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

Phase 1 Final Report

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

by

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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 of this work. 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 describes the performance of these trials and the subsequent analysis of the data produced.

FSEG, in discussion with CPNI, designed a series of trials in order to examine the impact that the presence of a BA might have upon an established pedestrian flow. A number of trials were conducted in order to assess this impact. The trials were designed to capture the conditions produced as the population left a simulated station: at the point of exit (Exit flow trials) and when this population is incident upon the BA (BA flow trials). These trials were designed to control a number of key parameters in order to explore two specific questions:

- How does BA stand-off distance impact exit flow?
- How does the BA impact flow passing through the BA?

As these effects were expected to be dependent on population density, two initial population densities were examined, 3 p/m^2 and 4 p/m^2. These densities were selected as they reflected the recommended maximum engineering design population densities and so were deemed representative of the conditions that may be encountered during evacuation situations at peak periods.

The exit flow results were generated for a 2.4m wide exit, with initial crowd densities of 3 p/m^2 and 4 p/m^2 and BA stand-offs of 3m and 6m with six bollards used in the BA. Additional trials were conducted using a single bollard placed in the centre of the exit. For the BA flow trials, the width of the exit path was 4.5m and the BA consisted of four bollards. For the BA flow trials involving cross-walkers, the cross-walkers were arranged in two rows a distance of 3.76m beyond the BA. The cross-walkers attempted to maintain their initial line density of 1.11 p/m per row and flow rate of 60 ppm per row. This was not always possible due to the disruption caused by the flow of people across their path. On average they managed a flow rate of 44.6 ppm across all the trials. In each set of trials, the bollards were 0.225m wide, 1.0m high and were spaced 1.2m apart.

In total 50 trials were conducted over three days on two weekends (16, 17 and 23 March 2013), 32 Exit flow trials and 18 BA flow trials. The experiment for each unique trial set up (excluding the cross-walking trials) was repeated three times in order to ensure that the collected data was repeatable and representative of the trial conditions. The trials took place in the Queen Anne Courtyard of the University of Greenwich. Some 630 participants were recruited to take part in the trials, of which 458 actually participated. 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 data was recorded using five video cameras.

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

Exit Flow:

- **On passing through the confines of the exit, a high density exit flow tends to spread out (or diffuse) into the available space as it approaches the BA.** The BA acts as a divergent lens and encourages the population to spread out slightly more than would be the case without the BA. The degree of population diffusion is greater, the smaller the initial exit population density and the further away from the exit point.
- **For a given exit flow population density there is a relationship between the exit width, stand-off distance and expanse of BA required to ensure that there is no detrimental effect on the exit flow.** Furthermore, for a given width of exit, the extent of the BA used by the flow will decrease with decreasing stand-off distance up to a distance of 3m from the exit. Assuming that the relationship between exit width, stand-off distance and extent of BA usage scales for exit widths not considered in this work, for a given exit width, the BA should be at least 50% wider than the exit at a 3m stand-off distance i.e. BA width/Exit Width > 1.5 at 3m.
- **Assuming that the population densities at the exit point are controlled (i.e. do not exceed 4 p/m^2) and there is sufficient width of BA for the exit and the BA is not placed closer than 3m from the exit, the impact of the BA upon the exit flow rates and the BA flow rate is negligible.** Given that the BA is not constraining the width available to the population, the presence of the BA does not appear to hinder the movement of the population through the exit.
- **Assuming that the population densities at the exit are controlled (do not exceed 4 p/m^2), positioning a single bollard at the centre of a 2.4m wide exit will have negligible impact on the exit flow rate.** The presence of the bollard in the exit generated a more ordered exit flow which results in an improved exit unit flow rate that partially compensates for the loss of exit width due to the presence of the bollard. It is unclear if this mechanism will be as effective in situations involving a large proportion of the population carrying luggage such as brief cases, suit cases, pushchairs, etc.

