in greater conflicts between pedestrians as they compete to utilise the three central gaps in the BA.
    - However, increasing the exit width beyond 4.5m will not result in more pedestrians vying for the central three gaps and so the overall degradation in performance is not likely to increase further, assuming that there is sufficient space to the sides to allow the crowd to diffuse. If correct, the maximum impact on exit flow may be a degradation of around 10%.
    - *The impact of the BA on exit flows increases with exit width from 2.4m to 4.5m. The maximum degradation in exit flow of a BA placed from 1m to 6m from the exit is thought to be a 10% reduction in exit flow which occurs for the widest exits. For narrow exits the degradation in exit flow is considerably less than 10%. The degradation in performance is not expected to continue to increase for exits wider than 4.5m however this has not been tested.*

- ***The maximum impact on peak exit unit flow occurs with a stand-off distance of 2m across all the exit widths examined, with the maximum degradation in exit performance being 9% for the largest exit width (4.5m) (see Section 4.4.6).*** Generally, the closer or further away the BA is located to the exit, the smaller the impact on the exit unit flow. The number of last minute bollard avoidance actions undertaken by pedestrians is a maximum for the 2m BA for the 3.5m and 4.5m exit widths. This high number of last minute bollard avoidance actions disrupts the flow behind the person taking the avoidance action. This impacts back onto the exit flow resulting in the reduced exit flow noted in these cases compared to the case without BA.
    - It is suggested that the 2m location of the BA is such that it does not allow sufficient time for the pedestrians in the flow to adjust their path so that they can take earlier avoidance measures and as such have to make a last minute avoiding action. The 3m location of the BA allows sufficient time for more of the population to take earlier avoiding measures and hence the exit flow is disrupted to a smaller extent.
    - While it is not clear what the precise critical stand-off distance is, it appears to be between 1m and 3m from the exit.
    - *The maximum degradation in exit flow occurs for a BA placed between 1m and 3m from the exit, with the maximum degradation observed in the trials occurring for a stand-off distance of 2m. Where possible positioning a BA in this region should be avoided and if it cannot be avoided, a degradation of 10% in exit flow should be expected.*
    - *It is suggested that if the crowd were aware of the location of the BA they may be able to take avoiding actions before reaching the BA and hence reduce the*

disruption to the flow at the BA line. The introduction of taller bollards, such that they could be located over the heads of the crowd, may reduce the number of last minute avoiding actions and hence decrease the reduction on exit flow However, taller bollards may also make it more difficult for people to manoeuvre around the bollard. This hypothesis could be tested in a series of trials.

- ***The 4.5m exit with a BA stand-off distance of 1m experiences a degradation in unit exit flow equal to the maximum degradation (observed at 2m stand-off) (see Section 4.4.6).*** This observation is unique to the 4.5m exit width and does not occur for the 2.4m or 3.5m exit widths.
    - For both the 2.4m and 3.5m wide exits there were only 2 bollards positioned directly within the expanse of the exit opening. For the 4.5m wide exit there were 4 bollards positioned within the expanse of the exit opening.
        - The more bollards within the exit opening the more avoidance actions the population must make increasing the disruption to the flow just behind the BA line which impacts back onto the exit flow resulting in a degraded performance compared with the case without BA.
    - It is also noted that it is not simply a matter of the number of bollards within the expanse of the exit width, as the 4.5m exit with 3m stand-off had the same number of bollards within the exit opening expanse but experienced fewer avoidance actions and produced a smaller degradation in exit performance. This is because the population had sufficient time to maneuverer to avoid the bollards without taking last minute avoidance action.
    - *This suggests that for BA's positioned close to an exit (within around 1m stand-off distance) if possible, the BA should be positioned such that the minimum number of bollards fall within the exit opening. Furthermore, the BA configuration should avoid positioned bollards in line with the inside edge of the exit. Given the standard diameter and separation of bollards and the width of the exit, this will mean that a bollard must either be placed on the centre line of the exit or a BA gap must occur across the centre line. To ensure this configuration it is advisable to configure the bollards first in the mouth of the exit and then work outwards to either side.*
    - If correct, this suggests that for the BA's with 1m stand-off explored in these trials:
        - For the 2.4m exit the impact of the BA on the exit flow would be ***reduced*** if a single bollard, placed on the symmetry axis of the exit was positioned across the exit opening, rather than the two used in the trials.
        - For the 4.5m exit, the impact of the BA on the exit flow would be ***reduced*** if three bollards were positioned across the exit opening, with one bollard on the exit symmetry axis rather than the four bollards used in the trials.
        - For the 3.5m exit, the impact of the BA on the exit flow would be ***increased*** if three bollards were positioned across the exit opening, with one bollard on the exit symmetry axis rather than the two bollards used in the trials.

As there is no experimental evidence to support these suggestions, it is advisable to test these configurations to ensure that the proposed hypothesis is correct.

- ***A correlation between the minimum expanse of BA required to minimise the impact of the BA on the exit flow and the exit width and stand-off distance can be determined from the experimental data derived from the trials (see Section 4.4.7)*** The correlation, which links exit width and stand-off distance to required BA expanse is:

$$B_g = 0.6026 + 0.5994 * E_w + 0.5782 * S_d + 0.0225 * E_w * S_d$$

Where:

- B_g — Minimum number of gaps in bollard array required to accommodate 90% of participants,
- E_w — Width of exit,
- S_d — Stand-off distance of bollard array.

  - The correlation is based on experimental data concerning BA gap usage for the three exit widths (2.4m, 3.5m and 4.5m) and the three stand-off distances (1m, 2m and 3m) examined, for BA configurations where a bollard is NOT placed on the symmetry axis of the exit.
  - *This relationship can be used to determine the minimum expanse of BA required for a given exit width and stand-off distance in order that the exit flow is not constrained; i.e. the BA does not constrain the natural expansion of the exit flow as it leaves the exit and comes into contact with the BA.*

Encumbered Flows with Bollards:

- The following results apply to the 2.4m exit with a single bollard at 0m stand-off placed on the symmetry axis of the exit (see Section 4.3).
  - ***At moderate levels of encumbrance (40%) introducing the bollard has negligible impact on exit flow.***
  - ***At high levels of encumbrance (60%), introducing the bollard has little impact on the exit flow, the maximum degradation in exit flow being 3%.*** However, this is four times the impact of introducing the bollard at low levels of encumbrance (40%).
  - **Compared to the exit flow without a bollard and 0% encumbrance the introduction of a bollard and 60% encumbrance *reduce* the flow at the exit by 18%.** Thus introducing high levels of encumbrance (60%) AND a bollard in the exit will reduce the exit flow by almost one fifth.
  - *At moderate levels of encumbrance (40%), the presence of a bollard in the exit flow has little effect and at high levels of encumbrance (60%) the presence of a bollard in the exit degrades the exit flow by only 3% and so is not a major hindrance. However, the combined effect of high levels of encumbrance (60%) and the presence of a bollard in the exit flow has a major impact on exit flow degrading the flow by almost 20% compared to the unencumbered no bollard flow. Thus in airports and rail stations where it may be expected that a large number of pedestrians will be encumbered by luggage the flow*

through exits which also have a bollard placed in the middle of the exit may experience flows reduced by as much as 20%. This level of degraded exit performance may have major implications to emergence evacuation flows and so must be addressed in the design assumptions for the facility.

These concluding remarks reflect the complexity of the impact of the BA upon exit flow. It is clear that the presence of a BA of sufficient width located from 1m to 3m from an exit with width between 2.4m and 4.5m will degrade the exit flow by up to 10%. The degradation in exit performance increases with exit width but is expected not to continue to increase for exits with width greater than 4.5m. Furthermore, the degradation in exit performance is a non-linear function of the BA stand-off distance, with the maximum degradation in performance occurring for a stand-off between 1m and 3m from the exit, with 2m being the critical stand-off distance observed in these trials. In addition, pedestrians with a high level of encumbrance can have significant effect on exit flow, degrading exit performance by 16% compared to the non-encumbered performance. This level of degradation in exit performance is greater than that of a bollard array alone. Furthermore, the combined effect of high levels of encumbrance and a single bollard placed in the centre of a 2.4m wide exit can reduce exit flow by almost 20%, a significant reduction compared to the non-encumbered bollard free performance. These levels of degraded exit performance should be taken into consideration when designing airport and rail station facilities,

This work suggests that it is possible to minimise the impact that a BA may have on high density evacuation flows through careful positioning of the BA:

- Ensuring that there is sufficient expanse of BA so as not to impede the diffusion of the crowd.
- Ensuring that the BA is not placed within 1m to 3m from an exit.
- If placed at around 1m from the exit ensuring that the array has the minimum possible number of bollards placed across the exit opening.
- Ensuring, through crowd management and information systems that large numbers of people are not encumbered with luggage.

6 FUTURE WORK

Over the two trail campaigns considerable experimental data has been collected concerning human performance and interaction with different exit and BA configurations. Furthermore, the experimental data is considered to be robust as the trials were repeated three times, which is not commonly undertaken in evacuation research. It is suggested that using this data a validation data-set be established for evacuation models together with a set of guidelines for the systematic and transparent use of the validation data-set. This would be similar to the work undertaken by FSEG in establishing a validation data-set and validation protocol for ship based evacuation models [6-8].

Following analysis of the bollard trials several other related trials are suggested for consideration. These trials are listed in an order of priority. The first four are considered the most important in framing our understanding of how evacuation flows interact with the BA. The number of trials suggested in each case is indicative: fewer trials could be conducted in most cases by simply reducing the number of options. Furthermore, it may be possible to reduce the number of trials if more than one option were adopted as several of the suggested trials are repeated in the various options.

1) Identification of the critical BA stand-off distance between 1m and 3m.

The exit flow trials conducted as part of this study placed the BA at stand-off distances of 1m to 3m. The results suggest that there is a non-linear relationship between the degradation in exit performance with stand-off distance, with 2m producing the greatest degradation in performance. However as only these three distances were investigated it is not clear at what stand-off distance the greatest degradation in performance is expected to occur.

To identify the critical distance an additional series of trials is required based on the TS3 configuration. Assuming that the results from the new trial campaign can be compared with those from the second trial campaign it is suggested that three exit widths be considered (2.4m, 3.5m and 4.5m) with three stand-off distances (1.5m, 2.0m and 2.5m). One stand-off distance will be the same as in the second trial campaign to check that the results from the second trial campaign are comparable to those from the third trial campaign. The trials should be conducted at the maximum initial crowd density of 4p/m^2.

This would require:

1 (density) x 3 (stand-off distances) x 3 (exit widths) x 3 (repeats) = 27 trials.

In addition, it would be necessary to conduct the NoBA trials

1 (density) x 1 (NoBA) x 3 (exit widths) x 3 (repeats) = 9 trials.

In total this would require 36 trials.

This would enable the critical stand-off distance to be identified. These trials would also provide additional data points for the BA expanse correlation (see equation 3).

2) Exit Flow Trials with exit width greater than 4.5m.

The degradation in exit performance was observed to increase with exit width. This is a concerning trend as it suggests the wider the exit the more significant the impact of the BA on exit flow. It was however suggested that as the exit width exceeds 4.5m so as to encompass additional BA gaps in line with the exit opening that the trend would no longer be valid. This can be tested using wider exits.

To identify the whether the degradation in exit performance continues to increase with exit width beyond exit widths of 4.5m an additional series of trials is required based on the TS3 configuration. Assuming that the results from the new trial campaign can be compared with those from the second trial campaign it is suggested that three exit widths be considered (4.5m, 5.5m and 6.5m) with three stand-off distances (1m, 2m and 3m). One exit width will be the same as in the second trial campaign to check that the results from the second trial campaign are comparable to those from the third trial campaign. The trials should be conducted at the maximum initial crowd density of $4p/m^2$. Assuming that the correlation presented in equation 3 is valid, the 6.5m wide exit would require a minimum expanse of BA comprising 7 gaps or 10.2m in width. This can be accommodated within the courtyard. However, these trials would require the recruitment of more volunteers than used in TS3.

This would require:

1 (density) x 3 (stand-off distances) x 3 (exit widths) x 3 (repeats) = 27 trials.

In addition, it would be necessary to conduct the NoBA trials

1 (density) x 1 (NoBA) x 3 (exit widths) x 3 (repeats) = 9 trials.

In total this would require 36 trials.

This would test the hypothesis that the degradation in exit performance will be abated and not continue to increase with exit width. These trials would also provide additional data points for the BA expanse correlation (see equation 3).

3) Exit Flow Trials with BA centred on the exit symmetry axis.

It was suggested that the configuration of the BA would influence the impact of the BA. In particular it was suggested that for BA's positioned close to an exit (within around 1m stand-off distance) if possible, the BA should be positioned such that the minimum number of bollards fall within the exit opening. Furthermore, the BA configuration should avoid positioned bollards in line with the inside edge of the exit.

To test this hypothesis an additional series of trials is required based on the TS3 configuration. Assuming that the results from the new trial campaign can be compared with those from the second trial campaign it is suggested that two exit widths be considered (3.5m and 4.5m) with three stand-off distances (1m, 2m and 3m). The BA will be positioned as suggested in the conclusions in order to determine whether or not the exit flow is further degraded or improved as predicted. The 2.4m wide exit will not be examined as the results from the second trial are not consistent with the TS3 layout. In addition, one exit width will be selected to repeat the results from the second trial campaign to check that the results from the second trial campaign are comparable to those from the third trial campaign. The trials should be conducted at the maximum initial crowd density of $4p/m^2$.

This would require:

1 (density) x 3 (stand-off distances) x 2 (exit widths) x 3 (repeats) = 18 trials.

In addition, it would be necessary to repeat one of the TS3 trials

1 (density) x 3 (stand-off distances) x 1 (exit width) x 3 (repeats) = 9 trials.

In addition, it would be necessary to conduct the NoBA trials

1 (density) x 1 (NoBA) x 3 (exit widths) x 3 (repeats) = 9 trials.

In total this would require 36 trials.

This would test the hypothesis that minimising the number of bollards within the exit opening will reduce the impact of the BA on the exit flow. These trials would also provide additional data points for the BA expanse correlation (see equation 3).

4) BA height

The height of the BA may influence the manner in which people approach the BA and the flow through the BA. Higher BAs, may be easier for people in high density crowds to see and so may influence the way in which they approach the BA. This may reduce the negative impact of the BA that was noted with stand-offs of 1m and 2m. However, higher BAs may influence the flow through the BA as pedestrians may not pass through the BA as easily as the low BA which does not obstruct the upper torso. Lower BAs will be more difficult to see and may become trip hazards. The higher BA is probably more likely to be of interest as it could represent situations in which the BA was a portal with an arch.

To determine the impact of the higher BA would require exit flow trials similar to that conducted for TS3. It is suggested that the 4.5m exit be used with three stand-off distances (1m, 2m and 3m). The required trials would consist of densities at $4p/m^2$ to be consistent with the earlier trials. In addition, one exit width would be selected to repeat the results from the second trial campaign to check that the results from the second trial campaign are comparable to those from the third trial campaign. This would require the following exit flow trials:

1 (density) x 1 (exit width) x 3 (stand-off distances with high bollards) x 3 (repeats) = 9 trials.

In addition, it would be necessary to repeat the corresponding TS3 trial with standard height BA:

1 (density) x 3 (stand-off distances) x 1 (exit width) x 3 (repeats) = 9 trials.

In addition, it would be necessary to conduct the NoBA trials

1 (density) x 1 (NoBA) x 1 (exit width) x 3 (repeats) = 3 trials.

In total this would require 21 trials.

This would test the hypothesis that making the bollards more noticeable would allow pedestrians to take avoiding actions earlier decreasing the number of last minute actions and hence reducing the negative impact on the exit flow.

5) Contra-flow trial

While not a situation that is expected to occur during evacuation situations, contra-flows do frequently occur in non-emergency pedestrian flow situations. For example people exiting a busy station at peak times through a BA while others are attempting to enter the station. It is therefore important to understand the impact of a BA on these frequent non-emergency flows, as this impact is likely to influence the daily operation of the station.

It is suggested that a setup similar to TS3 could be setup in the Queen Anne Courtyard, with two opposing populations, one moving from left to right (labelled Pop1), while the other population would move from right to left (labelled Pop2). Both populations would be placed an equal distance from the BA. Two different population densities could be considered for Pop1 and two for Pop2. These trials would require more participants than required for TS1 due to the two interacting populations. This would require the following number of trials:

3 (Pop densities (large-large; small-small; large-small)) x 2 (with and without BA) x 3 (repeats) = 18 trials.

In total this would require 18 trials.

This would examine the impact of a BA on contra-flows.

6) Exit Flow trials in low lighting.

All of the Exit flow trials were conducted in normal day-light lighting conditions. Low level visibility due to low levels of illumination may have an impact on how the pedestrians interact with the BA. This could be relevant to evacuation scenarios at night. In addition to walking at a slower speed due to reduced levels of illumination, the pedestrian interaction with the BA may also be affected due to low levels of illumination, decreasing the BA flow. This could be due to for example a greater number of participants being forced to take last minute avoiding actions.

To determine the impact of reduced illumination on the exit flow it is suggested that an additional series of trials are conducted with reduced levels of illumination. This could be achieved in day-light conditions by providing the participants with dark glasses or the trials could be conducted in the evening. The entire series of trials would not be repeated, but a selection of cases would be examined in low level illumination. This would require:

1 (density) x 1 (exit width) x 3 (1m, 2m, 3m stand-off) x 3 (repeats) = 9 trials.

In addition, it would be necessary to conduct the NoBA trials

1 (density) x 1 (NoBA) x 1 (exit width) x 3 (repeats) = 3 trials

In addition, it would be necessary to repeat the corresponding TS3 trial with standard height BA:

1 (density) x 3 (stand-off distances) x 1 (exit width) x 3 (repeats) = 9 trials.

In total this would require 21 trials.

This would examine the impact of low lighting on exit flow.

7) Exit Flow trials with alternate Target Point.

In the exit flow trials participants had an exit target point which was directly in front of the exit and the BA. This meant that the flow intercepted the BA perpendicular to the face of the BA. It is possible that an evacuating population may have a target point located off to one side; i.e. not directly opposite the exit. This may have an impact on the exit flow.

To determine the impact of location of end target points on the exit flow it is suggested that an additional series of trials are conducted with and without the BA with an end target point which is off to the side of the courtyard. These trials would be conducted at $4p/m^2$ to be consistent with the earlier trials. Two exit widths could be used. This would require:

1 (density) x 2 (exit widths) x 4 (1m, 2m and 3m stand-off and no BA) x 3 (repeats) = 24 trials.

In total this would require 24 trials.

This would examine the impact of a target point off to the side.

8) Exit Flow trials with multiple Target Points.

In the exit flow trials participants had a single exit target point which was directly in front of the exit and the BA. This meant that the flow intercepted the BA perpendicular to the face of the BA. It is possible that an evacuating population may have several target points e.g. located off to either side and directly opposite the exit. The pedestrian flows would then interact and interfere with each other, making the flow in the region between the exit and the BA more chaotic and possibly amplifying the impact of the BA. This may have an impact on the exit flow.

To determine the impact of location of multiple end target points on the exit flow it is suggested that an additional series of trials are conducted with and without the BA with three end target points, one to the left, one to the right and one directly opposite the exit. The participants would be randomly allocated to one of the end-points just prior to the trial. These trials would be conducted at $4p/m^2$ to be consistent with the earlier trials. Two exit widths would be examined. This would require:

1 (density) x 2 (Exit widths) x 4 (1m, 2m and 3m stand-off and no BA) x 3 (repeats) = 24 trials.

In total this would require 24 trials.

This would examine the impact of multiple target points a more realistic situation to that imposed in the first and second trial campaigns.

9) Exit Flow Trials involving people running.

It was suggested that the exit flow trials may have produced different trends if people in the evacuation were running. At the crowd densities that were examined it would not be possible for people to run as the densities were too large. Also, it is unlikely that in most evacuation situations pedestrians would actually run from the scene, unless it was at the very late stages of the fire where people were in contact with smoke, heat and flames. Also, it is unlikely that if the population could run (at lower densities) that the 3m and 6m stand-offs would have much of an impact on the exiting flows. However, BAs which were closer to the exit may have an impact. It is thought that with running participants, more participants would be forced to make last minute avoidance actions increasing the negative impact on the exit flow. Furthermore, the BA's further away from the exit may also incur a greater number of avoiding actions thereby increasing the negative impact on the exit flow.

To determine the impact of running pedestrians it is suggested that an additional series of exit flow trials are conducted with and without the BA at stand-offs of 1m, 2m and 3m. These trials would be conducted with a starting density of $4p/m^2$ to be consistent with the earlier trials and an exit width of 4.5m could be used. This would require:

1 (density) x 1 (exit width) x 4 (stand-off conditions 1m, 2m and 3m and NoBA) x 3 (repeats) = 12 trials.

In addition, it would be necessary to repeat the corresponding TS3 trial with walking participants:

1 (density) x 1 (exit width) x 4 (stand-off conditions 1m, 2m and 3m and NoBA) x 1 (exit width) x 3 (repeats) = 12 trials.

In total this would require 24 trials.

This would examine the impact of running on exit flow. It would examine if there is an increase in the number of last minute avoiding actions which would increase the negative effect on exit flow.

7 REFERENCES

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8 ANNEX A: FSEG DESCRIPTION

FIRE SAFETY ENGINEERING GROUP

The Fire Safety Engineering Group (FSEG) of the University of Greenwich was founded by Prof Galea in 1986. FSEG is one of Europe's leading centres of excellence concerned with Computational Fire Engineering (the mathematical modelling of fire and related phenomena). It is also one of the largest university based groups dedicated to the modelling of fire in the world. Application areas include, the built environment, aerospace, marine and rail. The work of FSEG includes research/consultancy, software development, international standards development and training. Since 2006, FSEG has generated over £6 million worth of research and consultancy funding and its research and consultancy activities have been supported by organisations such as:

Europe:
Agip, EADS, BAe Systems, BA, Buro Happold, BMT, Canary Wharf Management Ltd., Daimler-Chrysler, EPSRC, EU, European Space Agency, Evaclite, ASH, Building Research Establishment, Home Office, Cabinet Office, Office of the Deputy Prime Minister, LPC, MCA, NHS, Arup Transportation, RINA, Fujitsu, Borealis, Rockwool Int, Thales, The Engineering Link, UK MOD, Lloyds Register, RISKTEC and the UK CAA.
Australia:
Lincolne Scott International, Melbourne Fire Brigade, Australian Defence Dept and;
North America:
FAA, Boeing, NTSB, Bombardier Aerospace, Fleet Technology, Canadian Dept of Transportation, BMT, Canadian Transportation Safety Board, Arup Transportation, Federal Rail Administration, Volpe, Battelle Inc, Hughes.

A selection of consultancy projects undertaken by FSEG include:
- evacuation analysis for Agip concerning an onshore oil processing facility,
- evacuation analysis for off-shore oil facilities,
- evacuation analysis of large passenger and naval ships,
- evacuation analysis for Bombardier Aerospace concerning evacuation certification issues related to the CSeries aircraft concept,
- evacuation analysis for Mitsubishi concerning evacuation certification issues related to new aircraft concepts,
- evacuation analysis for Airbus concerning design and certification of new aircraft including the A380 and A340-600,
- evacuation analysis for Lloyds Register and Disney Cruise Line,
- evacuation analysis for DeHavilland of Canada concerning certification of new aircraft,
- evacuation analysis of high rise buildings,
- crowd safety and control analysis for Ascot Race Course,
- advice to the ESSEX fire Brigade on evacuation performance from large structures,
- analysis of ventilation and smoke movement characteristics for an underground station in London,
- a fire safety analysis of the International Space Station for the European Space Agency,
- CFD based pollution spread analysis for the HSE,

- project specific advice to the Melbourne Fire Brigade,
- expert witness advice for legal hearings and public inquires e.g. Ladbroke Grove Rail Disaster,
- assessment of emergency signage on UK rail rolling stock.

The group has published over 300 academic and professional publications concerning fire and related topics.

Software Development:
Research undertaken by FSEG has led to the development of the Computational Fire Engineering software buildingEXODUS, airEXODUS, maritimeEXODUS and SMARTFIRE. These products are distributed world-wide by FSEG. In 2003 FSEG achievements in developing the EXODUS suite of software was acknowledged through the award of the IST prize. The EU Commission-sponsored European IST (Information Society Technologies) Prize is awarded by the European Council of Applied Sciences, Technology and Engineering (Euro-CASE) to entrepreneurial teams that excel in generating novel ideas and converting them into marketable products. In 2002 the effort of FSEG in evacuation research was acknowledged through the award of the Queen's Anniversary Prize. In 2001, the EXODUS suite of software was awarded the coveted British Computer Society (BCS) IT Award (the Oscars of the IT industry). The EXODUS software also won a gold medal for achievement from the BCS. In 2002, maritimeEXODUS won the CITIS (Communications & IT in Shipping) Award for Innovation in IT for Ship Operation. Also in 2001, maritimeEXODUS won the RINA/LR (Royal Institution of Naval Architecture/Lloyds Register) Award for ship safety.

maritimeEXODUS is currently in use in the UK, Netherlands, China, Japan, Australia, Denmark, France, Korea and Canada. It has been used for the analysis of large passenger ships, naval vessels (Royal Navy) and large pleasure craft such as Thames River boats and off-shore facilities. maritimeEXODUS has been endorsed by the UK MOD as, "the escape tool that most closely meets the needs of the MOD for the development of warship escape design guidance and assessment". The buildingEXODUS building evacuation model is used by Fire Brigades, Regulatory authorities, Fire Engineers, Design Engineers, Urban Planners, Consultants and Universities and engineers with experience in the application of buildingEXODUS can be found in over 40 countries. The airEXODUS evacuation model has become the recognised world leading evacuation model in the aviation industry and has been used in projects for Boeing, Airbus, British Aerospace and Bombardier. Similarly, the SMARTFIRE fire field model is currently used in 11 countries, namely Australia, Denmark, Indonesia, Finland, Germany, Hong Kong, Taiwan, Korea, New Zealand, Switzerland and the UK.