BA Flow:

- **Assuming that the population densities at the BA are controlled (i.e. do not exceed 4 p/m^2), then the presence of the BA will have a more pronounced impact on the flow rate of pedestrians passing through the BA.** In these cases there is approximately an 8% reduction in flow rate at the BA location and approximately a 7% reduction 3m beyond the BA location. The presence of the BA in the exit path generated a more ordered flow which results in an improved unit flow rate that partially compensates for the loss of clear path width due to the presence of the BA. It is unclear if this mechanism will be as effective in situations involving a large proportion of the population carrying luggage such as brief cases, suit cases, pushchairs, etc.
- **The most significant impact on the BA flow rate was generated by the presence of the cross-walkers** (a line of pedestrians walking across the main exit path up to 4m from the BA). **The cross-walkers had twice the impact on the BA flow rate as the BA alone (reduction in flow rate of 14%), and the BA and cross-walkers combined had three times the impact of the BA alone (reduction in flow rate of 27%).** At a distance of 3m beyond the BA location (just before the line of cross-walkers), the cross-walkers have almost seven times the impact of the BA on the flow rate (reduction in flow rate of 48%).
- The findings from the cross-flow trials suggest that it is extremely important for station management to understand and, if possible, manage the pedestrian flow immediately outside

of the station during an incident. This might be achieved by the use of procedural measures (e.g. staff and notification systems) to cordon off the exit path from the station and divert non-evacuating pedestrians and through the co-ordination with authorities managing the conditions outside the station.

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 and through the management of external flows around the exit point. Further work, however, is required in order to better understand key factors and to extend the baseline scenario to include more representative situations. It is suggested that additional trials be conducted to explore the impact of:

- stand-off distances less than 3m,
- the relationship between exit width, stand-off distance and BA extent,
- pedestrians carrying luggage,
- cross-flow stand-off distance and flow rate upon BA flow rate,
- the presence of contra-flow,
- modifying BA height,
- different lighting levels,
- alternate/multiple pedestrian targets on exit flow rate,
- and the impact of people running.

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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 represents the final report of the 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. 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 control a number of key parameters (specifically population density and bollard array position) in order to establish the impact that these might have on the flow characteristics produced at the exit point and at the BA. The scenario characteristics were assumed to be representative of the conditions generated by pedestrian movement from an underground station.

1.1 SPECIFIC AIMS OF THE PROJECT

The aim of the 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 the flow of pedestrians at various crowd densities. These trials examined specific crowd densities of 3 p/m^2 and 4 p/m^2. These conditions both reflected the maximum engineering design densities and were deemed representative of the conditions typically experienced by station users during egress at peak periods. The trials were designed to capture the conditions produced as the population left a simulated station: at the point of exit and when this population is incident upon the BA. It is assumed that below a crowd density of $3p/m^2$ the population would have sufficient space available during their movement and therefore that the BA would have a reduced impact; i.e., that as the density reduced, so the BA would have a diminishing impact given the free space available. This assumption was not tested in these trials and so may warrant further analysis in future trials.

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 station 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 designs, liveries, etc.).

The project considered two separate components of crowd interaction with BAs:
(a) assuming that the participants are moving from an exit point to the BA, and
(b) assuming that the participants are already located around the BA.

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. The components were examined through a series of trials.

1.2 PROJECT TIMELINE

The trials were conducted over two weekends in March 2013. The trial planning, trial performance, data analysis and final reports were conducted/produced between November 2012 and August 2013. The organisation and performance of the trials were primarily influenced by the expected weather conditions. The performance of the trials in December and January was discounted due to the high likelihood of poor weather conditions and the recruitment issues that might arise during the Christmas/New Year period. Given the ethical constraints placed on the performance of such trials, it was understood that the trials could not go forward in severe weather, given that they were not being conducted within a protected in-doors space, but outside and hence subject to the weather. In this context, severe weather was deemed to be any conditions that might potentially cause physical injury to the participants or staff involved, or cause psychological distress.

The physical space identified to conduct the trials was reserved from 26 January to 30 March 2013. In the final event, the trials were conducted over 16-17 March and 23-24 March, 2013. The programme of work was followed as specified, requiring co-operation between FSEG and CPNI and numerous site visits. The project programme was specified in consultation with CPNI and completed as follows:

1. Discussion with CPNI to finalise trial design and recruitment policy.
2. FSEG finalised initial trial design and estates issues.
3. FSEG completed an ethics review process.
4. FSEG planned a pilot trial.
5. FSEG commenced design and implementation of web site for participant registration (KO + 4 weeks).
6. FSEG conducted pilot trials (KO + 6 weeks). These trials involved the use of FSEG and UoG human and technical resources.
7. FSEG finalised detailed trial planning following analysis of pilot trial results, including fixing of trial dates, in consultation with CPNI (KO + 8 weeks).
8. FSEG prepared participant questionnaire (KO + 12 weeks).
9. FSEG contacted local newspapers to initiate recruitment process.
10. FSEG arranged for crash barriers, technical equipment, participant materials (water, caps, etc.), first aid, security guards, catering and sundries for the trials.
11. CPNI arranged for BA delivery to FSEG.
12. Ethics review process completed.
13. FSEG configured test site for trials and completed trials (March 2013).
14. FSEG commenced data analysis (Trial Completion + 1 week).

15. FSEG provided top-sheet analysis of results to CPNI in presentation format (Trial Completion + 9 weeks, May 2013).
16. FSEG completed data analysis (Trial Completion + 13 weeks).
17. FSEG provides selected video footage of trials (as permitted by Ethics Committee) and final report to CPNI (Trial Completion + 16 weeks).

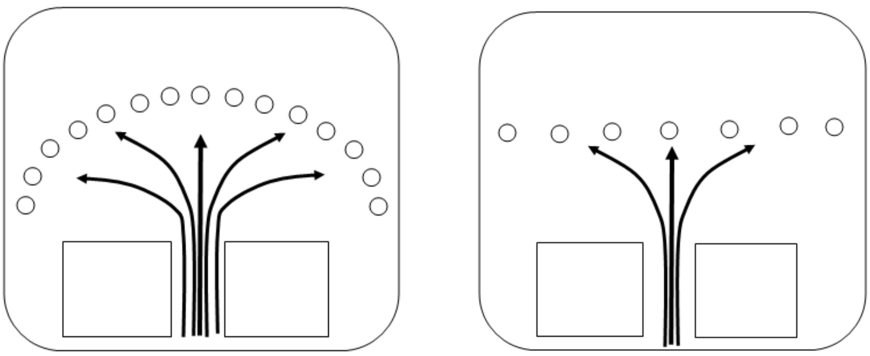
2 EXPERIMENTAL DEVELOPMENT

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 going to be conducted at an actual station, experimental scenarios had to be designed and developed in order to capture the key factors of interest 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 array from the exit (d) and the width of the exit from the station (w) and the width of the BA (baw). 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 station exit and the BA (i.e. the stand-off distance, d), is assumed to be one of the controlled variables that may impact pedestrian performance.

In addition to the configuration, the manner in which pedestrians interact with the BA (i) may also influence the impact that the BA has on pedestrian performance. For example, pedestrians may have various objectives (o) 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. Another control variable that will influence the impact of the BA on pedestrian performance is the number of pedestrians using the BA at any one time (p).



(a) (b)

Figure 1: (a) Potential pedestrian interaction with a BA in a station configuration. (b) Pedestrian interaction with BA in the experimental trial.

In reality, the width of the exit (w) will determine the number of people arriving at the BA at any one time, assuming that there is a constant supply of people feeding the exit.

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 (see Figure 1(a)). It would not have been possible to capture all of these in the experimental setting. However, a trial design has been produced that captured the key underlying elements of the different uses of the BA by varying the population densities either at the station exit (see Figure 1(b)) or at the BA itself. It may be important to examine the impact of targets off to one side. As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

On leaving the exit and passing the BA, pedestrians may encounter other pedestrians – both those originating from the station and others from elsewhere. This may involve flows of pedestrian then interacting, potentially influence movement and performance (f).

The experimental scenario was designed to capture the key factors highlighted above. In order to do this, two separate scenarios were examined: TS1 (Trial Series 1 – conducted over Days 1 and 2) and TS2 (Trial Series 2 – conducted on Day 3). In both 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 (see Figure 1(a)). Given this approach the TS1 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 2). 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 present will be 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, see Figure 1(b)).The TS1 design therefore focused on the impact of the distance between the BA and the exit given the population density present – focusing upon BA variables d and p (with w, o, s, f and baw kept constant). It is also assumed that there is sufficient width of BA so as not to adversely influence the movement of the pedestrians.

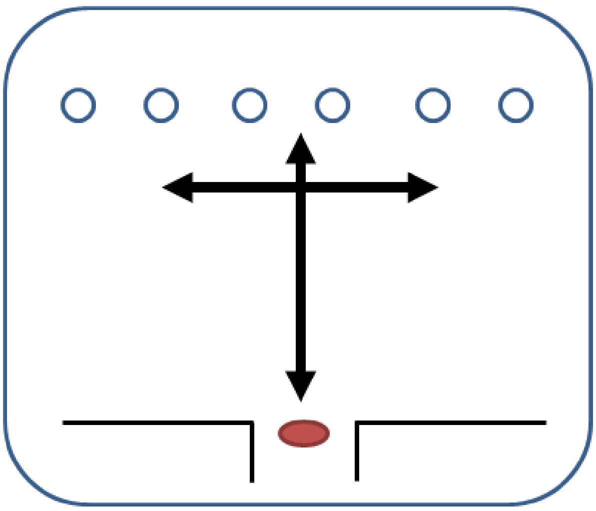


Figure 2: Opportunities for diffusion.