International Standards:
FSEG expertise is sought by standards bodies such as the BSI, IMO and ISO. Prof Galea serves on several British Standards Institute committees concerned with fire safety including FSH/24/5, which deals with issues concerned with life safety and evacuation and FSH/24/2 which deals with calculation methods for fire safety engineering. Through these activities, FSEG has contributed to the DD240 document and its planned revisions. In 1997, Prof Galea was the UK nominated expert on Life Safety for the international standards organisation committee concerned with fire safety, ISO TC92. In 1999, Prof Galea was invited to become a member of the Human Behaviour Task Group of the Society of Fire Protection Engineers

(USA). Prof Galea also serves as a UK expert on evacuation and fire on the International Maritime Committee dealing with fire safety.

Training Courses:
FSEG, through the University of Greenwich is helping to shape the future of fire safety engineering practice. Members of FSEG are involved in the supervision of doctoral and masters level research students concerned with fire safety and the development and delivery of fire safety engineering courses. Since 1997, FSEG have run two short courses aimed at the fire safety engineering community, namely:

- Principles and Practice of Fire Modelling (PPFM) and
- Principles and Practice of Evacuation Modelling (PPEM).

These courses are concerned with theoretical and practical issues of fire and evacuation modelling.

From 1997 - 2013 these courses have been run 18 times, attracting over 600 safety professionals from over 40 countries. Those attending were drawn from the Hospital Sector, Aviation Industry, Nuclear Industry, Oil Industry, Horse Racing Industry, Fire and Rescue Services, Fire Inspectrate, Building Control Inspectors, Police, Fire Safety Consultancies, Engineering Consultancies, Building Operators and Academia.

9 ANNEX B: PLANNING TIMELINE

Two types of trials will be conducted:

- TS1/TS4 – at the south arch of Queen Anne Court (at point [E] in Figure 80)
- TS2 – in the centre of the courtyard in Queen Anne Court (at point [F] in Figure 80)

OPENING TIMES:

- QM – 0930
- QA – 0800
- CAFÉ – 0730

The main actions and events before, during and after the experiment are presented in the timeline shown in Table 41. The roles adopted by those involved are described in Table 42. A schematic of the registration area is shown in Figure 79 and the experimental area is shown in Figure 80.

Table 41: Experimental Timeline.

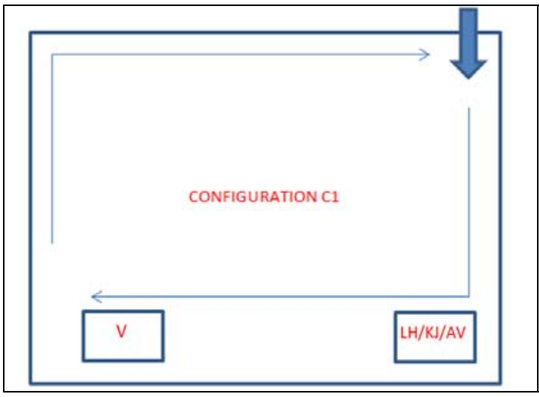
Time Step	People Management	Data Collection	Resources	Physical Environment
BEFORE TRIAL ORGANISATION IS COMPLETE				
-26			Ensure storage area in courtyard available. Update procedure and distribute for review. [SG]	Take courtyard measurements and confirm camera positions for TS2. Send feedback to Euan. [DC]
-25	Send out FSEG/Gre e-mail [EG]	Ensure cameras / still camera / walkie-talkies / clamps/laptops (including back-ups) available [DC]	Identify and distribute potential locations for pre-trial and trial luggage storage [SG] Get payment bags [KJ]	
-24			Organise first aiders [EG]	
-23			Confirm insurance / safety requirements [EG/SG]	
-22			Identify (C1/C2) locations [SG]	
-21			Purchase hats Purchase (or confirm) water and ensure delivery to site on day [DJP]	
-20			Develop group / trial allocation [SG]	
-19			Develop numbering system that carries through from registration to payment [SG – 20/2].	
-18			Provide feedback on luggage location [LF – 10/2]	Ensure rooms/space available. [Not available. Café will

				be used] Ensure barriers (boxing and barrier tape) are available [DC/DJP resolving]
-17			Produce participant roster, withdrawal forms and registration documents for cross checking [SG]	
-16			Provide KJ with new e-mail templates [XH] Confirm availability of high-vis jackets [DC]	
-15			Finalise participant briefing [SG]	
-14			First advertisement placed in media [PR Dept]	
-13		Identify footage numbering for output [DC – 19/2]	Participants to be allocated to days and then the list provided to KJ [XH – 27/2] Confirm resolution of security and money distribution [KJ – 28/2]	
-12	[SG] to provide[KJ] with final participant information sheet. [SG]		Prepare hats / numbers. Get tape measure, masking tape, pencils, markers, paper. [KJ- 28/2]	Ensure cones are available. [DC]
-11			Initial confirmation e-mail sent out [KJ – 28/2]	
-10			Second advertisement placed in media if need be [PR Dept – 10/3]	
-9			Reminder e-mail sent out. Remind participants of BST on Sunday. [KJ – 27/3] Print off registration documentation [XH – 27/3]	Confirm availability of seat/table for LF [DC – 27/3] Confirm with Terry whether we have access to the café after 1600 on Friday – to set-up [DC – 27/3]
-8		Charge Batteries [DC – 27/3]	Confirm Procedure – perform walkthrough [LF/SG – 28/3] **Ensure that everyone collects all resources from QM on the set-up day (the 24th and 29th March) as the building will not be available until 0930 on the day of the trial.**	Meet with Euan, go over set-up and mark up key locations [DC – 28/3]
BEFORE PARTICIPANTS ARRIVE				
-7	FSEG STAFF ARRIVE AT 0715		Ensure First Aiders	

			on site [EG]	
-6	[MP] waiting at A/B to manage early arrivals	Position cameras. Test quality of footage. Test longevity[XH/ DC]	[SD] arrive at (C) @ 07:30 to ensure that desk locations are set-up in configuration [C1] (see Figure 79). [A/V/CH/LH] clear tables/chairs if not already done. [SG, LF] provide assistance once luggage location complete. Include queuing system in case people arrive at same time [KJ] / distribution [V/A/ AV/MP]	Set-up laptop for randomisation [LF]
-5			Ensure accessibility of safe / money [EG] Distribute high vis jackets [DC]	
-4			Check water provisions [EG]	Prepare luggage location [LF/SG]
-3			[DC, XH, SD] collect equipment: cameras, laptop, clamps, walkie-talkies. Pass on walkie-talkie to [KJ/EG/AV/SG/MP]	Ensure barriers in place to delimit pen. [DC]
-2	[KJ] locates hats/documents as required in the registration area.	Take stills / test footage from camera positions [XH/ DC/SD]		Ensure packaging to prevent trip hazard. Check experimental markings [DC]
-1	Establish redundancy in staffing should people not turn up on the day. AV/MP, V/A already have some redundancy. [CH] goes A/B to help [MP].			TfL to set-up trial environment. Mark out 2m sections in two pens [DC]
DURING TRIAL				
0	Participants arrive@ 0800. Met at (A) and (B) by [MP and CH]. [EG] to meet and collect visitors at pre-determined location.			
1	Participants directed to cafeteria (C1) from (A) and (B) [CH]. [MP] should remain available to meet people. Monitor and record number of arrivals [A] (C). Report to [LH] to confirm.		[SG/LF] prepare holding areas and check pen. [DC] provides [KJ] with a walkie-talkie	
2	Registered at (desk 1, C1) by [KJ/LH/AV] and then provided with a hat selected from set behind the three registrars. [KJ/LH/AV] associates number to participant on their arrival. [KJ] keeps [EG] informed of registration process. [KJ]calls [EG] every 15 mins or when 25%, 50%, 75%, 100% have registered			
3	Move to (desk 2, C1 - [V] present) where participants are given documents, pencils and water.		Briefing document for [EG]	
4	Briefing in cafeteria (C) when sufficient number of people has arrived [EG].			
5	While still within (C), participants complete documentation (e.g. consent form) and return to [V] who collects and pass onto [KJ]. Participants are then taken to [SG] at holding area by [A] or to [LH] should they wish to withdraw, where hat is returned. [LH] notes withdrawal on a			

	withdrawal form, gets it signed, thanks them for their time, and informs [KJ]. [KJ] assigns free hat number to next available participant. [KJ] provides EG with updates of number of drop outs.			
6	In the holding area, participant numbers are logged ready for the trial [LF/SG]. This ensures that those actually taking part can be distinguished from those withdrawing. [SG] will check with [KJ] that his lists correspond.		[SG] will need a walkie-talkie from the registration period onwards.	
7	Assessment of viable participants made [SG/LF]. Number of sections to be used established [SG].	Config. Cam1 [DC] Config.Cam2 [XH] Config.Cam3 [No longer used] Config.Cam4 [SD]	Luggage allocated to participants if need be [SG/LF]. [CH] moves to luggage area if appropriate.	
8	[SG] lets [AV/MP] know when ready. When all of the group members have arrived, [AV] moves to pen (E or F). [MP/CH] still moving between (A) and (B) to meet latecomers. [LF] separates out groups. When full group available, sends them to [SG]. [LF] and [SG] continue process until sections are loaded.		[SG/CH] allocate luggage to participants as and when needed.	
9	[SG]Complete loading of pen (E) into the 9 sections of (20/15) people for TS1/4 and pen (F) with 9 sections of (36/28) people for TS2. Groups will be loaded into allocated pen section, according to defined procedure (managed by [SG] and [LF]). Each group instructed to remain in allocated section [SG]. [LH] and [KJ] should remain in (C) to process any late arrivals and prepare for check out. [V] remain in (C) to assist [LH/KJ]. [A] remains between (A) and (B). Once pen loaded, [AV] stands south of pen and [MP] moves north of pen location – acts as target and ensure path adopted by participants.	As people are loaded into pen, [SG/EG/DC] confirm density condition inside pen All camera positions confirm active to [DC] who then confirms with [EG]	[SG/DC] require walkie-talkies.	Close pen barrier behind last group. [SG]
10	[EG] stands in the courtyard to one side to start trial and during trial. [EG] gives ready signal to [DC], [SG], [LF],[MP] and [AV]. [A] guides latecomers from (A) and (B) for processing / withdrawals, met by [V] at (C). During Day 1[SG] stands at back of pen and walks behind crowd during trial. During Day 2 [SG] monitors movement from within courtyard. [LF] remains at holding area (D).	[DC] starts cameras rolling.	[EG] has loud hailer and emergency stop horn.	
11	[EG] final check with [DC], [SG] and [MP]. [EG] starts trial and sounds horn such that cameras can pick-up time anchor. [DC] and [SG] monitor crowd while in pen and if anyone in distress, they call [EG] who sounds horn to stop. [MP] walks ahead of participants and leads then along necessary path back to holding area. [AV] remains in courtyard ready for reloading of pen should participants still remain in holding area.		After trial commences, should there be leftover participants, [LF/SG] start to prepare them for the next trial.	
12	[EG] to alert camera crews that trial completed [via walkie-talkie]. On completion, [MP] move participants to holding area (D), through side or end arch and then return to position (@F) after assisting [LF] in holding area. [Clare Evenden] may be on site from 2pm, should the trials finish early. She will have to be contacted 30 minutes before she is needed. She will open the safe on her arrival.	[DC] ends if at break or lunch.		Check status of trial area [SG / DC] Trial configuration updated [DC/Euan]

13	Participants held at (D) by [LF] while allocation of participants for next trial resolved, and then sent on to (E/F) by [SG] and loaded into sections. This will be via outside of courtyard if [E] and internally if [F]. Participants kept in holding area until rest periods. [EG] will need to communicate with [A/V] to retrieve appropriate people from cafeteria at end of rest periods.		At D, distribute water from cafeteria as and when needed [A / V]	Adjust trial area as required [DC / AV] [KJ] prepares (C) for post-trial processing.
14	If last trial involving all participants, [LF] sends excess participants to (C) for registration, while others complete final trials. Go to time step <8>. At breaks/lunch, [EG] to announce break to participants at (D) or (C). Inform them to gather at (D) or (C) depending on required timescale.	[DC] to organise food/toilet breaks for camera crew.	Identify toilet locations for participants between trials [EG/A / V]	
IMMEDIATELY AFTER TRIALS				
15	Cafeteria furniture returned to normal positions for lunch. [A/V] Cafeteria furniture positioned for four stations for participant departure. (A/V – move cafeteria in Configuration C2.)			
16		[EG] to notify camera crews that equipment can be packed up. Camera crews to pack up. [DC] to drop his cameras to other camera location.		
17	On completion of trials, [LF/AV/MP] return to (C2) for administration.			
18	[SG] returns to (C2) provides [KJ] with any withdrawal information.			
19	[KJ] prepares payment lists, taking into account no shows, non-starters and withdrawals. No-shows and non-starting will be already known from registration and withdrawals provided by [SG]. [KJ] informs [EG] of the number of payments required to be made.			
20	[EG] makes announcement to participants of the desks/numbering system so that they know where to queue.			
20	Distribute Payments [KJ /LH/AV/LF] Hat storage by [A]. On return of hat, participant is marked off roster, signs document desk station and receives payment. Hat is passed back to [A] by [KJ /LH/AV/LF]. [KJ /LH] determines if remaining cash is correct. [KJ] passes on uncollected cash to [EG]. [EG] signs for the required number of returned envelopes and takes back to office in QM.			
21	Arrange furniture in cafeteria area in readiness for next day. Two stations required. [A/V]	Pack Cam1 [DC] Pack Cam2 [XH] Pack Cam3 [No long used] Pack Cam4 [SD]		



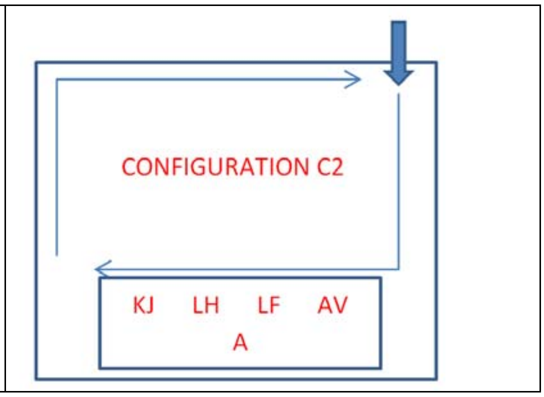


Figure 79: Location [C] Configurations.

Table 42: Staff roles.

STAFF	ROLE
EG	Coordinator
MP - Maria	People Management
DC - Dave	Camera / Resources
AV - Anand	People Management
XH - Xie	Camera / Resources
SD - Steve	Camera / Resources
LH - Lynne	People Management / Admin
KJ - Karen	Admin
V – Vicky	People Management
A - Ashish	People Management
SG - Steve	People Management
LF - Lazaros	People Management

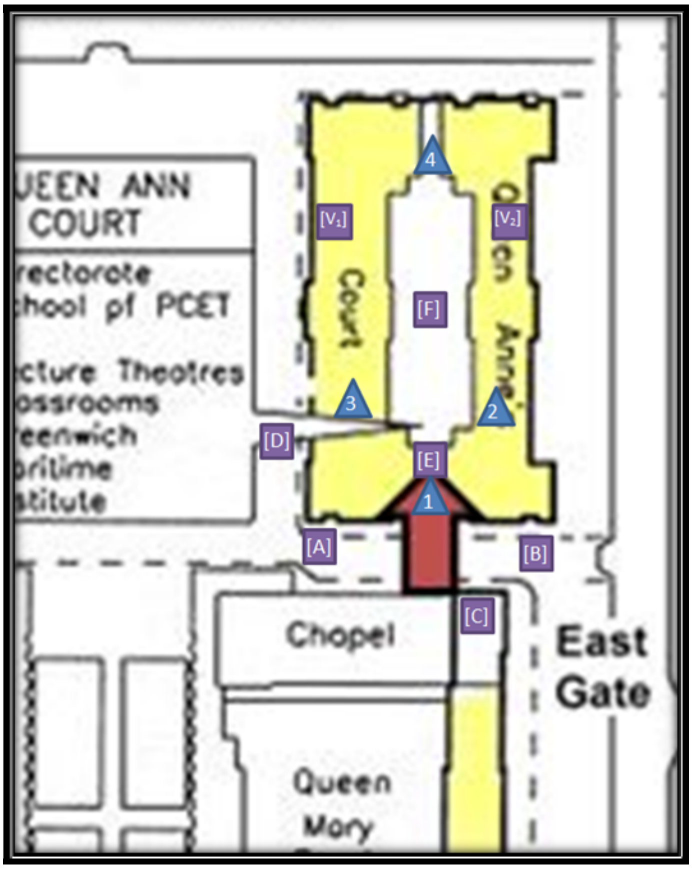


Figure 80: Experimental area. Triangles indicate camera positions. Squares indicate locations of interest.

10 ANNEX C: RISK ASSESSMENT

RISK ASSESSMENT

As part of the trial planning a number of potential risks which could compromise the successful completion of the trials has been identified. These concern risks associated with the trial procedures, potential injury to participants and environmental factors. For each of these risks, actions have been identified to mitigate the risk.

Procedural risks

Inability to recruit sufficient numbers of participants by the scheduled trial date. ***MEDIUM***

- The facility has been booked for more dates than required and so the trial could be rescheduled for a later date. It is thus essential to maintain a database of contact phone numbers and email addresses to contact the participants should rescheduling be required.
- In addition, a second recruitment advertisement has been planned and budgeted for via the contingency budget.
- However, should insufficient participants be initially recruited, the area over which the participants are initially dispersed could be reduced slightly, maintaining the density but reducing the number of required participants.
- As a last resort, the maximum density could be reduced slightly e.g. to 3.5 p/m^2 or 3 p/m^2.

No-shows mean that insufficient participants arrive on the trail day. ***HIGH***

- Additional participants will be recruited and held in reserve and available at short notice.
- However, should insufficient participants be available the area over which the participants are initially dispersed could be reduced slightly, maintaining the density but reducing the number of required participants.
- As a last resort, the maximum density could be reduced slightly e.g. to 3.5 p/m^2 or 3 p/m^2.

The participants are not able to perform the trials due to existing medical conditions. ***LOW***

- The participants will be screened during the recruitment phase to ensure that they do not suffer from any medical conditions that may preclude their involvement in the trials.
- Additional participants will be recruited and held in reserve.
- However, should insufficient participants be available the area over which the participants are dispersed could be reduced slightly, maintaining the density but reducing the number of required participants.

Inappropriate camera angles selected for recording the data. ***MEDIUM***

- Camera positioning will be confirmed in the Pilot Trial.

Technical equipment may fail. ***LOW***

- Reserve camera equipment will be ready and charged to replace failing cameras. All recorded material will be stored in several places to ensure against storage failure.

External factors/individuals may interfere with the experimental conditions. ***LOW***

- Perimeter control will be maintained by crowd management staff. This will be rehearsed during the Pilot Trial.

Required densities may not be reliably generated during the trials. ***MEDIUM***

- Conditions will be closely monitored during the trial in order to determine whether the density conditions are met.
- In addition, crowd managers will be on hand to adjust the population conditions.
- Procedures will be examined as far as possible during the Pilot Trial.

Inability to complete identified number of trials within the allocated time. ***MEDIUM***

- It is acknowledged that the schedule is tight, with many trials being planned each day. However, while 30 minutes have been allocated for the completion of each trial, it is anticipated that no more than 10 minutes will be required to conduct each trial, leaving 20 minutes to prepare the participants for the trial.
- Should this not prove adequate there are also two 30 minute breaks and a 1 hour lunch factored into each full trial day. The break time and lunch time can be reduced if necessary.
- Specifically for Trial Option 2: Day 1also has a spare 30 minutes at the end of the day and as a last resort, up to two repeat trials could be dropped at the end of the day saving 1 hour. For Day 2, up to 2 hours is available at the end of the day should this be required. Thus Trial Option 2 has sufficient flexibility to accommodate slippages in the schedule.
- Specifically for Trial Option 1: As there are 1.5 days scheduled for the first series of trials, additional time is available on the second day – however, the participant time has not been budgeted for. To take advantage of this additional time it is suggested that the contingency budget for Trial Option 1 be increased by £2400 which provides an additional 2 hours of flexibility (or £4800 which provides an additional 4 hours of flexibility). This additional contingency funding is required to pay the volunteers for their additional time should this be required. There will be no additional staff costs for UoG staff time should this additional funding be considered necessary. For Trial Option 1 Day 3 this offers similar flexibility as Trial Option 2, Day 1 (without the spare 30 minutes at the end of the day).
- Specifically for Trial Option 3: Day 3 this offers similar flexibility as Trial Option 2, Day 1 (without the spare 30 minutes at the end of the day).
- Finally, procedures will be examined as far as possible during the Pilot Trial.

Risk of injury to participants

The trial population densities may lead to minor injuries. ***LOW***

- The maximum crowd density to be examined during the trials is below the level likely to cause injury.

- However, crowd managers will be carefully monitoring conditions both before and during the trials. Should crowd densities or crowd behaviours be considered hazardous at any point during the trial, an "immediate stop" signal will be given. Participants will be briefed before the trial as to what to expect during the trial and the "immediate stop" signal will be demonstrated.
- Finally, a first aid team will be in place to treat minor injuries.

The trial population densities may lead to participant anxieties. ***LOW***

- Participants will be screened as part of the recruitment process.
- Crowd managers will be carefully monitoring conditions during the trials. Should a participant display signs of distress an "immediate stop" signal will be given. Participants will be briefed before the trial as to what to expect during the trial and the "immediate stop" signal will be demonstrated.
- In addition, participants will be briefed on the means by which they can indicate that they are in distress and which to stop the trial.
- Finally, a first aid team will be in place to treat minor injuries.

The bollard array may present a trip hazard to the participants. ***MEDIUM***

- Appropriate bollards are being sourced to minimise trip hazards. The suggested bollard array will be tested during the Pilot Trial.
- Participants will also be instructed to wear appropriate footwear.
- Crowd managers will be carefully monitoring conditions during the trials. Should participants trip at the bollards, an "immediate stop" signal will be given.
- Participants will be briefed before the trial as to what to expect during the trial and the "immediate stop" signal will be demonstrated.
- Finally, a first aid team will be in place to treat minor injuries.

Participants may become dehydrated. ***LOW***

- The trials will not be performed during the summer months reducing the likelihood of dehydration.
- Water will be made available to the participants.
- Finally, a first aid team will be in place to treat minor injuries.

Environmental risks

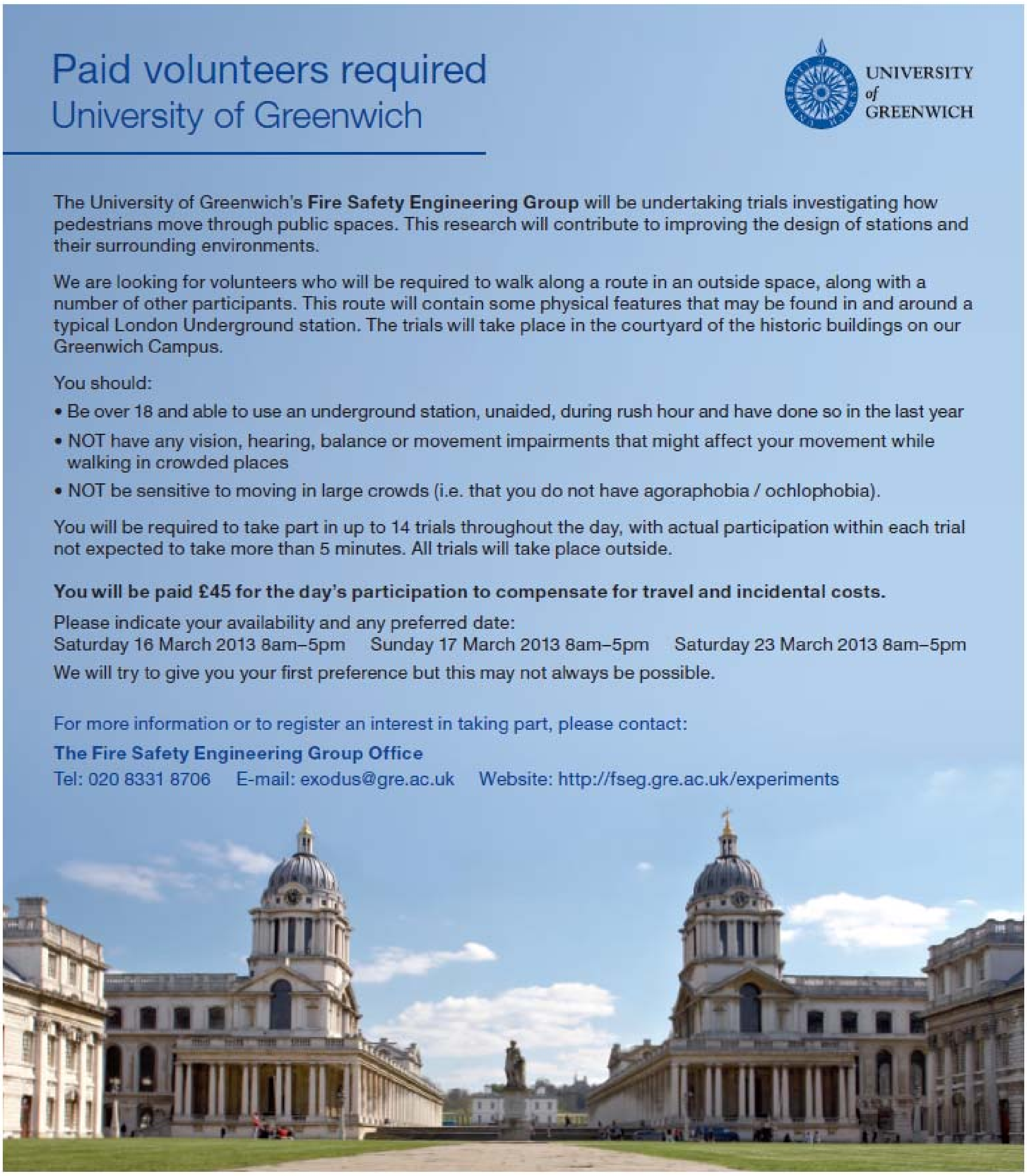
The weather may interfere with the experimental schedule. ***HIGH***

- Five day weather forecasts will be examined to avoid extreme weather conditions. The facility has been booked for more dates than required and so the trial could be rescheduled for a later date. It is thus essential to maintain a database of contact phone numbers and email addresses to contact the participants should rescheduling be required.
- Participants will be advised to bring wet weather clothing and the trials will continue in the event of light rain.
- In the event of heavy rain, the trials will be stopped and sheltered areas will be provided to ensure that participant exposure is limited. In the event of heavy rain, the trial schedule will be modified and the trials continued once the rain has stopped. However, it must be acknowledged that heavy rain during the trials may limit the number of trial repetitions.

A fire alarm is sounded in one of the buildings. ***LOW***

- During a fire alarm in the Queen Anne building, the trial will be stopped and participants will be evacuated to the assembly point in accordance with the evacuation procedure. The trial schedule will be modified and the trials continued after the participants have returned to the area. However, it must be acknowledged that a fire alarm in the Queen Anne building may limit the number of trial repetitions.
- A fire alarm in one of the neighbouring buildings will not have an immediate impact on the trials and will only be affected if the fire brigade or site officials request that the trials be stopped.

11 ANNEX D: ADVERTISEMENT



12 ANNEX E: WEB ADVERTISEMENT

Go to the following web address: http://fseg.gre.ac.uk/experiments/

13 ANNEX F: BRIEFING

We would like to welcome you to the Maritime Campus and thank you for assisting us with these experiments. We are performing these experiments in order to investigate how people move through public spaces. This research will improve both the safety and the design of stations and their surrounding environments.

During the trials, we will ask you to perform a simple task and you should be presented with no more difficulties than you might experience in moving around a train station and associated public spaces in normal use.

I would like to set the scene for the trial you are about to take part in:

- You will be told to walk towards a particular target from your starting location.
- You should imagine that you are walking out of a station with a number of other passengers during rush hour.
- You should move towards the location identified.
- Please do not attempt to run.
- Please do not attempt to push people in front of you.

If, for any reason, during the trial you wish to halt the trial or withdraw, please raise your hand.

If this occurs or if the trial needs to be halted for any other reason, you will hear the following sound [DEMONSTRATE].

On hearing this sound, you should stop moving and await further instructions.

Once again, we thank you for your participation.

14 ANNEX G: PARTICIPANT DETAILS

Table 1: Attendees that dropped out but provided warning.

	Drop-outs				
	Male	**Female**	**18-30**	**31-50**	**51+**
Day 1 29.03.14	21	20	11	2	2
Day 2 30.03.14	29	17	30	15	1

Table 2: Attendees that dropped out without warning.

	Drop-outs				
	Male	**Female**	**18-30**	**31-50**	**51+**
Day 1 29.03.14	13	13	18	4	4
Day 2 30.03.14	69	39	72	24	12

15 ANNEX H: EQUIPMENT DETAILS

The equipment used in the trials consisted of camera equipment and walkie-talkies for communication between team members. The equipment is detailed in the following tables.

Table 43: Itemised contents of Case 1

Equipment	Quantity
DV Camera	10
Long Life Battery	32
Walkie-Talkies	10

Table 44: Itemised contents of Case 2

Equipment	Quantity
Super Clamp	6
Long Arm	6
Camera Mount	6

Table 45: Equipment carried separately

Equipment	Quantity
Measuring Tape	1
Masking Tape	1
Tall Tripod*	1
Camera Head*	1

16 ANNEX I: RESULTS

16.1 TS1: 1m stand-off

Table 46: Exit flow measured in 5 sec intervals for the three 1m BA trials (data excluded from peak determination highlighted in red)

TS1_1mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
TS1_SD1_1(1mBA)	276.0	300.0	300.0	252.0	276.0	264.0	228.0	264.0	132.0	269.14
TS1_SD1_2(1mBA)	276.0	324.0	300.0	336.0	276.0	240.0	252.0	264.0	24.0	284.57
TS1_SD1_3(1mBA)	240.0	336.0	264.0	300.0	252.0	264.0	264.0	264.0	108.0	277.71
Average(1mBA)	264.0	320.0	288.0	296.0	268.0	256.0	248.0	264.0	88.0	**277.14**

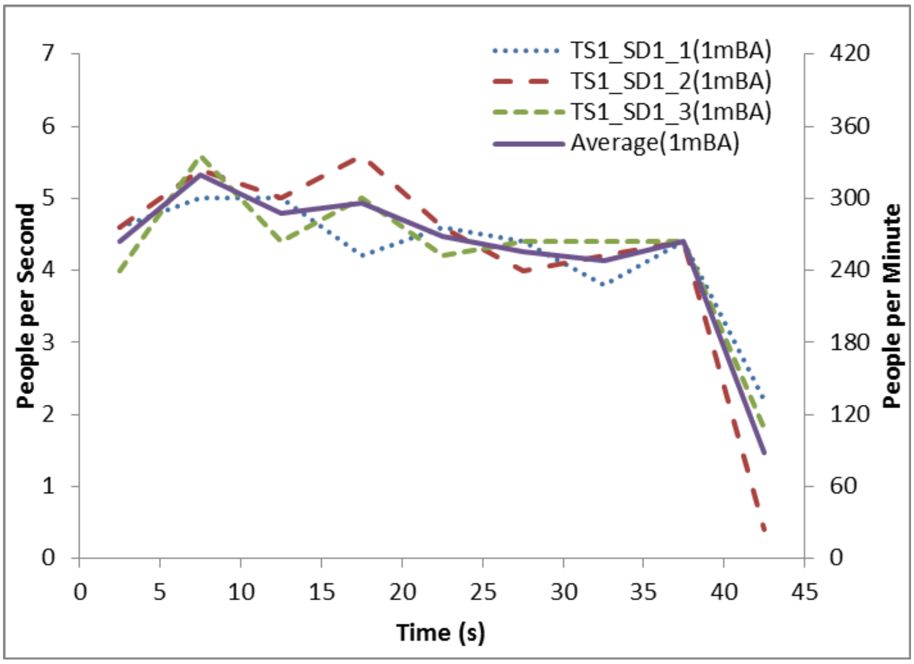


Figure 81: Exit flow measured in 5 sec intervals for the three 1m BA trials

Table 47: BA flow measured in 5 sec intervals for the three 1m BA trials (data excluded from peak determination highlighted in red)

TS1_1mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0- 5	5- 10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
TS1_SD1_1(1mBA)	228.0	312.0	300.0	264.0	252.0	276.0	240.0	252.0	168.0	270.86
TS1_SD1_2(1mBA)	240.0	300.0	324.0	336.0	276.0	240.0	264.0	240.0	72.0	282.86
TS1_SD1_3(1mBA)	204.0	324.0	300.0	288.0	240.0	264.0	276.0	264.0	132.0	279.43
Average(1mBA)	224.0	312.0	308.0	296.0	256.0	260.0	260.0	252.0	124.0	**277.71**

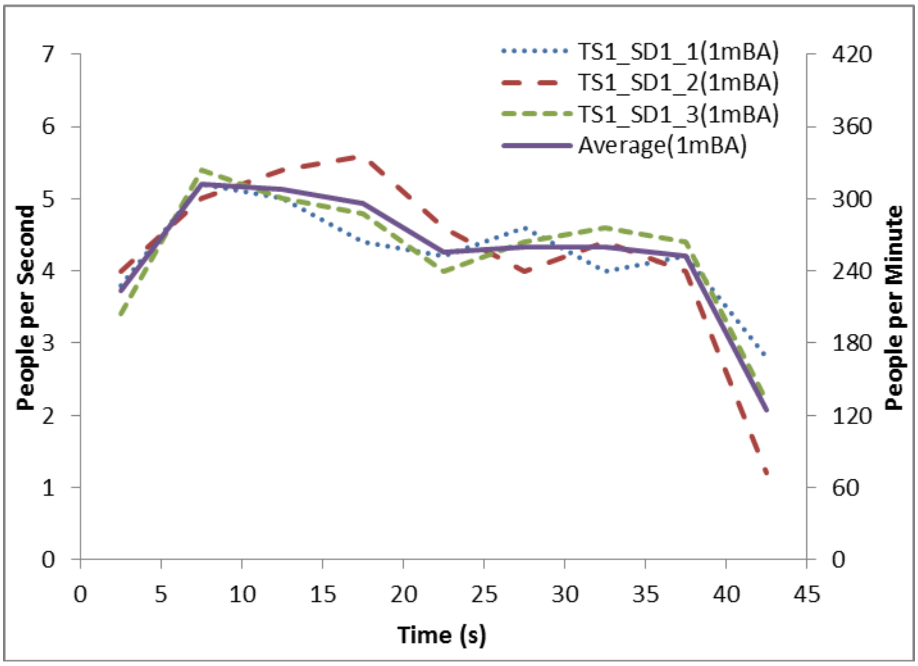


Figure 82: BA flow measured in 5 sec intervals for the three 1m BA trials

Table 48: Density measured in 5 sec intervals for the three 1m BA trials (data excluded from peak determination highlighted in red)

2.4mExit,1mBA		**Density Time Step (sec)**									**Peak Average (p/m2)**
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
TS1_SD1_1(1mBA)	A										
	B	0.00	1.20	1.20	0.90	0.75	1.20	0.90	0.75	1.05	1.02
	C										
	Total	0.00	1.20	1.20	0.90	0.75	1.20	0.90	0.75	1.05	1.02
TS1_SD1_2(1mBA)	A										
	B	0.00	1.20	1.35	0.75	0.90	1.05	0.75	0.75	1.05	1.05
	C										
	Total	0.00	1.20	1.35	0.75	0.90	1.05	0.75	0.75	1.05	1.05
TS1_SD1_3(1mBA)	A										
	B	0.00	0.75	1.05	0.75	0.75	0.90	0.90	1.05	0.90	0.83
	C										
	Total	0.00	0.75	1.05	0.75	0.75	0.90	0.90	1.05	0.90	0.83
Average Area B (2.4mExit,1mBA)		0.00	1.05	1.20	0.80	0.80	1.05	0.85	0.85	1.00	0.97

Table 49: Gap usage (%) for the three 1m BA trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
SD1_1(1mBA)	0.0%	25.1%	49.2%	25.7%	0.0%
SD1_2(1mBA)	0.0%	27.2%	46.1%	26.7%	0.0%
SD1_3(1mBA)	0.0%	26.7%	47.1%	26.2%	0.0%
Average(1mBA)	**0.0%**	**26.4%**	**47.5%**	**26.2%**	**0.0%**

16.2 TS1: 1.5m stand-off

Table 50: Exit flow measured in 5 sec intervals for the three 1.5m BA trials (data excluded from peak determination highlighted in red)

TS1_1.5mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
TS1_SD2_1(1.5mBA)	288.0	312.0	288.0	264.0	288.0	216.0	252.0	276.0	108.0	270.86
TS1_SD2_2(1.5mBA)	288.0	312.0	264.0	264.0	264.0	276.0	252.0	252.0	120.0	269.14
TS1_SD2_3(1.5mBA)	288.0	288.0	228.0	276.0	264.0	264.0	240.0	240.0	204.0	257.14
Average(1.5mBA)	288.0	304.0	260.0	268.0	272.0	252.0	248.0	256.0	144.0	**265.71**

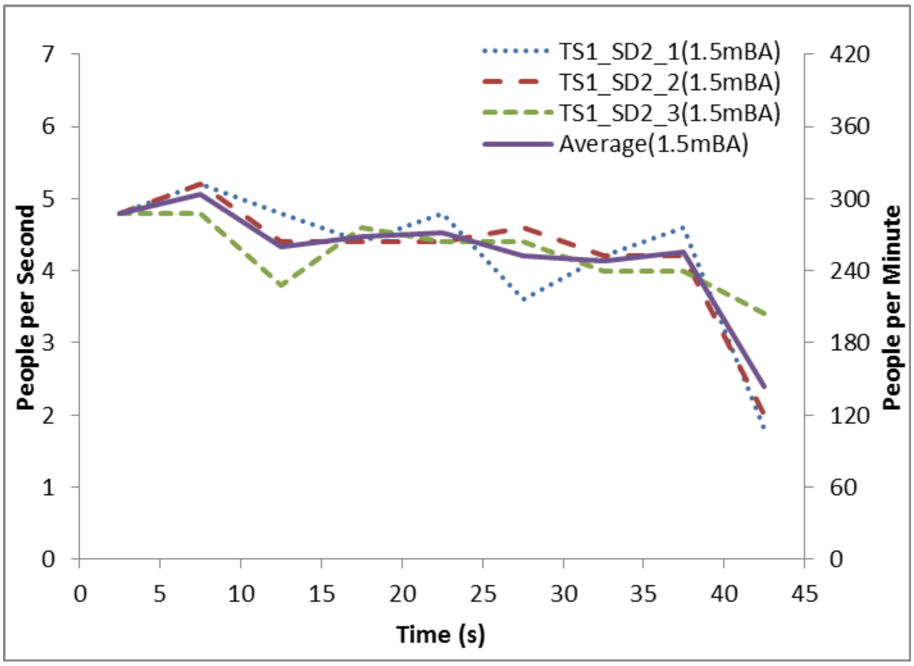


Figure 83: Exit flow measured in 5 sec intervals for the three 1.5m BA trials

Table 51: BA flow measured in 5 sec intervals for the three 1.5m BA trials (data excluded from peak determination highlighted in red)

TS1_1.5mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
TS1_SD2_1(1.5mBA)	240.0	288.0	300.0	276.0	276.0	228.0	228.0	276.0	180.0	267.43
TS1_SD2_2(1.5mBA)	228.0	312.0	264.0	264.0	252.0	312.0	240.0	240.0	180.0	269.14
TS1_SD2_3(1.5mBA)	192.0	324.0	264.0	228.0	276.0	276.0	252.0	240.0	240.0	265.71
Average(1.5mBA)	220.0	308.0	276.0	256.0	268.0	272.0	240.0	252.0	200.0	**267.43**

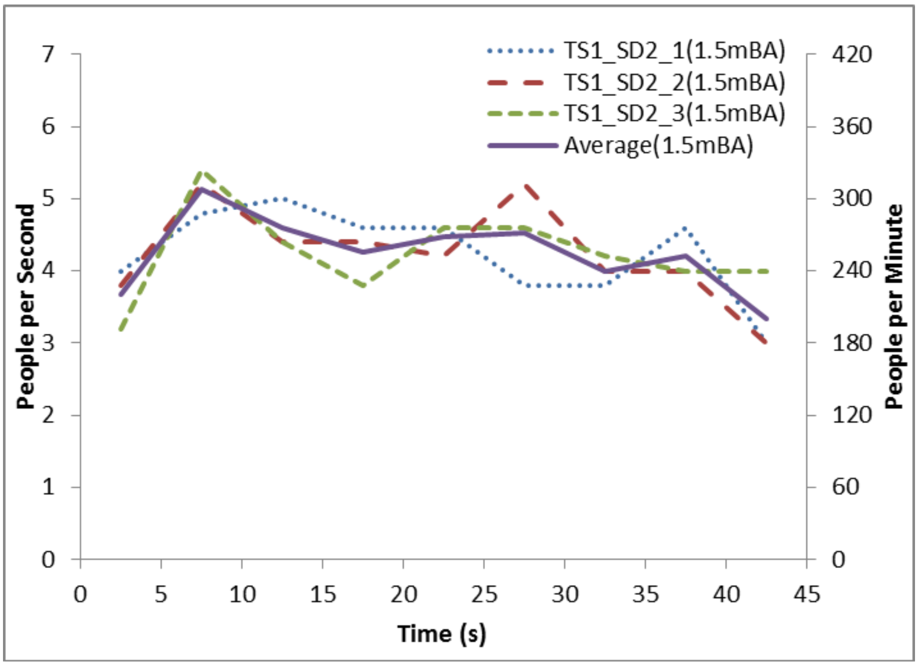


Figure 84: BA flow measured in 5 sec intervals for the three 1.5m BA trials

Table 52: Gap usage (%) for the three 1.5m BA trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
SD2_1(1.5mBA)	0.0%	28.8%	42.4%	28.8%	0.0%
SD2_2(1.5mBA)	0.0%	27.7%	42.9%	29.3%	0.0%
SD2_3(1.5mBA)	0.0%	27.2%	42.9%	29.8%	0.0%
Average(1.5mBA)	**0.0%**	**27.9%**	**42.8%**	**29.3%**	**0.0%**

16.3 TS1: 2m stand-off

Table 53: Exit flow measured in 5 sec intervals for the three 2m BA trials (data excluded from peak determination highlighted in red)

TS1_2mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
TS1_SD3_1(2mBA)	276.0	348.0	276.0	216.0	252.0	288.0	264.0	228.0	120.0	267.43
TS1_SD3_2(2mBA)	264.0	276.0	264.0	300.0	264.0	240.0	264.0	252.0	144.0	265.71
TS1_SD3_3(2mBA)	276.0	348.0	252.0	288.0	240.0	252.0	264.0	240.0	132.0	269.14
Average(2mBA)	272.0	324.0	264.0	268.0	252.0	260.0	264.0	240.0	132.0	**267.43**

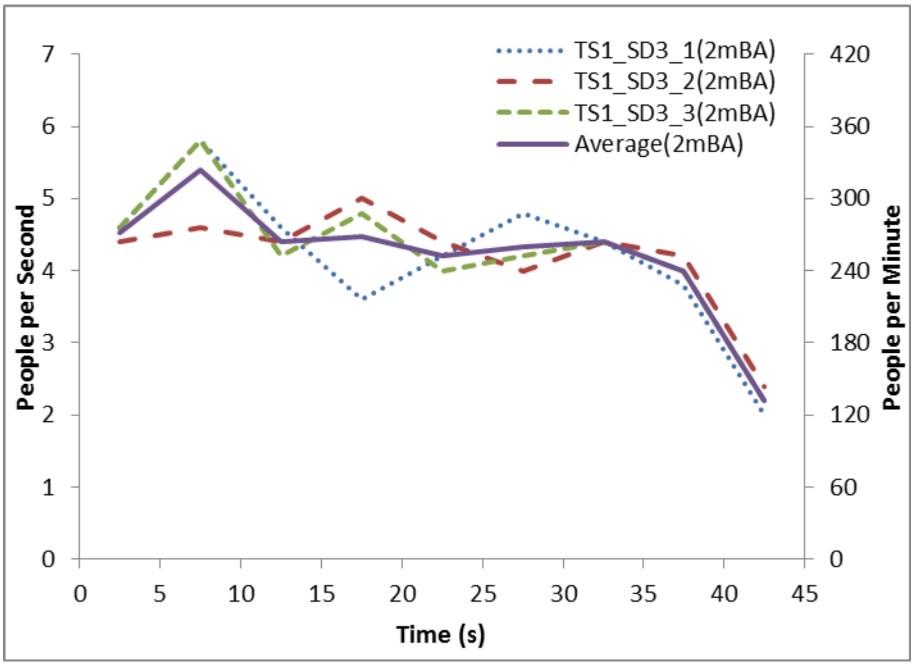


Figure 85: Exit flow measured in 5 sec intervals for the three 2m BA trials

Table 54: BA flow measured in 5 sec intervals for the three 2m BA trials (data excluded from peak determination highlighted in red)

TS1_2mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
TS1_SD3_1(2mBA)	180.0	348.0	300.0	216.0	276.0	276.0	264.0	216.0	192.0	270.86
TS1_SD3_2(2mBA)	180.0	312.0	264.0	288.0	264.0	240.0	252.0	276.0	192.0	270.86
TS1_SD3_3(2mBA)	192.0	348.0	312.0	252.0	264.0	216.0	264.0	252.0	192.0	272.57
Average(2mBA)	184.0	336.0	292.0	252.0	268.0	244.0	260.0	248.0	192.0	**271.43**

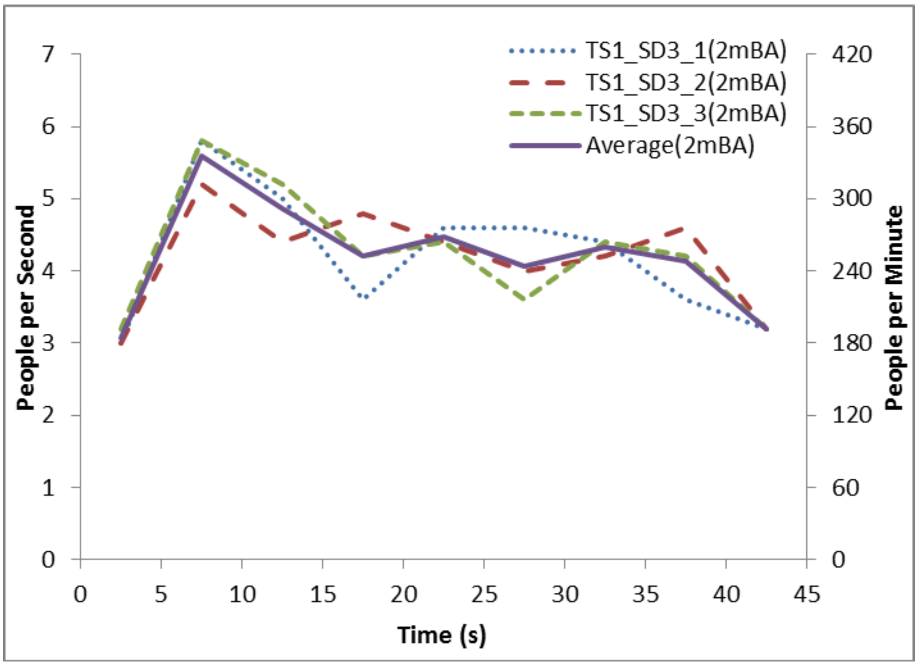


Figure 86: BA flow measured in 5 sec intervals for the three 2m BA trials

Table 55: Density measured in 5 sec intervals for the three 2m BA trials (data excluded from peak determination highlighted in red)

2.4mExit,2mBA		Density Time Step (sec)									Peak Average (p/m2)
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
TS1_SD1_1(2mBA)	A										
	B	0.00	0.90	1.20	0.75	0.45	0.90	0.90	0.75	0.75	0.83
	C										
	Total	0.00	0.90	1.20	0.90	0.45	0.90	0.90	0.75	0.75	0.86
TS1_SD1_2(2mBA)	A										
	B	0.00	0.60	0.90	1.05	1.05	0.75	0.60	1.05	0.75	0.90
	C										
	Total	0.00	0.60	0.90	1.20	1.05	0.75	0.60	1.05	0.90	0.94
TS1_SD1_3(2mBA)	A										
	B	0.00	1.20	0.90	0.60	0.90	0.60	0.60	1.05	0.90	0.90
	C										
	Total	0.00	1.20	1.05	0.60	0.90	0.60	0.60	1.05	0.90	0.94
Average Area B (2.4mExit,2mBA)		0.00	0.90	1.00	0.80	0.80	0.75	0.70	0.95	0.80	0.88

Table 56: Gap usage (%) for the three 2m BA trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
SD3_1(2mBA)	2.6%	25.9%	41.8%	27.0%	2.6%
SD3_2(2mBA)	1.1%	27.5%	42.9%	25.4%	3.2%
SD3_3(2mBA)	1.6%	28.3%	38.2%	30.4%	1.6%
Average(2mBA)	**1.8%**	**27.2%**	**41.0%**	**27.6%**	**2.5%**

16.4 TS2: BA in exit, 40% participants encumbered with luggage

Table 57: Exit flow measured in 5 sec intervals for the three 0m BA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,0mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA1_CD1_1(40%,0mBA)	228.0	276.0	264.0	264.0	264.0	252.0	216.0	252.0	180.0	255.43
BA1_CD1_2(40%,0mBA)	264.0	252.0	252.0	252.0	216.0	276.0	240.0	252.0	240.0	248.57
BA1_CD1_3(40%,0mBA)	252.0	264.0	264.0	240.0	276.0	216.0	264.0	264.0	216.0	255.43
Average(40%,0mBA)	248.0	264.0	260.0	252.0	252.0	248.0	240.0	256.0	212.0	**253.14**