TS1 was intended to represent an egress flow of pedestrians from a station exit. Within TS1, the crowd density conditions were prescribed within the station mock-up *just before 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 in TS1, 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 flow rates achieved at several locations within the experimental configuration, in particular just before the exit. Furthermore, the trials will be repeated without the BA in order to gauge the impact of the BA on the exiting flow.

The initial population density of the exiting flow was varied to represent possible evacuation conditions resulting from different station loadings up to a design maximum of 4 p/m^2 [3]. In addition, the BA stand-off distance from the exit was also varied from 3m to 6 m. The 6m stand-off was set as it was considered by CPNI to be an upper limit of likely stand-off distance. In addition, CPNI specified a special case in which a single bollard was placed at a stand-off distance of 0m. The influence of stand-off distances of between 0m and 3m were not examined and so it may be important to examine the impact of stand-off distances less than 3m. As this aspect was not was not tested in these trials it may warrant further analysis in future trials. *Thus, the impact that the BA has on exiting flow within the region of the exit will be assessed as a function of exit flow crowd density and BA stand-off distance.*

TS2 was intended to represent pedestrian flow at and around the BA. In TS2 the population density conditions as the crowd arrives at the BA are controlled. This deliberately removed diffusion from the trial ensuring that conditions at the BA are varied in a controlled manner. This allowed the specific interaction between prescribed population densities and the bollard configuration to be examined. This was an important test as in reality it is likely that not all exiting paths from a station are used evenly, resulting in additional loading on certain sections of the BA. Thus for a given (initial population density leading to an) exit flow, different sections of the BA may be subject to higher localised population densities than may be expected; i.e. local densities will be higher than expected given the overall capacity available. This might happen where, on leaving a station, a large proportion of the population adopt the same route due to a facility provided nearby. In addition, TS2 would be relevant in situations where the BA was positioned prior to the final station exit; i.e. on the concourse, and hence subject to potentially high crowd densities. In TS2, the population will start around the BA with the population density being varied to establish the impact upon performance. In a sub-set of the TS2 trials additional flows of pedestrians were introduced beyond the BA location to simulate possible cross-flow interaction. Therefore, the TS2 trials focused on the following variables: BA, p and f; while controlling for; d, w, o and s. Furthermore, the trials will be repeated without the BA in order to gauge the impact of the BA on the high density flow.

To summarise;

- TS1 was designed to establish the impact of the BA upon exit flow given the different population densities within the exit approach and different stand-off distances, assuming that a sufficiently wide expanse of BA is available so as not to restrict the flow at the BA.

- TS2 was designed to control the densities at the BA ensuring the flow rates achieved at the BA could then be tied specifically to the population densities present, precluding the impact of diffusion upon the results produced.

2.2 EXPERIMENTAL SCHEDULE

As described in the previous section, the trial scenarios were based around manipulating several control variables: (p) controlling exit or bollard population densities (at the exit or at the BA - 3 or 4 p/m^2); (BA) the presence of BA (present or absent); (d) the location of BA (0m, 3m or 6m). This required a total of 36 trials to be scheduled.

For TS1 two crowd densities, three stand-off distances, and three repeats were conducted, along with the trials where the BA were not present conducted at both densities, requiring 24 trials to be performed in total: 2x3x3 BA trials + 2x3 NoBA trials. For TS2, two crowd densities and three repeats were conducted where the BA was either present or absent, requiring 12 trials.

Trial Series 1 (TS1) explored the impact of the BA on the egress flow within the station while Trial Series 2 (TS2) explored the impact of the BA on the egress flow passing through the BA. However, given the efficient use of the time available and better than expected trial turnaround, eight additional trials were conducted on Day 2 and six additional trials were conducted on Day 3. In total the following trials were conducted:

- TS1 - Day 1: 12 exit flow rate trials.
- TS1 - Day 2: 20 exit flow rate trials.
- TS2 - Day 3: 18 bollard flow rate trials.

A modified schedule was produced that allowed additional repeats to be conducted and also additional (previously unplanned) conditions to be tested. This included the introduction of a cross-walk population into a section of the TS2 trials. The final trial schedule (and trial turnaround times) is described in Table 1 to Table 3.