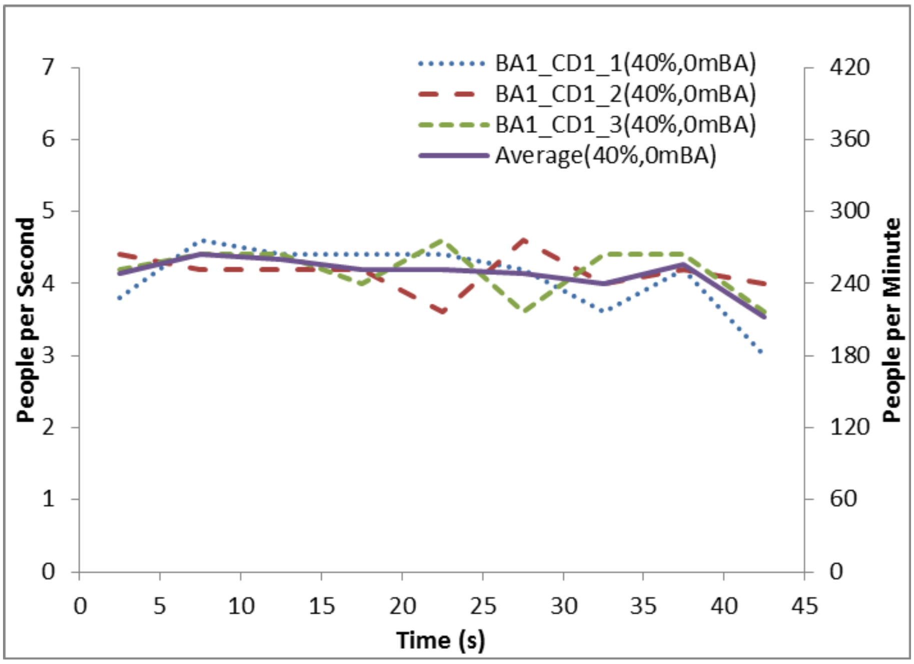


Figure 87: Exit flow measured in 5 sec intervals for the three 0m BA, 40% encumbered trials

16.5 TS2: BA in exit, 60% participants encumbered with luggage

Table 58: Exit flow measured in 5 sec intervals for the three 0m BA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,0mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA1_CD2_1(60%,0mBA)	228.0	252.0	240.0	204.0	204.0	228.0	240.0	252.0	216.0	231.43
BA1_CD2_2(60%,0mBA)	228.0	312.0	192.0	204.0	204.0	240.0	240.0	228.0	228.0	231.43
BA1_CD2_3(60%,0mBA)	228.0	288.0	180.0	192.0	204.0	204.0	228.0	216.0	240.0	216.00
Average(60%,0mBA)	228.0	284.0	204.0	200.0	204.0	224.0	236.0	232.0	228.0	**226.29**

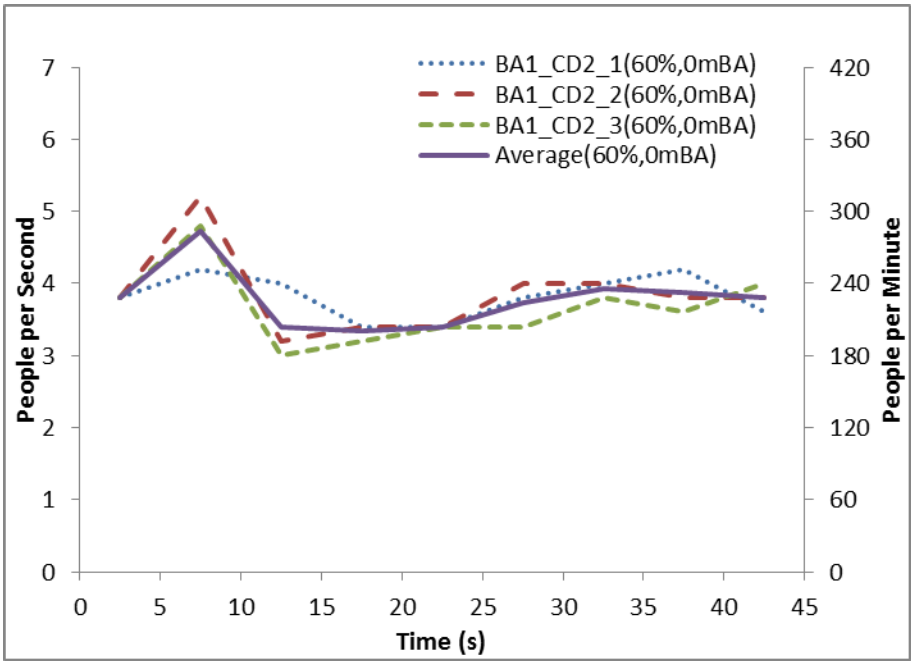


Figure 88: Exit flow measured in 5 sec intervals for the three 0m BA, 60% encumbered trials

16.6 TS2: No BA, 40% participants encumbered with luggage

Table 59: Exit flow measured in 5 sec intervals for the three NoBA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,0mNoBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD1_1(40%,0mNoBA)	264.0	288.0	264.0	192.0	252.0	228.0	264.0	276.0	192.0	252.00
BA2_CD1_2(40%,0mNoBA)	252.0	288.0	264.0	228.0	264.0	240.0	252.0	252.0	204.0	255.43
BA2_CD1_3(40%,0mNoBA)	264.0	300.0	264.0	204.0	240.0	264.0	240.0	216.0	204.0	246.86
Average(40%,0mNoBA)	260.0	292.0	264.0	208.0	252.0	244.0	252.0	248.0	200.0	**251.43**

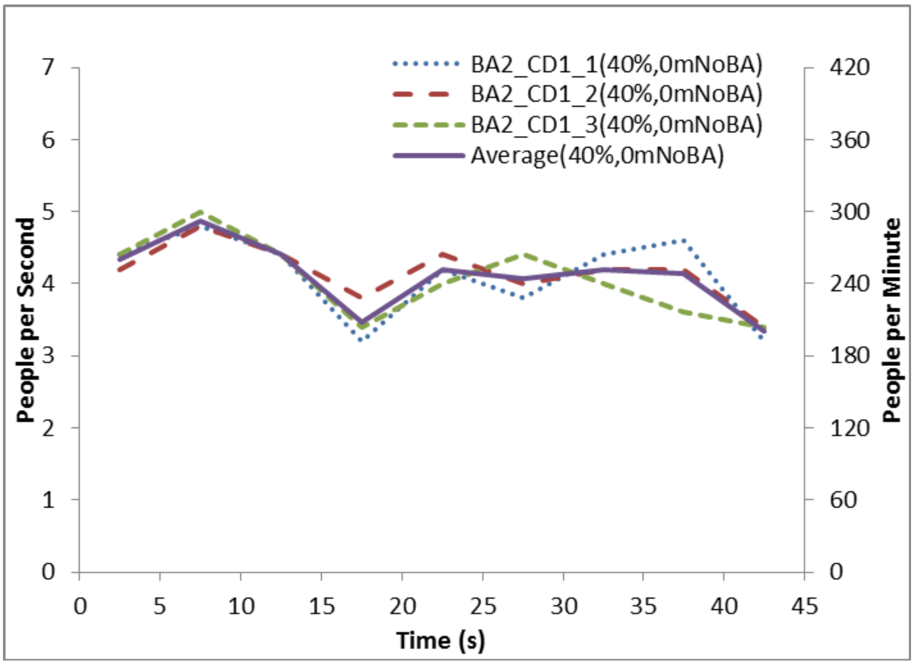


Figure 89: Exit flow measured in 5 sec intervals for the three NoBA, 40% encumbered trials

Table 60: Flow at 1m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,1mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD1_1(40%,1mNoBA)	216.0	312.0	252.0	192.0	264.0	228.0	264.0	252.0	240.0	252.00
BA2_CD1_2(40%,1mNoBA)	228.0	276.0	264.0	264.0	228.0	252.0	240.0	240.0	252.0	252.00
BA2_CD1_3(40%,1mNoBA)	228.0	300.0	252.0	240.0	228.0	240.0	264.0	204.0	240.0	246.86
Average(40%,1mNoBA)	224.0	296.0	256.0	232.0	240.0	240.0	256.0	232.0	244.0	**250.29**

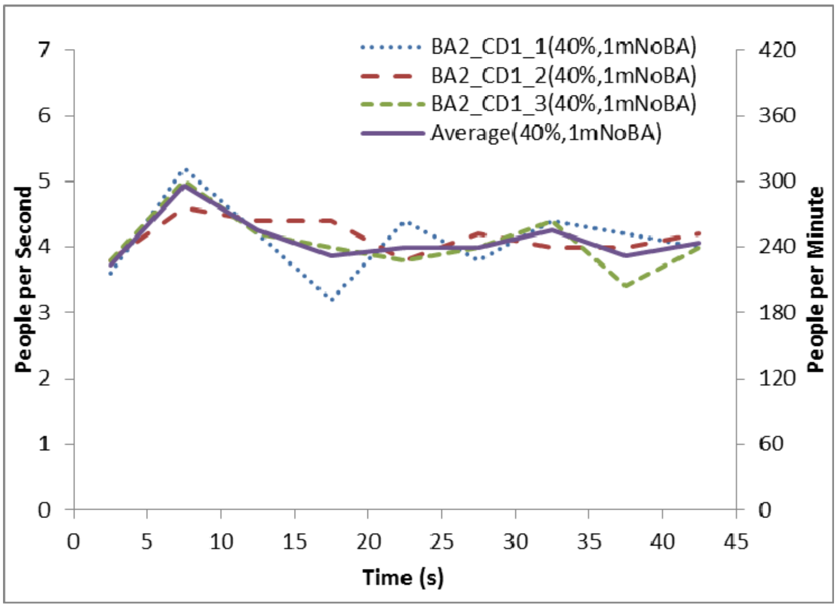


Figure 90: Flow at 1m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials

Table 61: Gap usage (%) at 1m for the three NoBA 40% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD1_1(40%,1mNoBA)	0.0%	27.9%	44.2%	27.9%	0.0%
BA2_CD1_2(40%,1mNoBA)	0.0%	26.7%	46.1%	27.2%	0.0%
BA2_CD1_3(40%,1mNoBA)	0.0%	25.1%	47.1%	27.7%	0.0%
Average(40%,1mNoBA)	**0.0%**	**26.6%**	**45.8%**	**27.6%**	**0.0%**

Table 62: Flow at 1.5m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,1.5mNoBA	BA Flow (ppm) Time interval (sec)									Overall Average (ppm)
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD1_1(40%,1.5mNoBA)	180.0	312.0	264.0	204.0	264.0	204.0	288.0	264.0	228.0	257.14
BA2_CD1_2(40%,1.5mNoBA)	216.0	264.0	276.0	240.0	264.0	240.0	228.0	252.0	240.0	252.00
BA2_CD1_3(40%,1.5mNoBA)	228.0	276.0	264.0	228.0	216.0	264.0	252.0	216.0	228.0	245.14
Average(40%,1.5mNoBA)	208.0	284.0	268.0	224.0	248.0	236.0	256.0	244.0	232.0	**251.43**

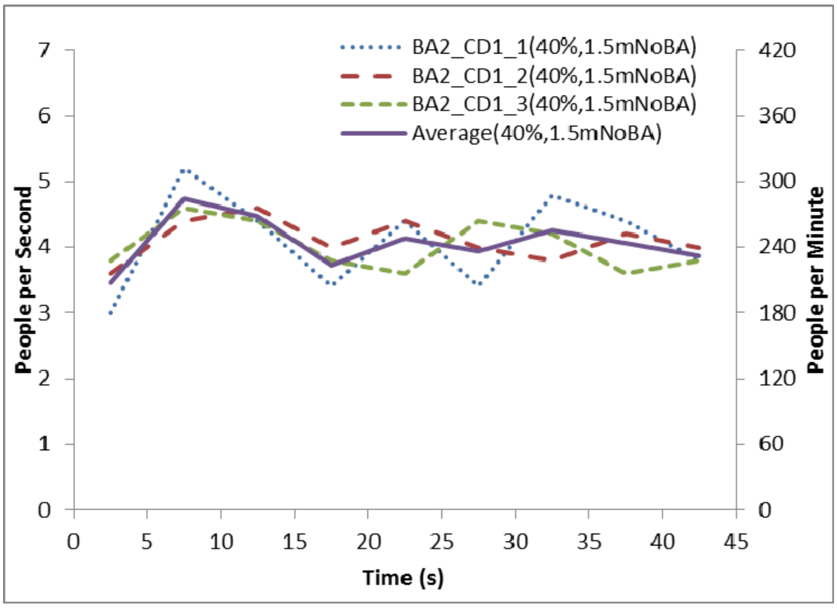


Figure 91: Flow at 1.5m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials

Table 63: Gap usage (%) at 1.5m for the three NoBA 40% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD1_1(40%,1.5mNoBA)	0.0%	28.9%	42.1%	28.9%	0.0%
BA2_CD1_2(40%,1.5mNoBA)	0.0%	27.2%	42.9%	29.8%	0.0%
BA2_CD1_3(40%,1.5mNoBA)	0.0%	26.2%	46.1%	27.7%	0.0%
Average(40%,1.5mNoBA)	**0.0%**	**27.5%**	**43.7%**	**28.8%**	**0.0%**

Table 64: Flow at 2m measured in 5 sec intervals for the three NoBA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,2mNoBA	BA Flow (ppm) Time interval (sec)									Overall Average (ppm)
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD1_1(40%,2mNoBA)	180.0	312.0	252.0	216.0	252.0	216.0	252.0	276.0	240.0	253.71
BA2_CD1_2(40%,2mNoBA)	192.0	252.0	300.0	240.0	252.0	228.0	264.0	240.0	240.0	253.71
BA2_CD1_3(40%,2mNoBA)	192.0	276.0	300.0	204.0	228.0	276.0	252.0	204.0	216.0	248.57
Average(40%,2mNoBA)	188.0	280.0	284.0	220.0	244.0	240.0	256.0	240.0	232.0	**252.00**

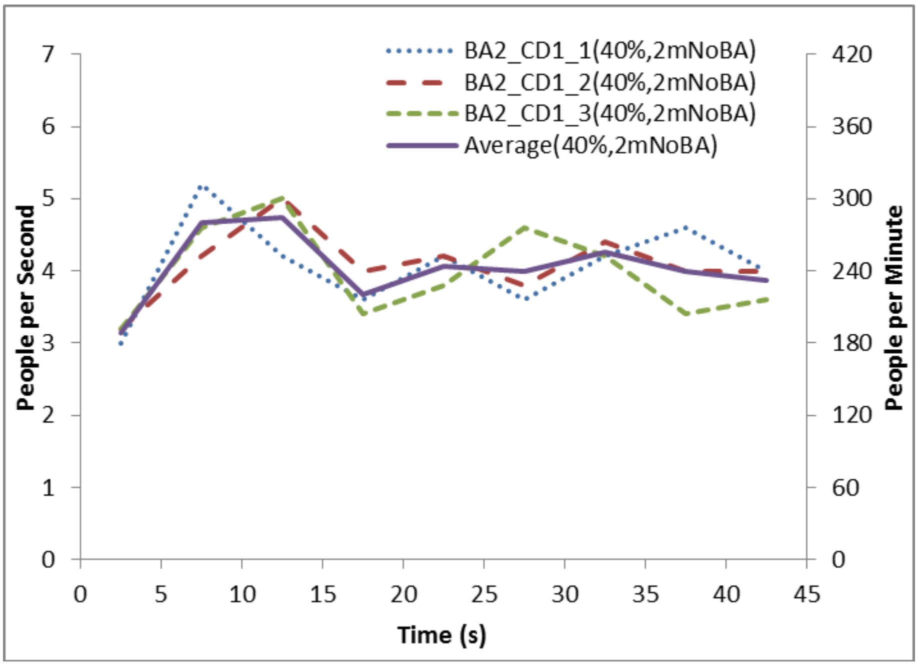


Figure 92: Flow at 2m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials

Table 65: Gap usage (%) at 2m for the three NoBA 40% encumbered trials

Trial	Gap (% Usage)				
	1	2	3	4	5
BA2_CD1_1(40%,2mNoBA)	1.1%	28.4%	41.1%	28.9%	0.5%
BA2_CD1_2(40%,2mNoBA)	0.5%	27.2%	41.4%	29.8%	1.0%
BA2_CD1_3(40%,2mNoBA)	1.6%	26.7%	42.4%	28.8%	0.5%
Average(40%,2mNoBA)	**1.0%**	**27.4%**	**41.6%**	**29.2%**	**0.7%**

Table 66: Flow at 3m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,3mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD1_1(40%,3mNoBA)	144.0	276.0	288.0	216.0	252.0	216.0	276.0	240.0	276.0	252.00
BA2_CD1_2(40%,3mNoBA)	168.0	252.0	300.0	252.0	216.0	240.0	240.0	252.0	276.0	250.29
BA2_CD1_3(40%,3mNoBA)	156.0	288.0	288.0	216.0	228.0	276.0	252.0	204.0	216.0	250.29
Average(40%,3mNoBA)	156.0	272.0	292.0	228.0	232.0	244.0	256.0	232.0	256.0	**250.86**

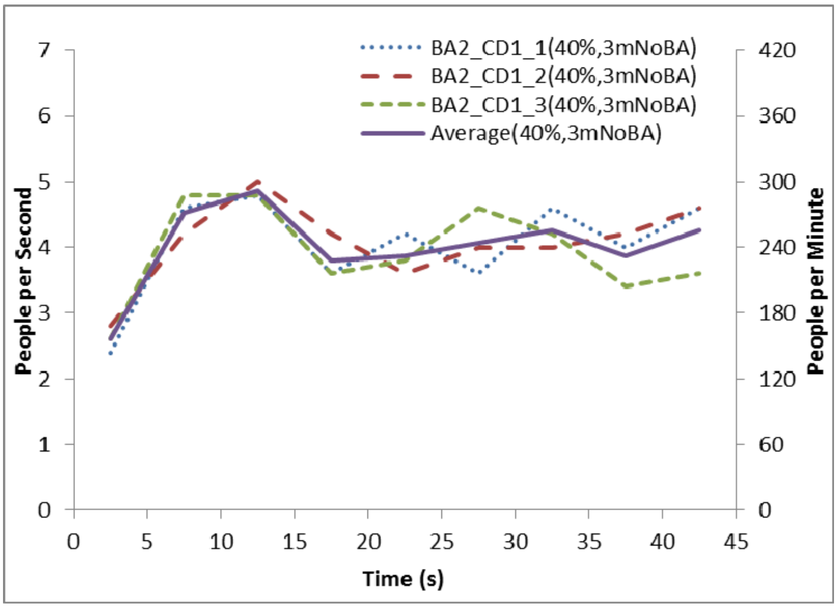


Figure 93: Flow at 3m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials

Table 67: Gap usage (%) at 3m for the three NoBA 40% encumbered trials

Trial	Gap (% Usage)				
	1	2	3	4	5
BA2_CD1_1(40%,3mNoBA)	2.6%	27.9%	37.4%	29.5%	2.6%
BA2_CD1_2(40%,3mNoBA)	5.2%	26.2%	34.0%	29.8%	4.7%
BA2_CD1_3(40%,3mNoBA)	2.6%	27.2%	38.7%	27.7%	3.7%
Average(40%,3mNoBA)	**3.5%**	**27.1%**	**36.7%**	**29.0%**	**3.7%**

Table 68: Flow at 6m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials (data excluded from peak determination highlighted in red)

40%,6mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD1_1(40%,6mNoBA)	48.0	360.0	216.0	240.0	216.0	228.0	228.0	288.0	264.0	253.71
BA2_CD1_2(40%,6mNoBA)	72.0	300.0	264.0	240.0	240.0	228.0	240.0	276.0	264.0	255.43
BA2_CD1_3(40%,6mNoBA)	60.0	264.0	300.0	228.0	252.0	216.0	300.0	192.0	252.0	250.29
Average(40%,6mNoBA)	60.0	308.0	260.0	236.0	236.0	224.0	256.0	252.0	260.0	**253.14**

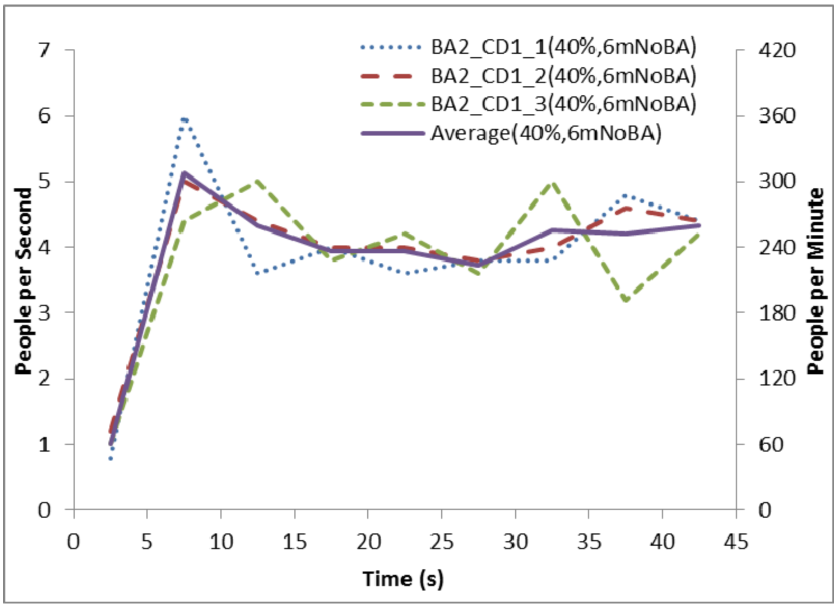


Figure 94: Flow at 6m, measured in 5 sec intervals for the three NoBA, 40% encumbered trials

Table 69: Gap usage (%) at 6m for the three NoBA 40% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD1_1(40%,6mNoBA)	11.6%	25.8%	28.9%	25.3%	8.4%
BA2_CD1_2(40%,6mNoBA)	14.1%	27.2%	22.5%	22.5%	13.6%
BA2_CD1_3(40%,6mNoBA)	11.5%	25.7%	29.8%	25.1%	7.9%
Average(40%,6mNoBA)	**12.4%**	**26.2%**	**27.1%**	**24.3%**	**10.0%**

16.7 TS2: NoBA, 60% participants encumbered with luggage

Table 70: Exit flow measured in 5 sec intervals for the three NoBA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,0mNoBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD2_1(60%,0mNoBA)	276.0	228.0	180.0	240.0	240.0	228.0	228.0	240.0	240.0	226.29
BA2_CD2_2(60%,0mNoBA)	252.0	276.0	252.0	216.0	240.0	240.0	216.0	264.0	192.0	243.43
BA2_CD2_3(60%,0mNoBA)	288.0	288.0	192.0	264.0	204.0	228.0	216.0	228.0	192.0	231.43
Average(60%,0mNoBA)	272.0	264.0	208.0	240.0	228.0	232.0	220.0	244.0	208.0	**233.71**

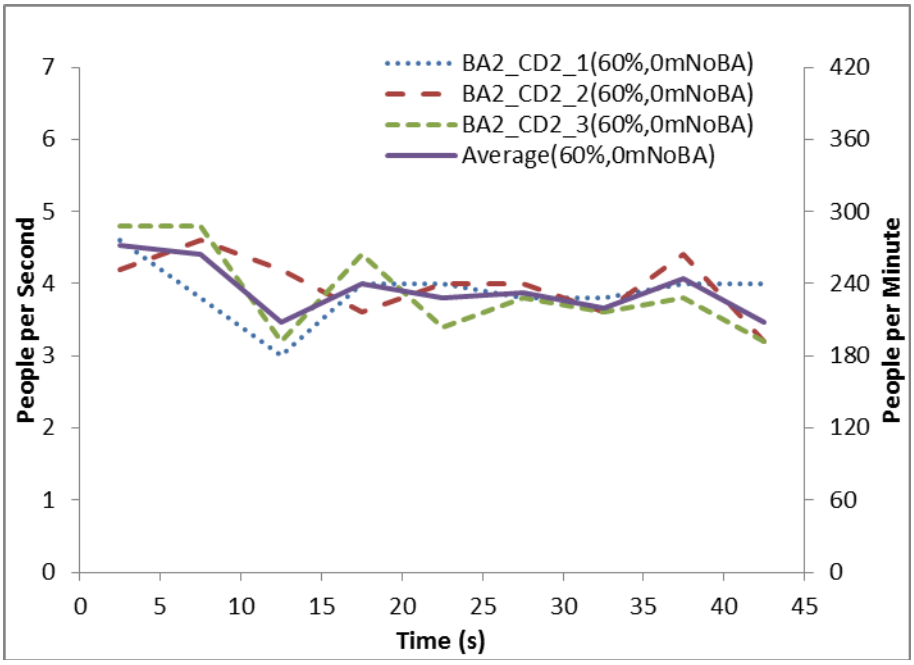


Figure 95: Exit flow measured in 5 sec intervals for the three NoBA, 60% encumbered trials

Table 71: Flow at 1m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,1mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD2_1(60%,1mNoBA)	228.0	240.0	168.0	228.0	276.0	228.0	216.0	240.0	240.0	228.00
BA2_CD2_2(60%,1mNoBA)	228.0	276.0	240.0	228.0	228.0	252.0	216.0	240.0	204.0	240.00
BA2_CD2_3(60%,1mNoBA)	252.0	300.0	192.0	240.0	228.0	216.0	216.0	240.0	180.0	233.14
Average(60%,1mNoBA)	236.0	272.0	200.0	232.0	244.0	232.0	216.0	240.0	208.0	**233.71**

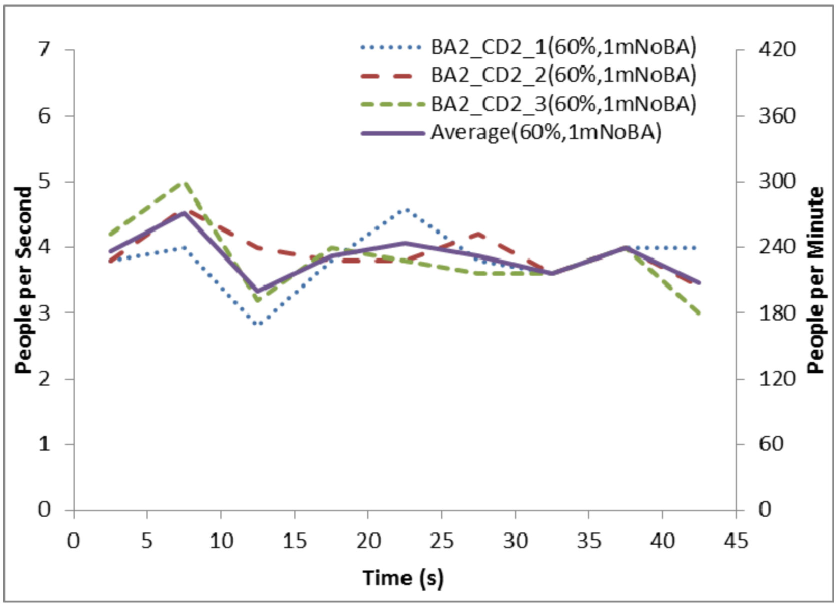


Figure 96: Flow at 1m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials

Table 72: Gap usage (%) at 1m for the three NoBA 60% encumbered trials

Trial	Gap (% Usage)				
	1	2	3	4	5
BA2_CD2_1(60%,1mNoBA)	0.0%	26.8%	46.8%	26.3%	0.0%
BA2_CD2_2(60%,1mNoBA)	0.0%	25.9%	45.0%	29.1%	0.0%
BA2_CD2_3(60%,1mNoBA)	0.0%	25.0%	47.3%	27.7%	0.0%
Average(60%,1mNoBA)	**0.0%**	**25.9%**	**46.4%**	**27.7%**	**0.0%**

Table 73: Flow at 1.5m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,1.5mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD2_1(60%,1.5mNoBA)	192.0	264.0	156.0	252.0	264.0	216.0	228.0	252.0	216.0	233.14
BA2_CD2_2(60%,1.5mNoBA)	204.0	288.0	252.0	180.0	264.0	252.0	204.0	252.0	216.0	241.71
BA2_CD2_3(60%,1.5mNoBA)	228.0	276.0	216.0	264.0	204.0	216.0	216.0	216.0	216.0	229.71
Average(60%,1.5mNoBA)	208.0	276.0	208.0	232.0	244.0	228.0	216.0	240.0	216.0	**234.86**

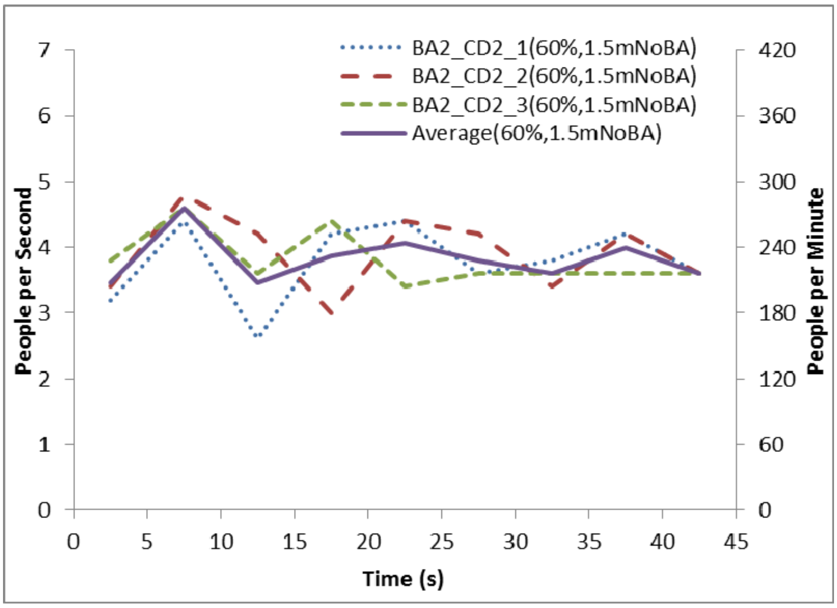


Figure 97: Flow at 1.5m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials

Table 74: Gap usage (%) at 1.5m for the three NoBA 60% encumbered trials

Trial	Gap (% Usage)				
	1	2	3	4	5
BA2_CD2_1(60%,1.5mNoBA)	0.0%	26.8%	45.3%	27.9%	0.0%
BA2_CD2_2(60%,1.5mNoBA)	0.0%	28.6%	41.8%	29.6%	0.0%
BA2_CD2_3(60%,1.5mNoBA)	0.0%	25.0%	46.8%	28.2%	0.0%
Average(60%,1.5mNoBA)	**0.0%**	**26.8%**	**44.6%**	**28.6%**	**0.0%**

Table 75: Flow at 2m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,2mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD2_1(60%,2mNoBA)	192.0	240.0	180.0	240.0	264.0	204.0	240.0	252.0	216.0	231.43
BA2_CD2_2(60%,2mNoBA)	204.0	264.0	264.0	192.0	252.0	264.0	168.0	264.0	228.0	238.29
BA2_CD2_3(60%,2mNoBA)	192.0	312.0	216.0	240.0	216.0	216.0	216.0	228.0	192.0	234.86
Average(60%,2mNoBA)	196.0	272.0	220.0	224.0	244.0	228.0	208.0	248.0	212.0	**234.86**

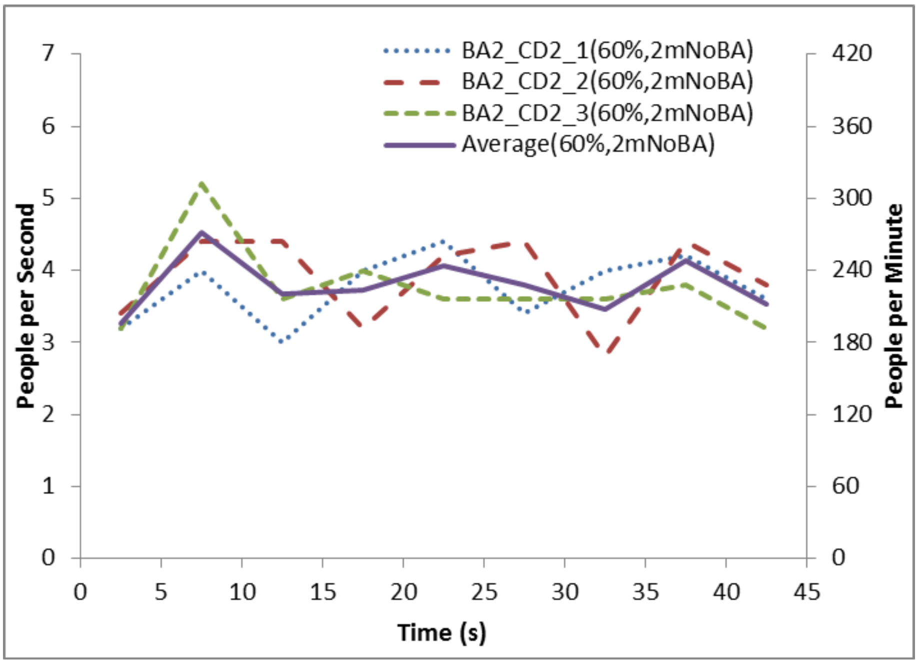


Figure 98: Flow at 2m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials

Table 76: Gap usage (%) at 2m for the three NoBA 60% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD2_1(60%,2mNoBA)	1.1%	28.9%	42.6%	25.3%	2.1%
BA2_CD2_2(60%,2mNoBA)	1.1%	29.6%	39.7%	29.1%	0.5%
BA2_CD2_3(60%,2mNoBA)	0.0%	29.3%	41.5%	29.3%	0.0%
Average(60%,2mNoBA)	**0.7%**	**29.3%**	**41.3%**	**27.9%**	**0.9%**

Table 77: Flow at 3m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,3mNoBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD2_1(60%,3mNoBA)	168.0	252.0	180.0	204.0	300.0	204.0	240.0	228.0	204.0	229.71
BA2_CD2_2(60%,3mNoBA)	156.0	288.0	252.0	192.0	252.0	252.0	204.0	264.0	192.0	243.43
BA2_CD2_3(60%,3mNoBA)	180.0	288.0	228.0	240.0	228.0	204.0	228.0	216.0	180.0	233.14
Average(60%,3mNoBA)	168.0	276.0	220.0	212.0	260.0	220.0	224.0	236.0	192.0	**235.43**

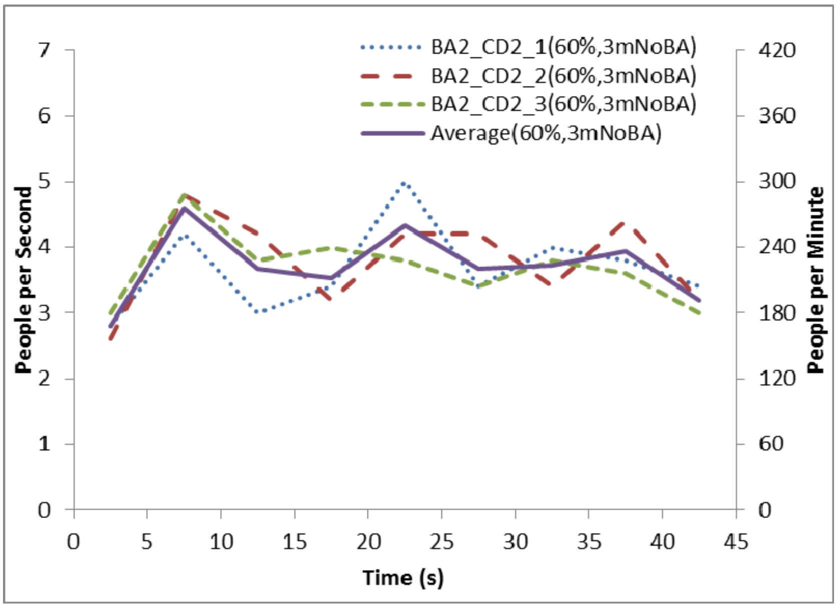


Figure 99: Flow at 3m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials

Table 78: Gap usage (%) at 3m for the three NoBA 60% encumbered trials

Trial	Gap (% Usage)				
	1	2	3	4	5
BA2_CD2_1(60%,3mNoBA)	3.7%	26.3%	40.0%	24.7%	5.3%
BA2_CD2_2(60%,3mNoBA)	2.6%	29.6%	36.5%	25.9%	5.3%
BA2_CD2_3(60%,3mNoBA)	3.2%	27.7%	37.8%	26.6%	4.8%
Average(60%,3mNoBA)	**3.2%**	**27.9%**	**38.1%**	**25.8%**	**5.1%**

Table 79: Flow at 6m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials (data excluded from peak determination highlighted in red)

60%,6mNoBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD2_1(60%,6mNoBA)	108.0	276.0	168.0	216.0	240.0	216.0	204.0	228.0	240.0	221.14
BA2_CD2_2(60%,6mNoBA)	84.0	240.0	300.0	228.0	216.0	264.0	192.0	240.0	216.0	240.00
BA2_CD2_3(60%,6mNoBA)	72.0	276.0	276.0	240.0	228.0	180.0	240.0	216.0	204.0	236.57
Average(60%,6mNoBA)	88.0	264.0	248.0	228.0	228.0	220.0	212.0	228.0	220.0	**232.57**

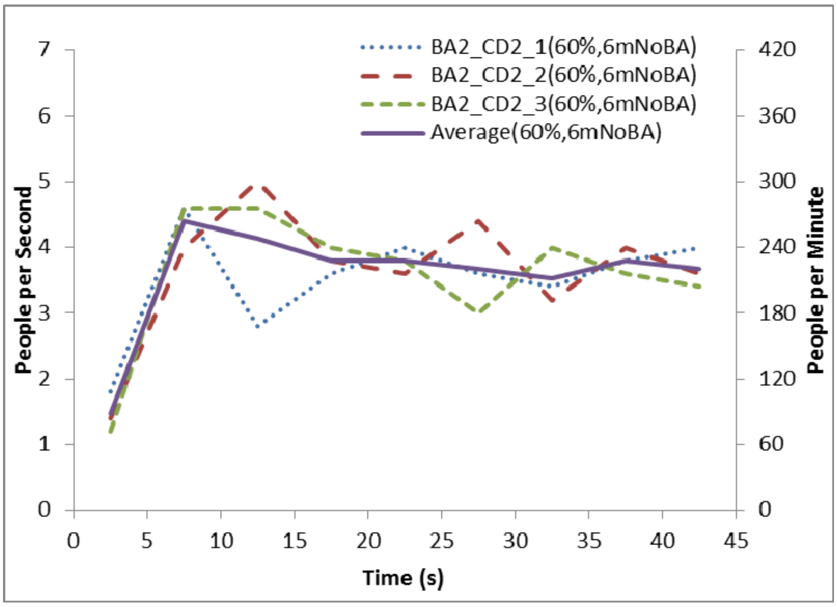


Figure 100: Flow at 6m, measured in 5 sec intervals for the three NoBA, 60% encumbered trials

Table 80: Gap usage (%) at 6m for the three NoBA 60% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD2_1(60%,6mNoBA)	11.1%	25.3%	28.4%	24.7%	10.5%
BA2_CD2_2(60%,6mNoBA)	11.1%	28.0%	27.5%	22.2%	11.1%
BA2_CD2_3(60%,6mNoBA)	11.2%	26.1%	25.0%	28.2%	9.6%
Average(60%,6mNoBA)	**11.1**	**26.5**	**27.0**	**25.1**	**10.4**

16.8 TS2: No BA, 0% participants encumbered with luggage

Table 81: Exit flow measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

0m,NoBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD0_1(0mNoBA)	300.0	324.0	288.0	312.0	216.0	252.0	216.0	228.0	132.0	268.00
BA2_CD0_2(0mNoBA)	300.0	384.0	312.0	276.0	264.0	204.0	240.0	192.0	120.0	280.00
BA2_CD0_3(0mNoBA)	384.0	372.0	348.0	288.0	252.0	252.0	204.0	144.0	36.0	286.00
Average(0mNoBA)	328.0	360.0	316.0	292.0	244.0	236.0	220.0	188.0	96.0	**278.00**

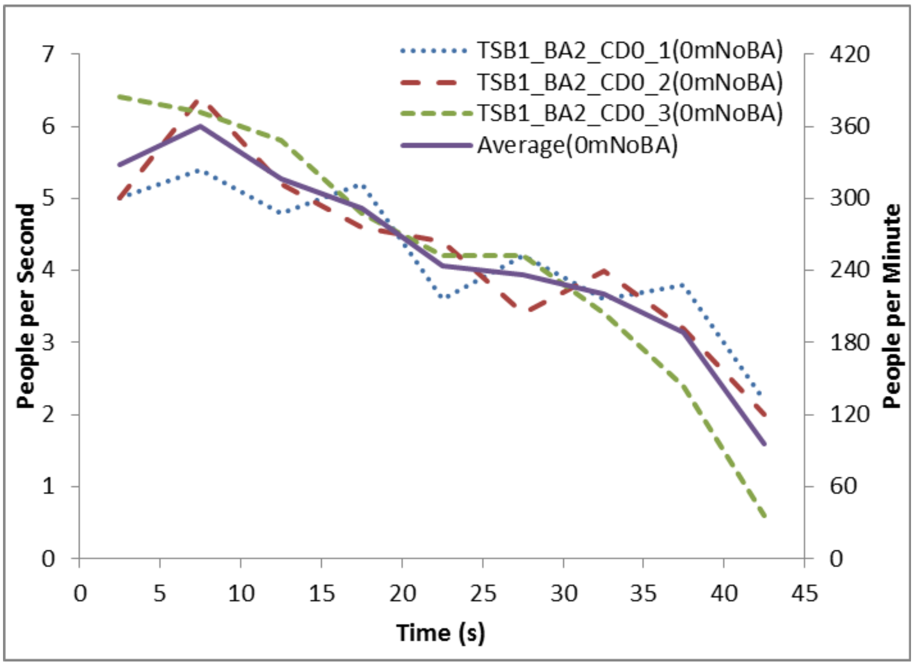


Figure 101: Exit flow measured in 5 sec intervals for the three NoBA, 0% encumbered trials

Table 82: Flow at 1m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

1m,NoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD0_1(1mNoBA)	264.0	348.0	264.0	300.0	240.0	252.0	204.0	252.0	132.0	268.00
BA2_CD0_2(1mNoBA)	288.0	360.0	300.0	276.0	288.0	204.0	228.0	192.0	156.0	276.00
BA2_CD0_3(1mNoBA)	360.0	384.0	348.0	276.0	252.0	228.0	228.0	144.0	60.0	286.00
Average(1mNoBA)	304.0	364.0	304.0	284.0	260.0	228.0	220.0	196.0	116.0	**276.67**

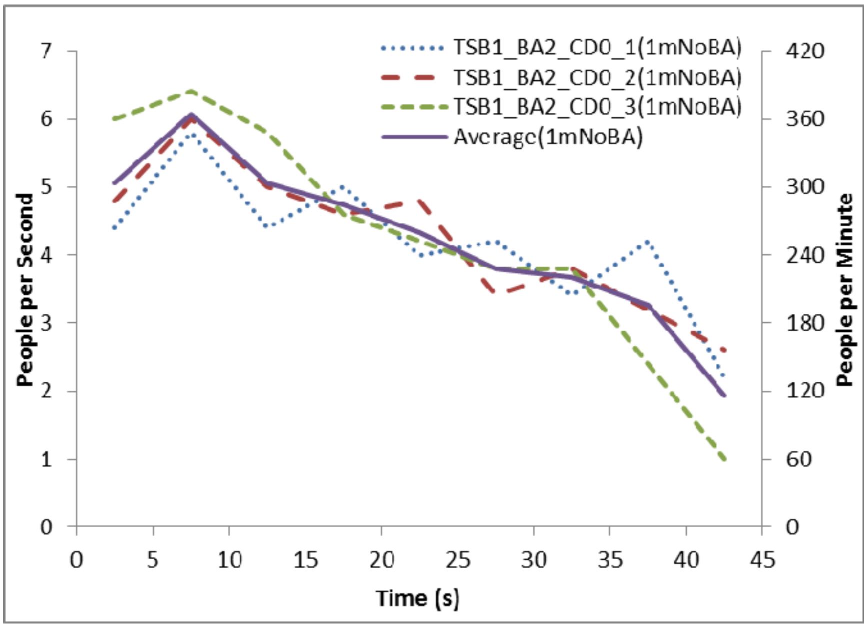


Figure 102: Flow at 1m, measured in 5 sec intervals for the NoBA, 0% encumbered trials

Table 83: Density at 1m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

2.4mExit,1mNoBA		**Density Time Step (sec)**									**Peak Average (p/m2)**
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
BA2_CD0_1 (1mNoBA)	A										
	B	0.00	0.89	0.89	0.89	1.03	0.89	0.89	0.89	0.59	0.92
	C										
	Total	0.00	0.89	0.89	0.89	1.03	0.89	0.89	0.89	0.59	0.92
BA2_CD0_2 (1mNoBA)	A										
	B	0.00	0.89	1.03	0.74	1.03	0.89	0.89	0.89	0.59	0.92
	C										
	Total	0.00	0.89	1.03	0.74	1.03	0.89	0.89	0.89	0.59	0.92
BA2_CD0_3 (1mNoBA)	A										
	B	0.00	1.18	0.89	0.74	0.89	0.74	0.89	0.74	0.59	0.92
	C										
	Total	0.00	1.18	0.89	0.74	0.89	0.74	0.89	0.74	0.59	0.92
Average Area B (2.4mExit,1mNoBA)		0.00	0.00	0.99	0.94	0.79	0.99	0.84	0.89	0.84	0.59

Table 84: Gap usage (%) at 1m for the three NoBA 0% encumbered trials

Trial	**Gap (% Usage)**				
	1	**2**	**3**	**4**	**5**
BA2_CD0_1(1mNoBA)	0.0%	25.4%	47.6%	27.0%	0.0%
BA2_CD0_2(1mNoBA)	0.0%	28.8%	45.0%	26.2%	0.0%
BA2_CD0_3(1mNoBA)	0.0%	24.6%	48.7%	26.7%	0.0%
Average(1mNoBA)	**0.0%**	**26.3%**	**47.1%**	**26.6%**	**0.0%**

Table 85: Flow at 1.5m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

1.5m,NoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD0_1(1.5mNoBA)	252.0	324.0	300.0	300.0	216.0	252.0	216.0	252.0	144.0	268.00
BA2_CD0_2(1.5mNoBA)	264.0	348.0	324.0	276.0	288.0	192.0	240.0	204.0	156.0	278.00
BA2_CD0_3(1.5mNoBA)	336.0	396.0	324.0	276.0	276.0	228.0	216.0	156.0	72.0	286.00
Average(1.5mNoBA)	284.0	356.0	316.0	284.0	260.0	224.0	224.0	204.0	124.0	**277.33**

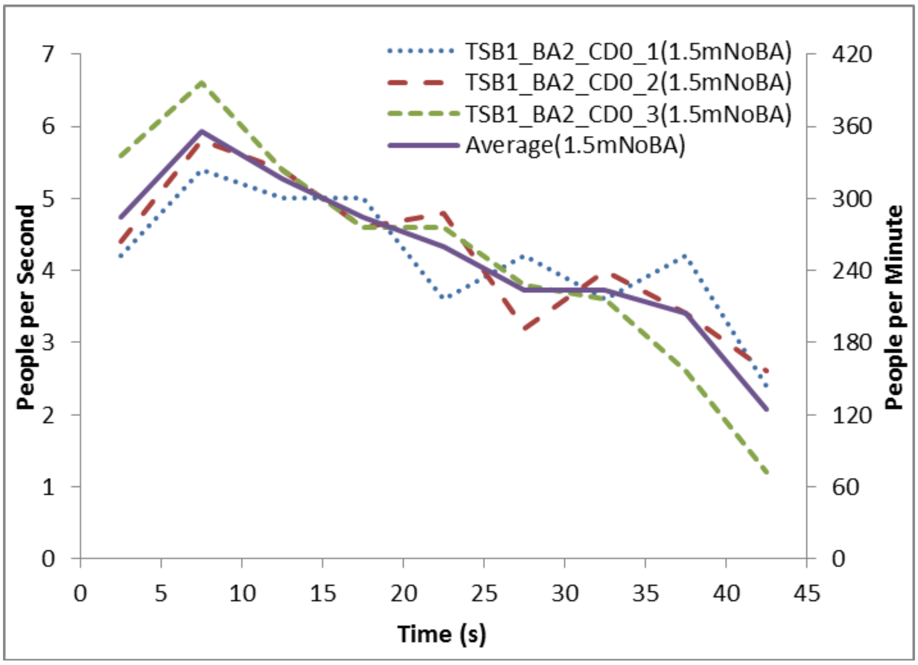


Figure 103: Flow at 1.5m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials

Table 86: Gap usage (%) at 1.5m for the three NoBA 0% encumbered trials

Trial	**Gap (% Usage)**				
	1	**2**	**3**	**4**	**5**
BA2_CD0_1(1.5mNoBA)	0.0%	26.5%	43.9%	29.6%	0.0%
BA2_CD0_2(1.5mNoBA)	0.0%	29.3%	42.9%	27.7%	0.0%
BA2_CD0_3(1.5mNoBA)	0.0%	25.7%	47.1%	26.7%	0.5%
Average(1.5mNoBA)	**0.0%**	**27.1%**	**44.7%**	**28.0%**	**0.2%**

Table 87: Flow at 2m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

2m,NoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD0_1(2mNoBA)	228.0	324.0	300.0	288.0	252.0	240.0	204.0	252.0	168.0	268.00
BA2_CD0_2(2mNoBA)	240.0	372.0	324.0	264.0	264.0	216.0	240.0	204.0	144.0	280.00
BA2_CD0_3(2mNoBA)	324.0	372.0	360.0	276.0	264.0	228.0	216.0	156.0	84.0	286.00
Average(2mNoBA)	264.0	356.0	328.0	276.0	260.0	228.0	220.0	204.0	132.0	**278.00**