On Day 1, up to 149 people participated in the TS1 trials: Exit Flow Rate trials (see Table 1). The first few trials took a long time to assemble the people. This however improved after the first three trials as the procedure was executed more efficiently – especially the loading of the participants.

Table 1: Final Schedule - Day 1

Trial #	Trial Type	Approximate Trial Start Time
1	6m Bollards, 4p/m^2	09:14
2	6m Bollards, 3p/m^2	09:37
3	6m Bollards, 4p/m^2	10:00
4	6m Bollards, 3p/m^2	10:38
5	6m Bollards, 4p/m^2	10:46
6	6m Bollards, 3p/m^2	10:55

7	No Bollards, 4p/m^2	11:57
8	No Bollards, 3p/m^2	12:05
9	No Bollards, 4p/m^2	12:12
10	No Bollards, 3p/m^2	12:22
11	No Bollards, 4p/m^2	13:00
12	No Bollards, 3p/m^2	13:10

On Day 2, up to 170 people participated in the TS1 trials: Exit Flow Rate trials (see Table 2). Given the improvement in the trial turnaround, there were 8 additional trials (A1 – A8) performed. The 6m Trials A1–A4 used the same barrier arrangement as 3m Trials 1-6. This differed slightly from the Day 1 6m trial setup (discussed further in Section 2.3.4). These trials were performed to ensure consistency in the results produced and establish whether this minor change in the overall area available influenced performance. (As it transpired, this configuration did not influence performance.)

Table 2: Final Schedule - Day 2

Trial #	Trial Type	Approximate Trial Start Time
1	3m Bollards, 4p/m^2	08:53
2	3m Bollards, 3p/m^2	09:02
3	3m Bollards, 4p/m^2	09:13
4	3m Bollards, 3p/m^2	09:19
5	3m Bollards, 4p/m^2	09:32
6	3m Bollards, 3p/m^2	09:42
7	0m Bollards, 4p/m^2	10:15
8	0m Bollards, 3p/m^2	10:24
9	0m Bollards, 4p/m^2	10:34
10	0m Bollards, 3p/m^2	10:41
11	0m Bollards, 4p/m^2	10:49
12	0m Bollards, 3p/m^2	10:58
B1	6m Bollards, 4p/m^2	11:49
B2	6m Bollards, 3p/m^2	11:58
B3	6m Bollards, 4p/m^2	12:06
B4	6m Bollards, 3p/m^2	12:15
B5	No Bollards, 4p/m^2	12:49
B6	No Bollards, 3p/m^2	12:57
B7	No Bollards, 4p/m^2	13:04
B8	No Bollards, 3p/m^2	13:15

On Day 3, up to 135 people participated in the TS2 trials: Bollard Flow Rate trials (see Table 3).

Table 3: Final Schedule - Day 3. CW – Cross Walking present

Trial #	Trial Type	Approximate Trial Start Time
1	Bollards, $4p/m^2$	08:48
2	Bollards, $3p/m^2$	08:53
3	Bollards, $4p/m^2$	09:00
4	Bollards, $3p/m^2$	09:13
5	Bollards, $4p/m^2$	09:18
6	Bollards, $3p/m^2$	09:25
B1	Bollards, CW, $4p/m^2$	09:33
B2	Bollards, CW, $4p/m^2$	09:42
7	No Bollards, $4p/m^2$	10:36
8	No Bollards, $3p/m^2$	10:41
9	No Bollards, $4p/m^2$	10:46
10	No Bollards, $3p/m^2$	10:50
11	No Bollards, $4p/m^2$	10:56
12	No Bollards, $3p/m^2$	11:01
B3	No Bollards, CW, $4p/m^2$	11:22
B4	No Bollards, CW, $4p/m^2$	11:28
B5	No Bollards, CW, $3p/m^2$	11:33
B6	No Bollards, CW, $3p/m^2$	11:39

Given the improvement in the trial turnaround, there were 6 additional trials (B1 – B6) performed. These trials involved participants walking perpendicular to the main flow in a loop, forming a cross-flow. The cross-flow was formed from 14-17 people. These additional trials were both with and without bollards.

2.3 EXPERIMENTAL DESIGN

A detailed design was produced to ensure the scheduling and management of the resources involved in the experimental trials. 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.

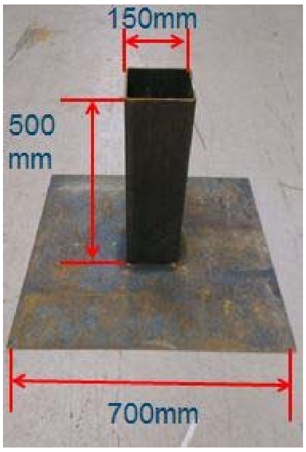
These categories are now discussed.