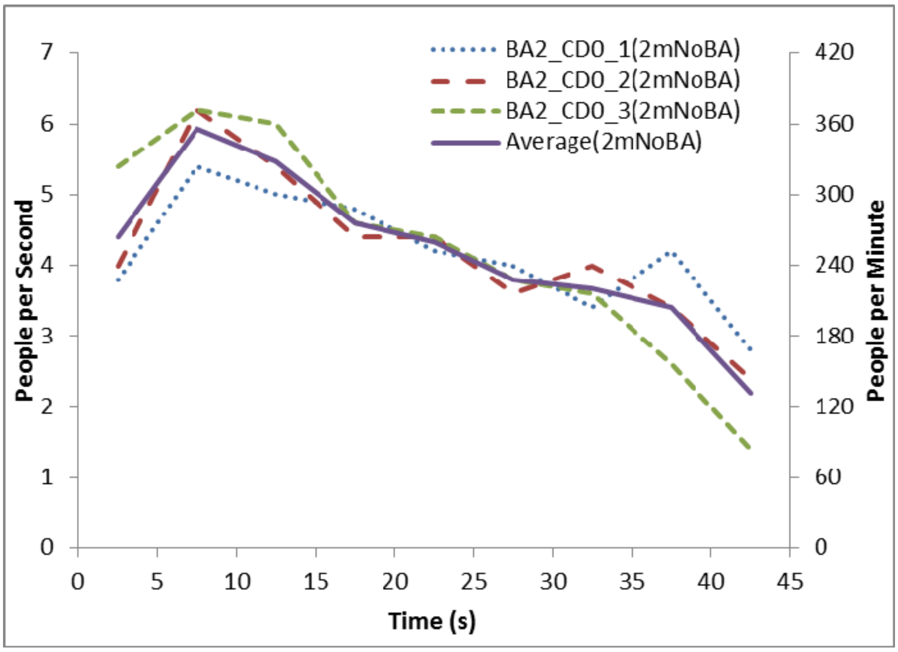


Figure 104: Flow at 2m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials

Table 88: Density at 2m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

2.4mExit,2mNoBA		**Density Time Step (sec)**									**Peak Average (p/m2)**
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
BA2_CD0_1 (2mNoBA)	A										
	B	0.00	1.03	0.89	0.89	0.89	0.59	1.03	0.74	0.89	0.92
	C										
	Total	0.00	1.03	0.89	0.89	0.89	0.59	1.03	0.74	0.89	0.92
BA2_CD0_2 (2mNoBA)	A										
	B	0.59	1.18	0.89	0.74	1.03	0.74	1.18	0.44	0.30	0.96
	C										
	Total	0.59	1.18	1.03	0.74	1.03	0.74	1.18	0.44	0.30	1.00

BA2_CD0_3 (2mNoBA)	A										
	B	0.44	1.03	0.74	1.03	0.74	0.74	1.03	0.30	0.15	0.89
	C										
	Total	0.59	1.18	0.89	1.03	0.74	0.74	1.03	0.30	0.15	0.96
Average Area B (2.4mExit,2mNoBA)		0.00	0.34	1.08	0.84	0.89	0.89	0.69	1.08	0.49	0.44

Table 89: Gap usage (%) at 2m for the three NoBA 0% encumbered trials

Trial	**Gap (% Usage)**				
	1	**2**	**3**	**4**	**5**
BA2_CD0_1(2mNoBA)	0.5%	27.5%	42.3%	29.1%	0.5%
BA2_CD0_2(2mNoBA)	0.0%	33.0%	36.6%	29.3%	1.0%
BA2_CD0_3(2mNoBA)	0.5%	27.2%	43.5%	26.2%	2.6%
Average(2mNoBA)	**0.4%**	**29.2%**	**40.8%**	**28.2%**	**1.4%**

Table 90: Flow at 3m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

3m,NoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD0_1(3mNoBA)	192.0	348.0	276.0	300.0	252.0	228.0	216.0	240.0	192.0	270.00
BA2_CD0_2(3mNoBA)	240.0	336.0	312.0	288.0	264.0	216.0	216.0	240.0	156.0	272.00
BA2_CD0_3(3mNoBA)	288.0	360.0	360.0	264.0	300.0	216.0	216.0	192.0	72.0	286.00
Average(3mNoBA)	240.0	348.0	316.0	284.0	272.0	220.0	216.0	224.0	140.0	**276.00**

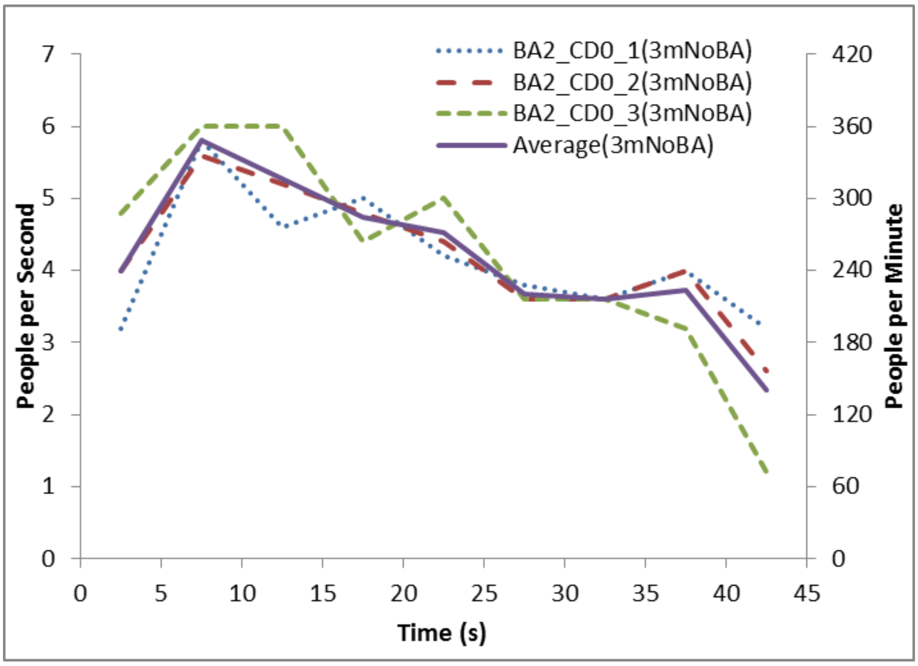


Figure 105: Flow at 3m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials

Table 91: Gap usage (%) at 3m for the three NoBA 0% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD0_1(3mNoBA)	2.6%	29.1%	36.0%	29.6%	2.6%
BA2_CD0_2(3mNoBA)	2.1%	33.0%	33.0%	27.7%	4.2%
BA2_CD0_3(3mNoBA)	3.7%	28.3%	35.1%	26.2%	6.8%
Average(3mNoBA)	**2.8%**	**30.1%**	**34.7%**	**27.9%**	**4.5%**

Table 92: Flow at 6m, measured in 5 sec intervals for the three NoBA, 0% encumbered trials (data excluded from peak determination highlighted in red)

6m,NoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
BA2_CD0_1(6mNoBA)	84.0	312.0	312.0	276.0	300.0	204.0	252.0	192.0	228.0	276.00
BA2_CD0_2(6mNoBA)	108.0	360.0	324.0	312.0	252.0	252.0	192.0	240.0	144.0	282.00
BA2_CD0_3(6mNoBA)	180.0	360.0	360.0	264.0	312.0	252.0	192.0	216.0	108.0	290.00
Average(6mNoBA)	124.0	344.0	332.0	284.0	288.0	236.0	212.0	216.0	160.0	**282.67**

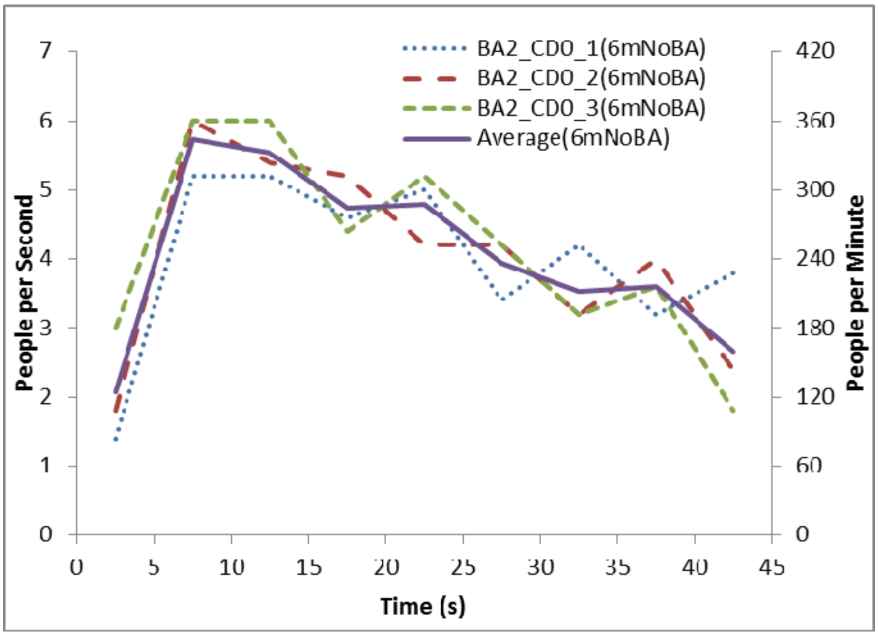


Figure 106: Flow at 6m measured in 5 sec intervals for the three NoBA, 0% encumbered trials

Table 93: Gap usage (%) at 6m for the three NoBA 0% encumbered trials

Trial	Gap (% Usage)				
	1	**2**	**3**	**4**	**5**
BA2_CD0_1(6mNoBA)	13.2%	24.3%	27.5%	25.9%	9.0%
BA2_CD0_2(6mNoBA)	12.6%	26.7%	26.7%	24.1%	9.9%
BA2_CD0_3(6mNoBA)	14.1%	25.1%	25.7%	23.6%	11.5%
Average(6mNoBA)	**13.3%**	**25.4%**	**26.6%**	**24.5%**	**10.2%**

16.9 TS3: Exit width (EW) 3.5m and 1m standoff

Table 94: Exit flow measured in 5 sec intervals for the three 3.5m EW, 1m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,1mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD1_EW2_1(3.5mExit,1mBA)	372.0	432.0	444.0	372.0	420.0	432.0	396.0	0.0	0.0	416.00
SD1_EW2_2(3.5mExit,1mBA)	372.0	408.0	408.0	408.0	420.0	396.0	372.0	108.0	0.0	402.00
SD1_EW2_2(3.5mExit,1mBA)	300.0	420.0	396.0	360.0	384.0	396.0	336.0	300.0	0.0	391.20
Average(3.5mExit,1mBA)	348.0	420.0	416.0	380.0	408.0	408.0	384.0	136.0	0.0	**403.07**

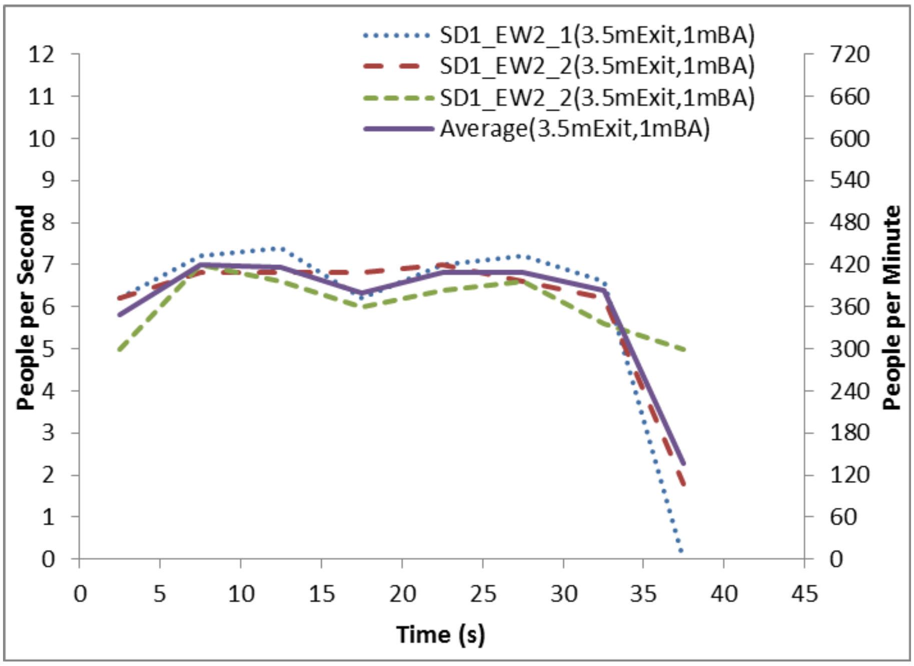


Figure 107: Exit flow measured in 5 sec intervals for the three 3.5m EW, 1m BA trials

Table 95: BA flow measured in 5 sec intervals for the three 3.5m EW, 1m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,1mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD1_EW2_1(3.5mExit,1mBA)	324.0	432.0	420.0	384.0	408.0	456.0	420.0	24.0	0.0	420.00
SD1_EW2_2(3.5mExit,1mBA)	300.0	420.0	408.0	408.0	432.0	372.0	408.0	132.0	12.0	408.00
SD1_EW2_2(3.5mExit,1mBA)	264.0	360.0	420.0	360.0	396.0	384.0	372.0	336.0	0.0	384.00
Average(3.5mExit,1mBA)	296.0	404.0	416.0	384.0	412.0	404.0	400.0	164.0	4.0	**404.00**

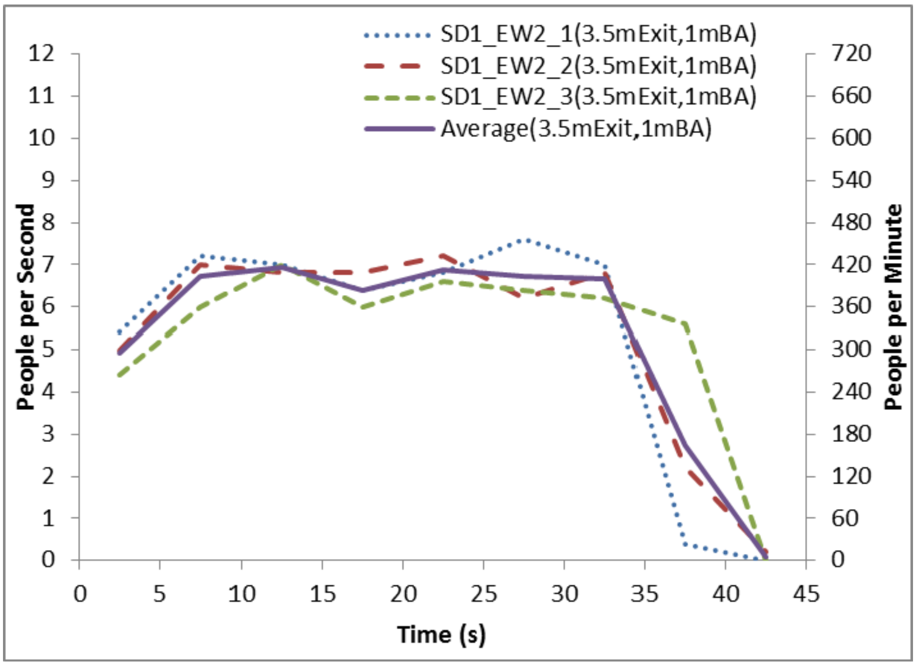


Figure 108: BA flow measured in 5 sec intervals for the three 3.5m EW, 1m BA trials

Table 96: Density measured in 5 sec intervals for the three 3.5m EW, 1m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,1mBA		Density Time Step (sec)									Peak Average (p/m2)
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
SD1_EW2_1 (3.5mExit,1mBA)	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	B	0.00	1.20	1.35	1.35	1.20	1.35	1.35	0.90	0.00	1.29
	C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	0.00	0.72	0.81	0.81	0.72	0.81	0.81	0.54	0.00	0.78
SD1_EW2_2 (3.5mExit,1mBA)	A	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.45	0.00	0.09
	B	0.00	1.20	1.20	1.20	1.20	1.35	1.20	1.05	0.15	1.23
	C	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.09
	Total	0.00	0.72	0.81	0.72	0.81	0.81	0.72	0.72	0.09	0.78
SD1_EW2_3 (3.5mExit,1mBA)	A	0.00	0.00	0.45	0.90	0.00	0.00	0.00	0.00	0.00	0.27
	B	0.00	1.20	1.20	1.05	0.90	0.90	1.20	0.75	0.15	1.05
	C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	0.00	0.72	0.81	0.81	0.54	0.54	0.72	0.45	0.09	0.69
Average Total (3.5mExit,1mBA)		0.00	0.72	0.81	0.78	0.69	0.72	0.75	0.57	0.06	0.75
Average Area B (3.5mExit,1mBA)		0.00	1.20	1.25	1.20	1.10	1.20	1.25	0.90	0.10	1.19

Table 97: Gap usage (%) at 1m for the three 3.5mExit, 1mBA trials

Trial	Gap (% Usage)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SD1_EW2_1(3.5mExit,1mBA)	0.0%	0.0%	0.4%	31.8%	36.4%	29.7%	1.7%	0.0%	0.0%
SD1_EW2_2(3.5mExit,1mBA)	0.0%	0.0%	1.7%	29.0%	38.2%	29.5%	1.7%	0.0%	0.0%
SD1_EW2_2(3.5mExit,1mBA)	0.0%	0.0%	3.7%	27.4%	37.3%	29.9%	1.7%	0.0%	0.0%
Average(3.5mExit,1mBA)	0.0%	0.0%	1.9%	29.4%	37.3%	29.7%	1.7%	0.0%	0.0%

16.10 TS3: Exit width (EW) 3.5m and 2m standoff

Table 98: Exit flow measured in 5 sec intervals for the three 3.5m EW, 2m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,2mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD2_EW2_1(3.5mExit,2mBA)	372.0	384.0	396.0	360.0	336.0	360.0	360.0	264.0	24.0	367.20
SD2_EW2_2(3.5mExit,2mBA)	312.0	432.0	396.0	384.0	372.0	324.0	348.0	264.0	36.0	381.60
SD2_EW2_2(3.5mExit,2mBA)	360.0	336.0	408.0	384.0	336.0	360.0	372.0	288.0	36.0	364.80
Average(3.5mExit,2mBA)	348.0	384.0	400.0	376.0	348.0	348.0	360.0	272.0	32.0	**371.20**

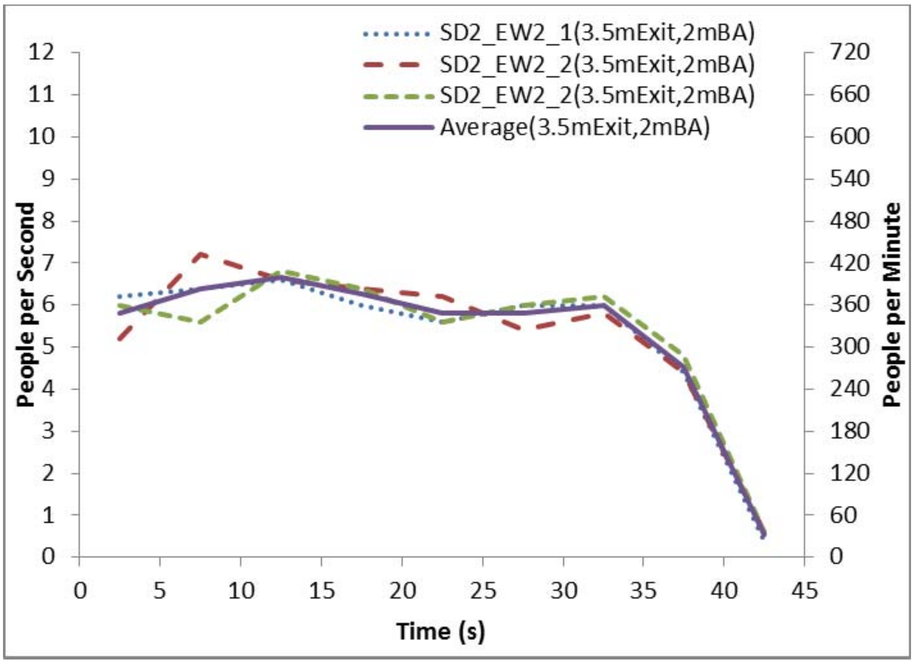


Figure 109: Exit flow measured in 5 sec intervals for the three 3.5m EW, 2m BA trials

Table 99: BA flow measured in 5 sec intervals for the three 3.5m EW, 2m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,2mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD2_EW2_1(3.5mExit,2mBA)	264.0	372.0	396.0	384.0	348.0	348.0	360.0	324.0	60.0	369.60
SD2_EW2_2(3.5mExit,2mBA)	240.0	396.0	396.0	408.0	348.0	348.0	336.0	336.0	60.0	379.20
SD2_EW2_2(3.5mExit,2mBA)	288.0	336.0	408.0	384.0	360.0	312.0	384.0	336.0	72.0	360.00
Average(3.5mExit,2mBA)	264.0	368.0	400.0	392.0	352.0	336.0	360.0	332.0	64.0	**369.60**

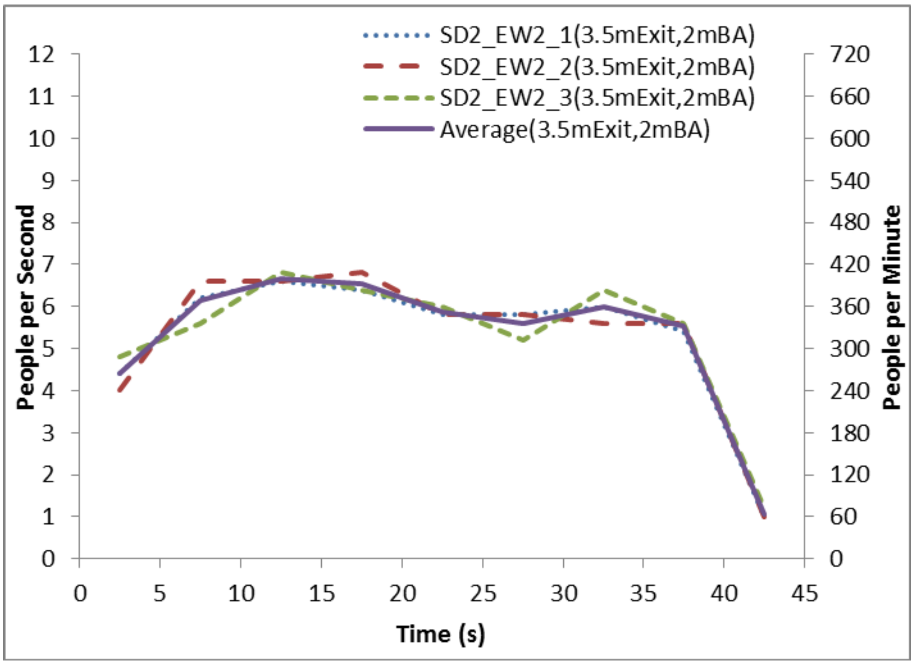


Figure 110: BA flow measured in 5 sec intervals for the three 3.5m EW, 2m BA trials

Table 100: Density measured in 5 sec intervals for the three 3.5m EW, 2m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,2mBA		Density Time Step (sec)									Peak Average
Trial	Region	0	5	10	15	20	25	30	35	40	(p/m2)
SD1_EW2_1 (3.5mExit,2mBA)	A	0.00	0.00	0.45	0.00	0.45	0.45	0.00	0.00	0.00	0.27
	B	0.00	1.05	0.90	1.35	0.90	0.90	0.90	0.75	0.90	1.02
	C	0.00	0.00	0.00	0.00	0.45	0.45	0.00	0.45	0.45	0.18
	Total	0.00	0.63	0.63	0.81	0.72	0.72	0.54	0.54	0.63	0.70
SD1_EW2_2 (3.5mExit,2mBA)	A	0.00	0.45	0.00	1.35	0.45	0.45	0.45	0.45	0.45	0.54
	B	0.00	0.90	0.90	1.05	0.90	1.05	0.75	0.90	0.75	0.96
	C	0.00	0.45	0.45	0.00	0.45	0.00	0.90	0.90	0.00	0.27
	Total	0.00	0.72	0.63	0.90	0.72	0.72	0.72	0.81	0.54	0.74
SD1_EW2_3 (3.5mExit,2mBA)	A	0.00	0.45	0.00	0.45	0.45	0.45	0.45	0.90	0.90	0.36
	B	0.00	0.90	0.60	0.75	0.75	0.75	0.90	1.05	0.60	0.75
	C	0.00	0.00	0.45	0.45	0.00	0.00	0.45	0.00	0.00	0.18
	Total	0.00	0.63	0.45	0.63	0.54	0.54	0.72	0.81	0.54	0.56
Average Total (3.5mExit,2mBA)		0.00	0.66	0.57	0.78	0.66	0.66	0.66	0.72	0.57	0.67
Average Area B (3.5mExit,2mBA)		0.00	0.95	0.80	1.05	0.85	0.90	0.85	0.90	0.75	0.91

Table 101: Gap usage (%) at 2m for the three 3.5mExit, 2mBA trials

	Gap (% Usage)								
Trial	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SD2_EW2_1(3.5mExit,2mBA)	0.0%	0.0%	7.1%	24.4%	36.1%	26.1%	6.3%	0.0%	0.0%
SD2_EW2_2(3.5mExit,2mBA)	0.0%	0.0%	9.2%	25.1%	33.9%	24.3%	7.5%	0.0%	0.0%
SD2_EW2_2(3.5mExit,2mBA)	0.0%	0.0%	10.0%	24.2%	34.6%	24.6%	6.7%	0.0%	0.0%
Average(3.5mExit,2mBA)	0.0%	0.0%	8.8%	24.5%	34.9%	25.0%	6.8%	0.0%	0.0%

16.11 TS3: Exit width (EW) 3.5m and 3m standoff

Table 102: Exit flow measured in 5 sec intervals for the three 3.5m EW, 3m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,3mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD3_EW2_1(3.5mExit,3mBA)	420.0	420.0	444.0	384.0	372.0	348.0	144.0	0.0	0.0	393.60
SD3_EW2_2(3.5mExit,3mBA)	360.0	396.0	384.0	408.0	408.0	372.0	360.0	0.0	0.0	393.60
SD3_EW2_2(3.5mExit,3mBA)	372.0	396.0	372.0	420.0	384.0	360.0	384.0	120.0	0.0	386.40
Average(3.5mExit,3mBA)	384.0	404.0	400.0	404.0	388.0	360.0	296.0	40.0	0.0	**391.20**

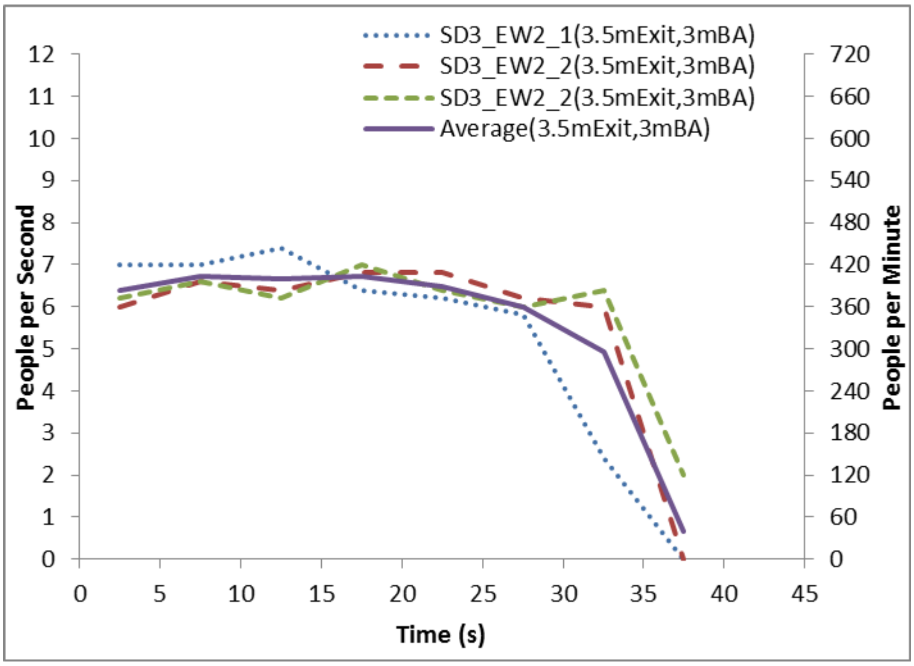


Figure 111: Exit flow measured in 5 sec intervals for the three 3.5m EW, 3m BA trials

Table 103: BA flow measured in 5 sec intervals for the three 3.5m EW, 3m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,3mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD3_EW2_1(3.5mExit,3mBA)	240.0	420.0	420.0	408.0	420.0	420.0	204.0	0.0	0.0	417.60
SD3_EW2_2(3.5mExit,3mBA)	216.0	444.0	348.0	444.0	360.0	360.0	408.0	108.0	0.0	391.20
SD3_EW2_2(3.5mExit,3mBA)	240.0	396.0	372.0	408.0	396.0	348.0	384.0	264.0	0.0	384.00
Average(3.5mExit,3mBA)	232.0	420.0	380.0	420.0	392.0	376.0	332.0	124.0	0.0	**397.60**

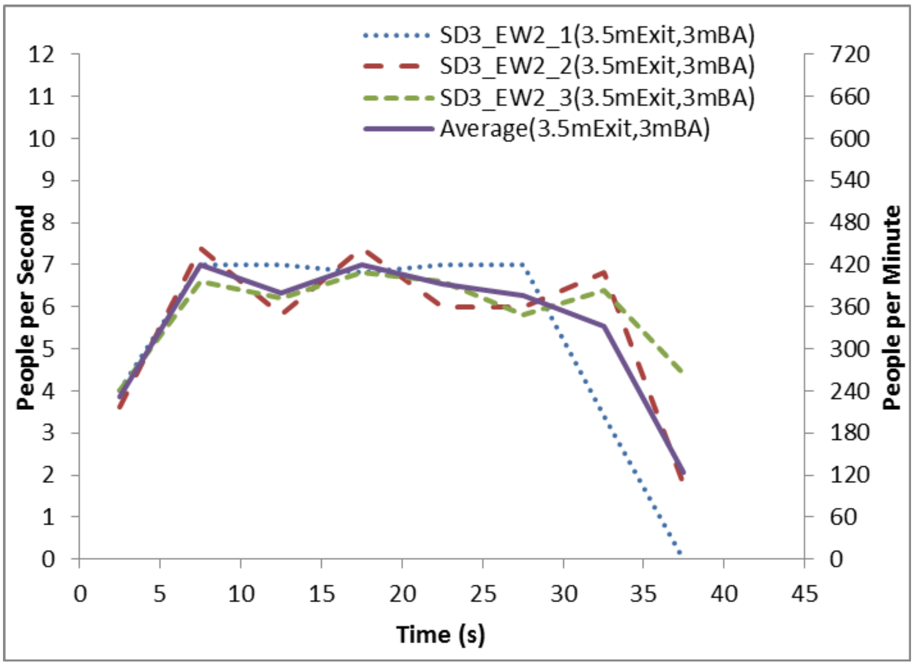


Figure 112: BA flow measured in 5 sec intervals for the three 3.5m EW, 3m BA trials

Table 104: Density measured in 5 sec intervals for the three 3.5m EW, 3m BA trials (data excluded from peak determination highlighted in red)

3.5mExit,3mBA		Density Time Step (sec)									Peak Average (p/m2)
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
SD1_EW2_1 (3.5mExit,3mBA)	A	0.00	0.45	0.00	0.45	0.45	0.90	0.45	0.00	0.00	0.45
	B	0.00	1.35	0.90	0.60	0.90	0.60	0.60	0.00	0.00	0.87
	C	0.00	0.00	0.45	0.90	0.45	0.00	0.45	0.45	0.00	0.36
	Total	0.00	0.90	0.63	0.63	0.72	0.54	0.54	0.09	0.00	0.69
SD1_EW2_2 (3.5mExit,3mBA)	A	0.00	0.90	0.45	0.90	0.45	0.45	0.45	0.00	0.00	0.63
	B	0.00	0.60	0.75	0.60	1.05	0.90	0.75	1.05	0.00	0.78
	C	0.00	0.00	0.45	0.45	0.45	0.45	0.45	0.00	0.00	0.36
	Total	0.00	0.54	0.63	0.63	0.81	0.72	0.63	0.63	0.00	0.67
SD1_EW2_3 (3.5mExit,3mBA)	A	0.00	0.45	0.00	0.90	0.45	0.45	0.00	0.45	0.00	0.45
	B	0.00	0.60	0.75	0.90	0.75	0.90	0.75	0.75	0.00	0.78
	C	0.00	0.90	0.45	0.00	0.45	0.00	0.00	0.45	0.00	0.36
	Total	0.00	0.63	0.54	0.72	0.63	0.63	0.45	0.63	0.00	0.63
Average Total (3.5mExit,3mBA)		0.00	0.69	0.60	0.66	0.72	0.63	0.54	0.45	0.00	0.66
Average Area B (3.5mExit,3mBA)		0.00	0.85	0.80	0.70	0.90	0.80	0.70	0.60	0.00	0.81

Table 105: Gap usage (%) at 3m for the three 3.5mExit, 3mBA trials

Trial	**Gap (% Usage)**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SD3_EW2_1 (3.5mExit,3mBA)	0.0%	0.5%	12.8%	24.2%	28.4%	21.8%	11.8%	0.5%	0.0%
SD3_EW2_2 (3.5mExit,3mBA)	0.0%	0.0%	11.2%	23.2%	31.3%	21.9%	12.5%	0.0%	0.0%
SD3_EW2_2 (3.5mExit,3mBA)	0.0%	0.4%	12.4%	22.2%	30.8%	23.5%	10.7%	0.0%	0.0%
Average(3.5mExit,3mBA)	0.0%	0.3%	12.1%	23.2%	30.2%	22.4%	11.7%	0.2%	0.0%

16.12 TS3: Exit width (EW) 4.5m and 1m standoff

Table 106: Exit flow measured in 5 sec intervals for the three 4.5m EW, 1m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,1mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD1_EW1_1(4.5mExit,1mBA)	420.0	504.0	444.0	504.0	468.0	456.0	96.0	0.0	0.0	475.20
SD1_EW1_2(4.5mExit,1mBA)	420.0	516.0	492.0	492.0	432.0	468.0	72.0	0.0	0.0	480.00
SD1_EW1_2(4.5mExit,1mBA)	444.0	504.0	480.0	492.0	432.0	432.0	120.0	0.0	0.0	468.00
Average(4.5mExit,1mBA)	428.0	508.0	472.0	496.0	444.0	452.0	96.0	0.0	0.0	**474.40**

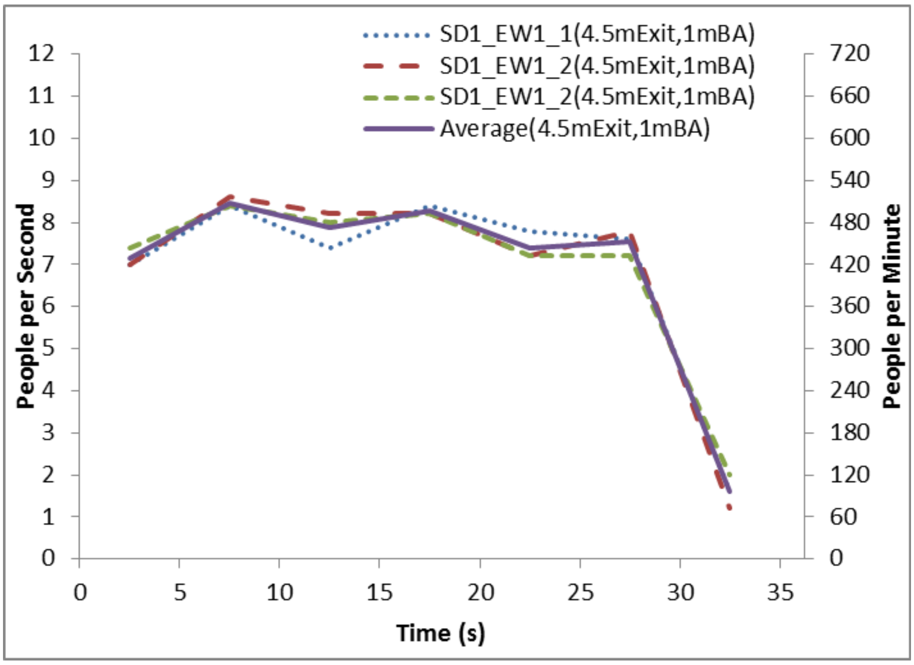


Figure 113: Exit flow measured in 5 sec intervals for the three 4.5m EW, 1m BA trials

Table 107: BA flow measured in 5 sec intervals for the three 4.5m EW, 1m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,1mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD1_EW1_1(4.5mExit,1mBA)	348.0	492.0	504.0	468.0	480.0	432.0	168.0	0.0	0.0	486.00
SD1_EW1_2(4.5mExit,1mBA)	360.0	504.0	492.0	516.0	444.0	432.0	144.0	0.0	0.0	489.00
SD1_EW1_2(4.5mExit,1mBA)	384.0	504.0	456.0	516.0	444.0	384.0	216.0	0.0	0.0	480.00
Average(4.5mExit,1mBA)	364.0	500.0	484.0	500.0	456.0	416.0	176.0	0.0	0.0	**485.00**

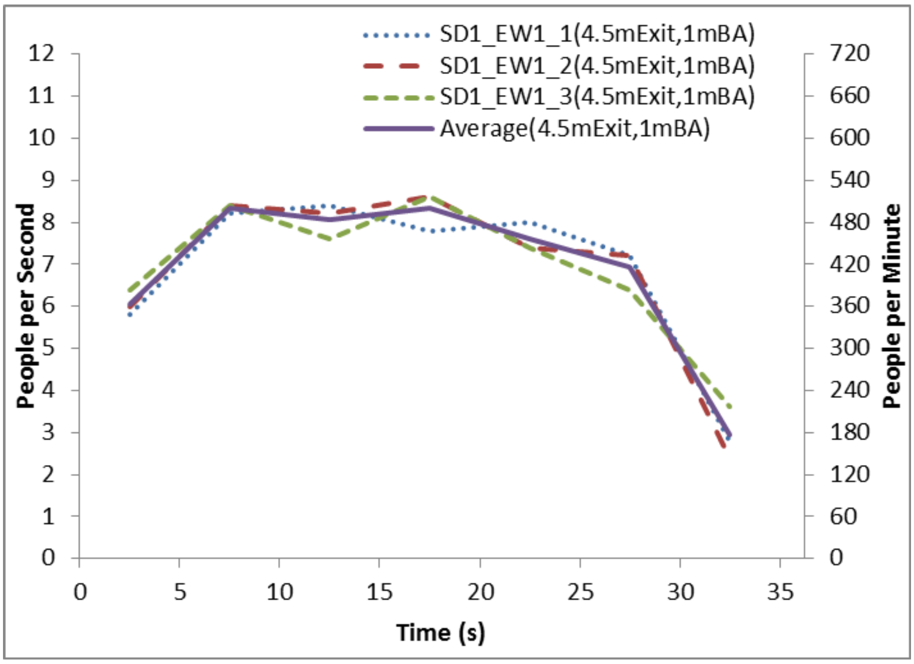


Figure 114: BA flow measured in 5 sec intervals for the three 4.5m EW, 1m BA trials

Table 108: Density measured in 5 sec intervals for the three 4.5m EW, 1m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,1mBA		**Density Time Step (sec)**									**Peak Average (p/m2)**
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
SD1_EW2_1 (4.5mExit,1mBA)	A	0.00	0.45	0.45	0.45	0.90	0.90	0.45	0.00	0.00	0.56
	B	0.00	0.90	1.05	0.90	1.05	1.05	1.05	0.00	0.00	0.98
	C	0.00	0.45	0.45	0.00	0.45	0.45	0.45	0.00	0.00	0.34
	Total	0.00	0.72	0.81	0.63	0.90	0.90	0.81	0.00	0.00	0.77
SD1_EW2_2 (4.5mExit,1mBA)	A	0.00	0.45	0.45	0.90	0.45	0.45	0.90	0.00	0.00	0.56
	B	0.00	1.05	1.20	1.05	1.05	1.05	1.05	0.00	0.00	1.09
	C	0.00	0.45	0.45	0.45	0.45	0.00	0.00	0.00	0.00	0.45
	Total	0.00	0.81	0.90	0.90	0.81	0.72	0.81	0.00	0.00	0.86
SD1_EW2_3 (4.5mExit,1mBA)	A	0.00	0.90	0.45	0.90	0.90	0.45	1.35	0.00	0.00	0.79
	B	0.00	1.35	1.35	1.65	1.05	1.20	0.90	0.00	0.00	1.35
	C	0.00	0.00	0.00	0.45	0.45	0.45	0.45	0.00	0.00	0.23
	Total	0.00	0.99	0.90	1.26	0.90	0.90	0.90	0.00	0.00	1.02
Average Total (4.5mExit,1mBA)		0.00	0.84	0.87	0.93	0.87	0.84	0.84	0.00	0.00	0.88
Average Area B (4.5mExit,1mBA)		0.00	1.10	1.20	1.20	1.05	1.10	1.00	0.00	0.00	1.14

Table 109: Gap usage (%) at 1m for the three 4.5mExit, 1mBA trials

Trial	Gap (% Usage)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SD1_EW1_1(4.5mExit,1mBA)	0.0%	0.0%	11.2%	26.1%	29.0%	24.9%	8.7%	0.0%	0.0%
SD1_EW1_2(4.5mExit,1mBA)	0.0%	0.0%	11.2%	24.9%	29.5%	26.1%	8.3%	0.0%	0.0%
SD1_EW1_2(4.5mExit,1mBA)	0.0%	0.0%	10.7%	23.6%	31.0%	24.4%	10.3%	0.0%	0.0%
Average(4.5mExit,1mBA)			11.1	24.9	29.8	25.1	9.1		

16.13 TS3: Exit width (EW) 4.5m and 2m standoff

Table 110: Exit flow measured in 5 sec intervals for the three 4.5m EW, 2m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,2mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD2_EW1_1(4.5mExit,2mBA)	432.0	504.0	456.0	480.0	480.0	432.0	48.0	0.0	0.0	470.40
SD2_EW1_2(4.5mExit,2mBA)	420.0	468.0	504.0	480.0	480.0	396.0	84.0	0.0	0.0	483.00
SD2_EW1_2(4.5mExit,2mBA)	420.0	480.0	420.0	480.0	516.0	432.0	96.0	0.0	0.0	465.60
Average(4.5mExit,2mBA)	424.0	484.0	460.0	480.0	492.0	432.0	76.0	0.0	0.0	**473.00**

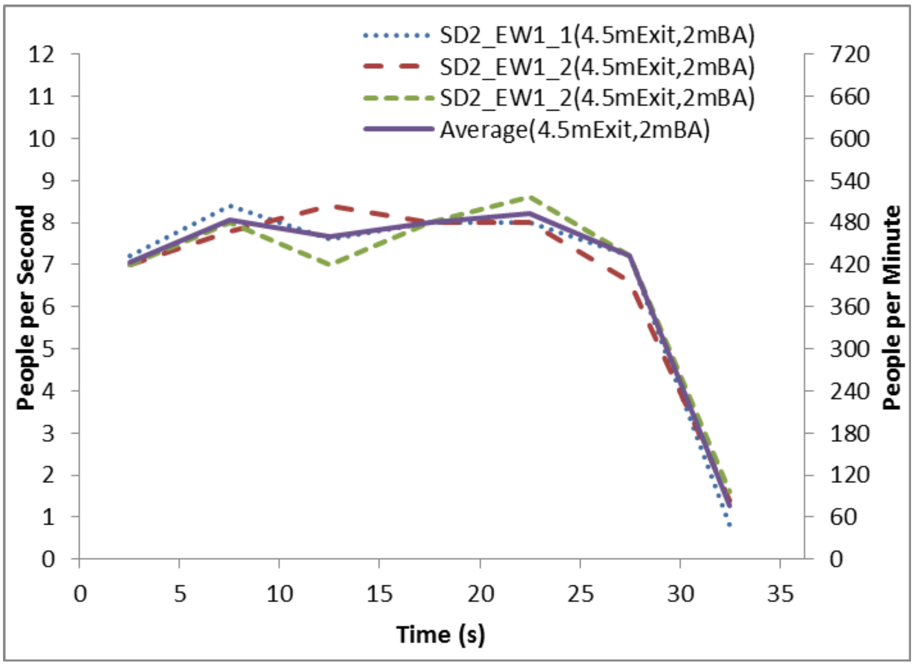


Figure 115: Exit flow measured in 5 sec intervals for the three 4.5m EW, 2m BA trials

Table 111: BA flow measured in 5 sec intervals for the three 4.5m EW, 2m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,2mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD2_EW1_1(4.5mExit,2mBA)	300.0	504.0	456.0	540.0	444.0	420.0	168.0	0.0	0.0	486.00
SD2_EW1_2(4.5mExit,2mBA)	288.0	480.0	552.0	468.0	492.0	384.0	168.0	0.0	0.0	498.00
SD2_EW1_2(4.5mExit,2mBA)	264.0	492.0	480.0	492.0	468.0	444.0	204.0	0.0	0.0	483.00
Average(4.5mExit,2mBA)	284.0	492.0	496.0	500.0	468.0	416.0	180.0	0.0	0.0	**489.00**

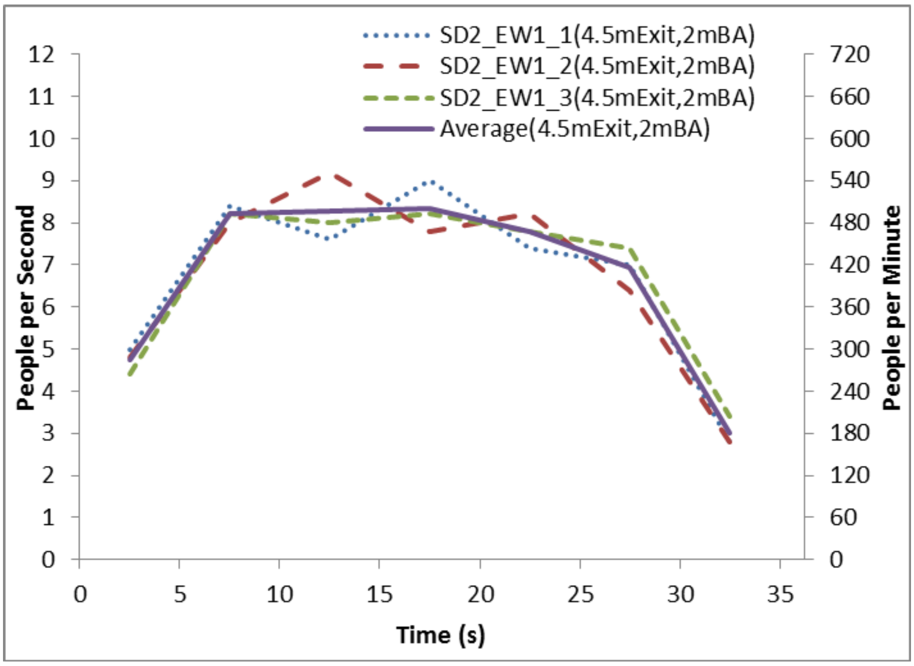


Figure 116: BA flow measured in 5 sec intervals for the three 4.5m EW, 2m BA trials

Table 112: Density measured in 5 sec intervals for the three 4.5m EW, 2m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,2mBA		Density Time Step (sec)									Peak Average
Trial	Region	0	5	10	15	20	25	30	35	40	(p/m2)
SD1_EW2_1 (4.5mExit,2mBA)	A	0.00	0.45	0.90	0.90	0.00	0.45	1.35	0.00	0.00	0.56
	B	0.00	1.20	1.35	1.20	1.50	1.05	0.60	0.00	0.00	1.32
	C	0.00	0.45	0.00	0.90	0.45	0.45	0.45	0.00	0.00	0.45
	Total	0.00	0.90	0.99	1.08	0.99	0.81	0.72	0.00	0.00	0.99
SD1_EW2_2 (4.5mExit,2mBA)	A	0.00	1.81	0.90	1.35	0.90	0.90	0.90	0.45	0.00	1.24
	B	0.00	1.35	1.20	1.20	1.50	1.05	0.90	0.30	0.00	1.32
	C	0.00	0.00	0.45	0.45	0.90	1.35	0.45	0.00	0.00	0.45
	Total	0.00	1.17	0.99	1.08	1.26	1.08	0.81	0.27	0.00	1.13
SD1_EW2_3 (4.5mExit,2mBA)	A	0.00	0.00	1.35	1.35	1.81	0.90	0.45	0.00	0.00	1.13
	B	0.00	1.20	1.35	0.75	1.20	1.35	1.05	0.60	0.00	1.13
	C	0.00	0.00	0.90	0.45	0.45	0.00	0.00	0.00	0.00	0.45
	Total	0.00	0.72	1.26	0.81	1.17	0.99	0.72	0.36	0.00	0.99
Average Total (4.5mExit,2mBA)		0.00	0.93	1.08	0.99	1.14	0.96	0.75	0.21	0.00	1.04
Average Area B (4.5mExit,2mBA)		0.00	1.25	1.30	1.05	1.40	1.15	0.85	0.30	0.00	1.25

Table 113: Gap usage (%) at 2m for the three 4.5mExit, 2mBA trials

Trial	Gap (% Usage)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SD2_EW1_1(4.5mExit,2mBA)	0.0%	0.0%	11.4%	25.0%	28.8%	22.5%	12.3%	0.0%	0.0%
SD2_EW1_2(4.5mExit,2mBA)	0.0%	0.0%	13.6%	24.2%	27.5%	22.9%	11.4%	0.4%	0.0%
SD2_EW1_2(4.5mExit,2mBA)	0.0%	0.4%	13.5%	22.8%	30.0%	22.4%	10.1%	0.8%	0.0%
Average(4.5mExit,2mBA)	0.0%	0.1%	12.8%	24.0%	28.8%	22.6%	11.3%	0.4%	0.0%

16.14 TS3: Exit width (EW) 4.5m and 3m standoff

Table 114: Exit flow measured in 5 sec intervals for the three 4.5m EW, 3m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,3mBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD3_EW1_1(4.5mExit,3mBA)	456.0	492.0	492.0	492.0	480.0	420.0	24.0	0.0	0.0	475.20
SD3_EW1_2(4.5mExit,3mBA)	444.0	516.0	516.0	456.0	492.0	408.0	48.0	0.0	0.0	477.60
SD3_EW1_2(4.5mExit,3mBA)	480.0	492.0	540.0	468.0	492.0	372.0	12.0	0.0	0.0	498.00
Average(4.5mExit,3mBA)	460.0	500.0	516.0	472.0	488.0	414.0	28.0	0.0	0.0	**483.60**

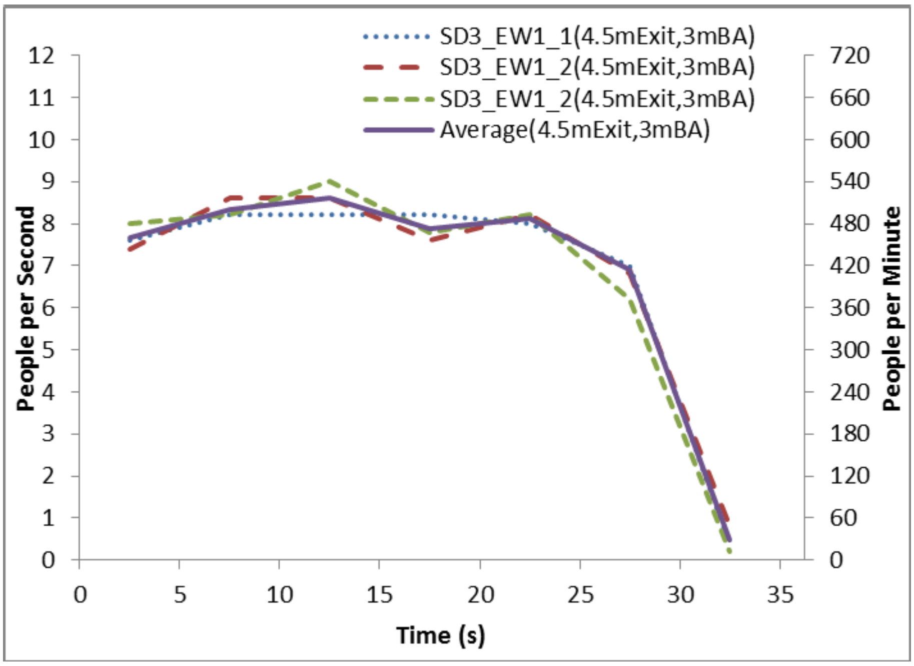


Figure 117: Exit flow measured in 5 sec intervals for the three 4.5m EW, 3m BA trials

Table 115: BA flow measured in 5 sec intervals for the three 4.5m EW, 3m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,3mBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
SD3_EW1_1(4.5mExit,3mBA)	312.0	468.0	504.0	480.0	444.0	480.0	168.0	0.0	0.0	474.00
SD3_EW1_2(4.5mExit,3mBA)	276.0	492.0	516.0	492.0	444.0	468.0	192.0	0.0	0.0	486.00
SD3_EW1_2(4.5mExit,3mBA)	300.0	528.0	468.0	516.0	480.0	432.0	132.0	0.0	0.0	498.00
Average(4.5mExit,3mBA)	296.0	496.0	496.0	496.0	456.0	460.0	164.0	0.0	0.0	**486.00**

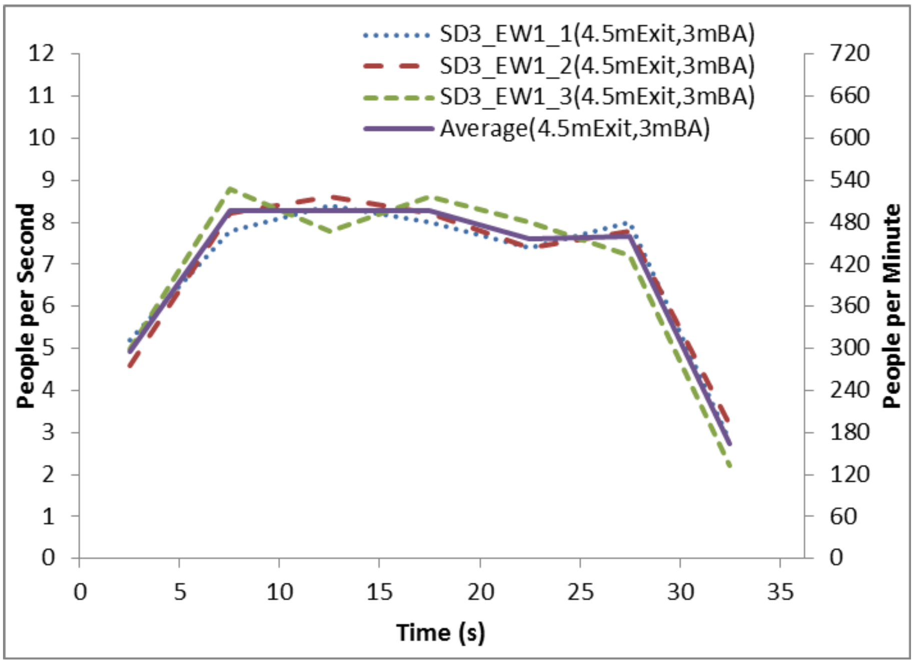


Figure 118: BA flow measured in 5 sec intervals for the three 4.5m EW, 3m BA trials

Table 116: Density measured in 5 sec intervals for the three 4.5m EW, 3m BA trials (data excluded from peak determination highlighted in red)

4.5mExit,3mBA		**Density Time Step (sec)**									**Peak Average (p/m2)**
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
SD1_EW2_1 (4.5mExit,3mBA)	A	0.00	0.90	0.90	0.45	0.90	0.45	0.45	0.00	0.00	0.79
	B	0.00	0.90	1.20	0.60	1.05	1.20	1.05	0.00	0.00	0.94
	C	0.00	0.90	0.45	0.90	0.90	0.45	0.45	0.00	0.00	0.79
	Total	0.00	0.90	0.99	0.63	0.99	0.90	0.81	0.00	0.00	0.88
SD1_EW2_2 (4.5mExit,3mBA)	A	0.00	0.00	0.90	0.90	1.35	0.45	0.90	0.00	0.00	0.79
	B	0.00	1.20	0.75	0.75	1.05	1.05	0.45	0.00	0.00	0.94
	C	0.00	0.45	0.00	0.45	0.45	0.90	0.90	0.00	0.00	0.34
	Total	0.00	0.81	0.63	0.72	0.99	0.90	0.63	0.00	0.00	0.79
SD1_EW2_3 (4.5mExit,3mBA)	A	0.00	0.90	0.00	0.90	0.45	0.45	0.45	0.00	0.00	0.56
	B	0.00	1.05	1.05	1.05	0.75	1.35	0.75	0.00	0.00	0.98
	C	0.00	0.90	0.00	0.90	0.00	0.90	0.00	0.00	0.00	0.45
	Total	0.00	0.99	0.63	0.99	0.54	1.08	0.54	0.00	0.00	0.79
Average Total (4.5mExit,3mBA)		0.00	0.90	0.75	0.78	0.84	0.96	0.66	0.00	0.00	0.82
Average Area B (4.5mExit,3mBA)		0.00	1.05	1.00	0.80	0.95	1.20	0.75	0.00	0.00	0.95

Table 117: Gap usage (%) at 3m for the three 4.5mExit, 3mBA trials

Trial	Gap (% Usage)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SD3_EW1_1(4.5mExit,3mBA)	0.0%	1.7%	14.7%	22.3%	27.7%	19.3%	13.9%	0.4%	0.0%
SD3_EW1_2(4.5mExit,3mBA)	0.0%	0.4%	15.8%	22.5%	27.1%	20.8%	12.5%	0.8%	0.0%
SD3_EW1_2(4.5mExit,3mBA)	0.0%	1.3%	13.0%	22.3%	28.2%	21.4%	13.0%	0.8%	0.0%
Average(4.5mExit,3mBA)	0.0.%	1.1%	14.5%	22.3%	27.7%	20.5%	13.1%	0.7%	0.0%

16.15 TS3: Exit width (EW) 4.5m and No Bollard Array(NoBA)

Table 118: Exit flow measured in 5 sec intervals for the three 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,0mNoBA	Exit Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
NB_EW1_1(4.5mExit,0mNoBA)	504.0	552.0	492.0	528.0	468.0	228.0	0.0	0.0	0.0	510.00
NB_EW1_2(4.5mExit,0mNoBA)	516.0	576.0	552.0	528.0	468.0	240.0	0.0	0.0	0.0	531.00
NB_EW1_3(4.5mExit,0mNoBA)	552.0	552.0	564.0	456.0	492.0	180.0	0.0	0.0	0.0	516.00
Average(4.5mExit,0mNoBA)	524.0	560.0	536.0	504.0	476.0	216.0	0.0	0.0	0.0	**519.00**

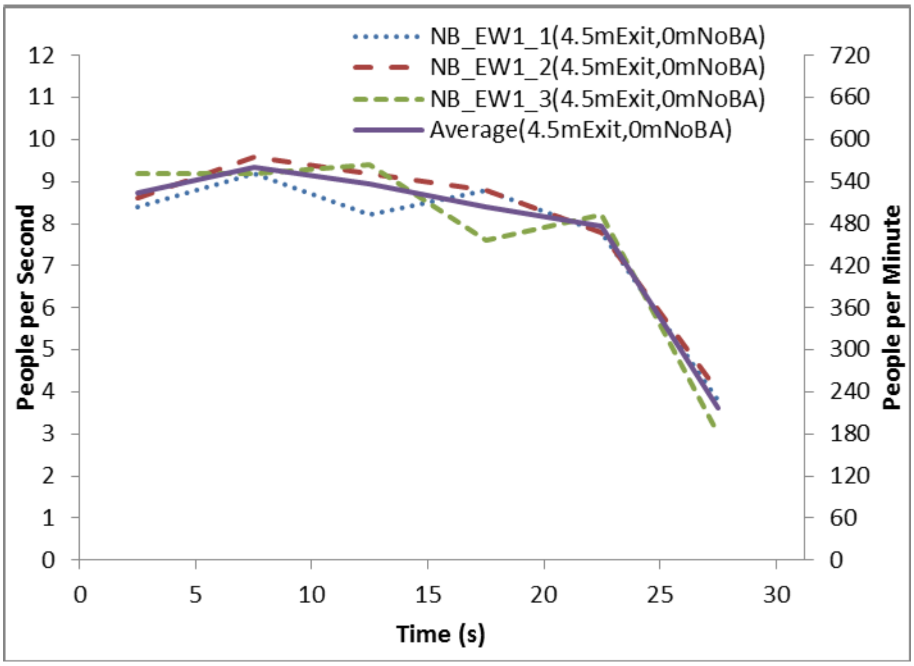


Figure 119: Exit flow measured in 5 sec intervals for the three 4.5m EW, NoBA trials

Table 119: Flow at 1m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,1mNoBA	BA Flow (ppm)									Overall Average (ppm)
	Time interval (sec)									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
NB_EW1_1(4.5mExit,1mNoBA)	468.0	552.0	468.0	516.0	504.0	264.0	0.0	0.0	0.0	510.00
NB_EW1_2(4.5mExit,1mNoBA)	480.0	528.0	564.0	540.0	504.0	264.0	0.0	0.0	0.0	534.00
NB_EW1_3(4.5mExit,1mNoBA)	528.0	552.0	600.0	420.0	456.0	240.0	0.0	0.0	0.0	507.00
Average(4.5mExit,1mNoBA)	492.0	544.0	544.0	492.0	488.0	256.0	0.0	0.0	0.0	**517.00**

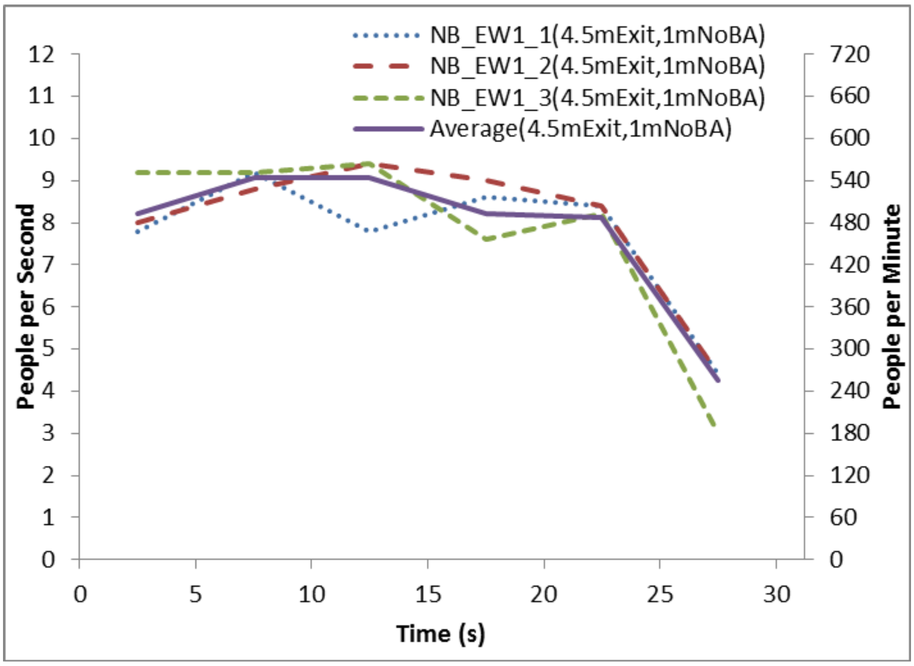


Figure 120: Flow at 1m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials

Table 120: Density at 1m measured in 5 sec intervals for the three 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,1mNoBA		Density Time Step (sec)									Peak Average (p/m2)
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	
NB_EW1_1 (4.5mExit,1mNoBA)	A	0.00	0.00	0.44	0.44	0.44	0.00	0.00	0.00	0.00	0.33
	B	0.00	0.89	1.18	1.48	0.74	0.89	0.00	0.00	0.00	1.07
	C	0.00	0.44	0.44	0.44	0.44	0.00	0.00	0.00	0.00	0.44
	Total	0.00	0.62	0.89	1.06	0.62	0.53	0.00	0.00	0.00	0.80
NB_EW1_2 (4.5mExit,1mNoBA)	A	0.00	0.89	0.89	0.00	0.89	0.44	0.00	0.00	0.00	0.66
	B	0.00	1.18	1.33	1.48	1.48	0.74	0.00	0.00	0.00	1.37
	C	0.00	0.00	0.44	0.44	0.00	0.00	0.00	0.00	0.00	0.22
	Total	0.00	0.89	1.06	0.98	1.06	0.53	0.00	0.00	0.00	1.00
NB_EW1_3 (4.5mExit,1mNoBA)	A	0.00	0.44	0.44	0.44	0.44	0.00	0.00	0.00	0.00	0.44
	B	0.00	1.33	1.33	1.33	1.18	1.33	0.00	0.00	0.00	1.29
	C	0.00	0.44	0.44	0.44	0.00	0.44	0.00	0.00	0.00	0.33
	Total	0.00	0.98	0.98	0.98	0.80	0.89	0.00	0.00	0.00	0.93
Average Total (4.5mExit,1mNoBA)		0.00	0.83	0.98	1.00	0.83	0.65	0.00	0.00	0.00	0.91
Average Area B (4.5mExit,1mNoBA)		0.00	1.13	1.28	1.43	1.13	0.99	0.00	0.00	0.00	1.24

Table 121: Gap usage (%) at 1m for the three 4.5mExit, NoBA trials

Trial	Gap (% Usage)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
NB_EW1_1(4.5mExit,1mNoBA)	0.0%	0.0%	10.4%	25.5%	27.7%	29.4%	6.9%	0.0%	0.0%
NB_EW1_2(4.5mExit,1mNoBA)	0.0%	0.0%	12.5%	25.4%	28.8%	27.9%	5.4%	0.0%	0.0%
NB_EW1_3(4.5mExit,1mNoBA)	0.0%	0.0%	10.3%	27.5%	27.9%	28.3%	6.0%	0.0%	0.0%
Average(4.5mExit,1mNoBA)	0.0%	0.0%	11.1%	26.1%	28.1%	28.6%	6.1%	0.0%	0.0%

Table 122: Flow at 2m, measured in 5 sec intervals for 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,2mNoBA	BA Flow (ppm) Time interval (sec)									Overall Average (ppm)
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
NB_EW1_1(4.5mExit,2mNoBA)	408.0	540.0	492.0	552.0	480.0	300.0	0.0	0.0	0.0	516.00
NB_EW1_2(4.5mExit,2mNoBA)	396.0	540.0	564.0	528.0	528.0	324.0	0.0	0.0	0.0	540.00
NB_EW1_3(4.5mExit,2mNoBA)	372.0	540.0	612.0	516.0	456.0	300.0	0.0	0.0	0.0	531.00
Average(4.5mExit,2mNoBA)	392.0	540.0	556.0	532.0	488.0	308.0	0.0	0.0	0.0	**529.00**

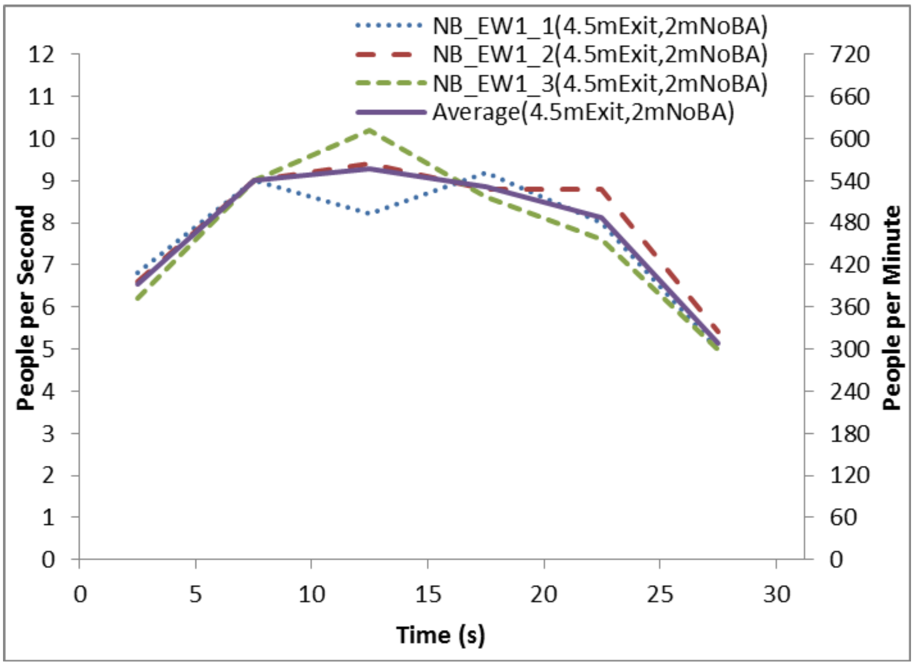


Figure 121: Flow at 2m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials

Table 123: Density at 2m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,2mNoBA		**Density Time Step (sec)**									**Peak Average (p/m2)**
Trial	**Region**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	

NB_EW1_1 (4.5mExit,2mNoBA)	A	0.00	0.44	0.89	0.89	0.89	0.44	0.00	0.00	0.00	0.78
	B	0.00	1.18	1.03	1.48	0.89	1.48	0.00	0.00	0.00	1.15
	C	0.00	0.44	0.44	0.00	0.00	0.00	0.44	0.00	0.00	0.22
	Total	0.00	0.89	0.89	1.06	0.71	0.98	0.09	0.00	0.00	0.89
NB_EW1_2 (4.5mExit,2mNoBA)	A	0.00	0.89	0.89	0.44	1.33	0.89	0.00	0.00	0.00	0.89
	B	0.00	1.33	1.33	1.18	0.74	1.03	0.30	0.00	0.00	1.15
	C	0.00	0.44	0.00	0.44	0.44	0.44	0.00	0.00	0.00	0.33
	Total	0.00	1.06	0.98	0.89	0.80	0.89	0.18	0.00	0.00	0.93
NB_EW1_3 (4.5mExit,2mNoBA)	A	0.00	0.89	0.44	0.44	0.44	0.44	0.00	0.00	0.00	0.55
	B	0.00	1.33	1.03	1.63	0.89	0.59	0.30	0.00	0.00	1.22
	C	0.00	0.44	0.44	0.89	0.44	0.89	0.00	0.00	0.00	0.55
	Total	0.00	1.06	0.80	1.24	0.71	0.62	0.18	0.00	0.00	0.95
Average Total (4.5mExit,2mNoBA)		0.00	1.00	0.89	1.06	0.74	0.83	0.15	0.00	0.00	0.92
Average Area B (4.5mExit,2mNoBA)		0.00	1.28	1.13	1.43	0.84	1.03	0.20	0.00	0.00	1.17

Table 124: Gap usage (%) at 2m for the three 4.5mExit, NoBA trials

	Gap (% Usage)								
Trial	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
NB_EW1_1(4.5mExit,2mNoBA)	0.0%	0.0%	14.3%	25.1%	26.4%	23.8%	10.4%	0.0%	0.0%
NB_EW1_2(4.5mExit,2mNoBA)	0.0%	0.0%	15.0%	25.0%	29.6%	22.1%	8.3%	0.0%	0.0%
NB_EW1_3(4.5mExit,2mNoBA)	0.0%	0.4%	12.9%	27.0%	24.5%	24.0%	11.2%	0.0%	0.0%
Average(4.5mExit,2mNoBA)	0.0%	0.1%	14.1%	25.7%	26.8%	23.3%	10.0%	0.0%	0.0%

Table 125: Flow at 3m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,3mNoBA	BA Flow (ppm) Time interval (sec)									Overall Average (ppm)
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	
NB_EW1_1(4.5mExit,3mNoBA)	360.0	564.0	456.0	516.0	468.0	396.0	12.0	0.0	0.0	501.00
NB_EW1_2(4.5mExit,3mNoBA)	348.0	612.0	552.0	528.0	444.0	372.0	24.0	0.0	0.0	534.00
NB_EW1_3(4.5mExit,3mNoBA)	264.0	540.0	600.0	540.0	456.0	372.0	24.0	0.0	0.0	534.00
Average(4.5mExit,3mNoBA)	324.0	572.0	536.0	528.0	456.0	380.0	20.0	0.0	0.0	**523.00**

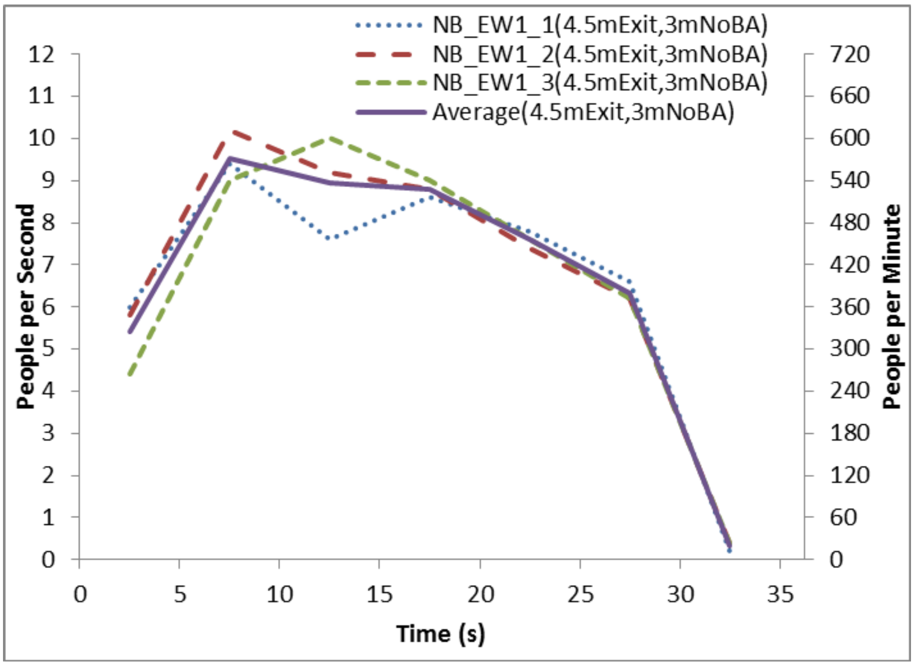


Figure 122: Flow at 3m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials

Table 126: Density at 3m, measured in 5 sec intervals for the three 4.5m EW, NoBA trials (data excluded from peak determination highlighted in red)

4.5mExit,3mNoBA		Density Time Step (sec)									Peak Average (p/m2)
Trial	Region	0	5	10	15	20	25	30	35	40	
NB_EW1_1 (4.5mExit,3mNoBA)	A	0.00	0.44	0.44	0.44	0.89	1.33	0.44	0.00	0.00	0.55
	B	0.00	1.03	1.18	0.89	1.18	1.33	0.44	0.00	0.00	1.07
	C	0.00	0.44	0.44	0.44	0.89	0.44	0.00	0.00	0.00	0.55
	Total	0.00	0.80	0.89	0.71	1.06	1.15	0.35	0.00	0.00	0.86
NB_EW1_2 (4.5mExit,3mNoBA)	A	0.00	0.89	0.00	0.89	1.33	0.89	0.00	0.00	0.00	0.78
	B	0.00	1.63	1.33	1.03	0.74	0.74	0.44	0.00	0.00	1.18
	C	0.00	0.44	0.44	1.33	0.89	0.44	0.44	0.00	0.00	0.78
	Total	0.00	1.24	0.89	1.06	0.89	0.71	0.35	0.00	0.00	1.02
NB_EW1_3 (4.5mExit,3mNoBA)	A	0.00	0.44	0.89	0.89	0.89	0.89	0.00	0.00	0.00	0.78
	B	0.00	1.03	1.48	1.33	0.59	0.74	0.30	0.00	0.00	1.11
	C	0.00	0.44	0.44	0.89	0.44	0.89	0.00	0.00	0.00	0.55
	Total	0.00	0.80	1.15	1.15	0.62	0.80	0.18	0.00	0.00	0.93
Average Total (4.5mExit,3mNoBA)		0.00	0.95	0.98	0.98	0.86	0.89	0.30	0.00	0.00	0.94
Average Area B (4.5mExit,3mNoBA)		0.00	1.23	1.33	1.08	0.84	0.94	0.39	0.00	0.00	1.12

Table 127: Gap usage (%) at 3m for the three 4.5mExit, NoBA trials

Trial	Gap (% Usage)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
NB_EW1_1(4.5mExit,3mNoBA)	0.0%	0.9%	14.3%	24.2%	24.2%	23.4%	12.6%	0.4%	0.0%
NB_EW1_2(4.5mExit,3mNoBA)	0.0%	1.7%	14.6%	22.5%	27.5%	23.3%	10.4%	0.0%	0.0%
NB_EW1_3(4.5mExit,3mNoBA)	0.0%	0.4%	14.2%	24.0%	25.8%	22.3%	13.3%	0.0%	0.0%
Average(4.5mExit,3mNoBA)	0.0%	1.0%	14.3%	23.6%	25.8%	23.0%	12.1%	0.1%	0.0%