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.

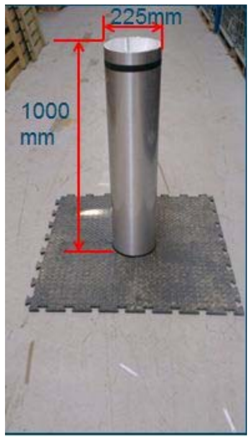
Given the intended arrival patterns of the participants, their movement during the trials and the length of the time that the participants were active, the trials required the road between the Queen Ann Courtyard arch and Queen Mary Courtyard Cafeteria to be closed during each of the trial days. In addition, 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 trials consisted of:

- A solid square metal base plate (3mm thick and 0.7m wide) with a square column (0.15m wide) extending perpendicular to the base plate to a height of 0.5m (see Figure 3a)
- A circular cylindrical sheath with 0.225m outer diameter and 1.0m in height made of PVC drain pipe represented the actual bollard (see Figure 3b).
- 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 3c).
- The sheath was placed over the supporting column (see Figure 3d).
- Four floor tiles were used to cover the base plate and secure the bollard in place (see Figure 3e).
- In the TS2 and TS1 6m and 3m BA trials, the spacing between bollards was 1.2m.
- In TS1 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 6 bollards were used in the 6m and 3m BA, three either side of the centre line.
- In TS2 a total of 4 bollards were used with 4.05m between the inner surfaces of the outer bollards in the array, providing 3.6m 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 3: Bollard Arrangement

TS1 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, 3m and 6m 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 4).

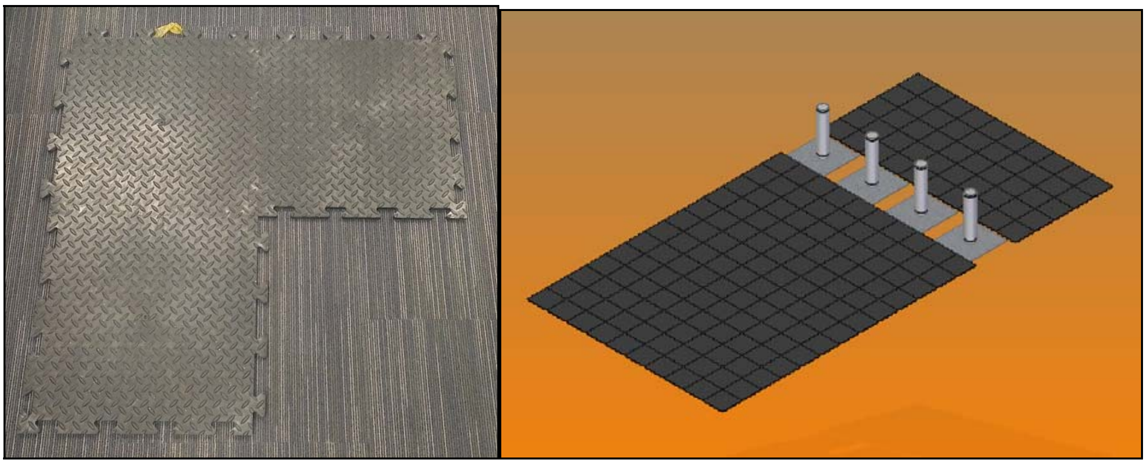


Figure 4: (a) Interlocking floor tiles. (b) BA base plates slipped under custom cut tiles.

The spatial configuration for TS1 is shown in Figure 5. TS1 also 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 (see Figure 6).

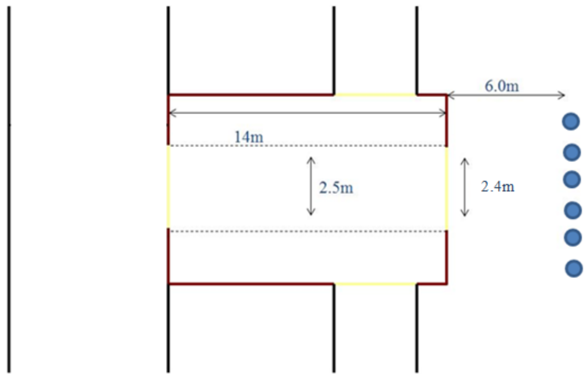


Figure 5: Dimensions of archway in Queen Anne Court.

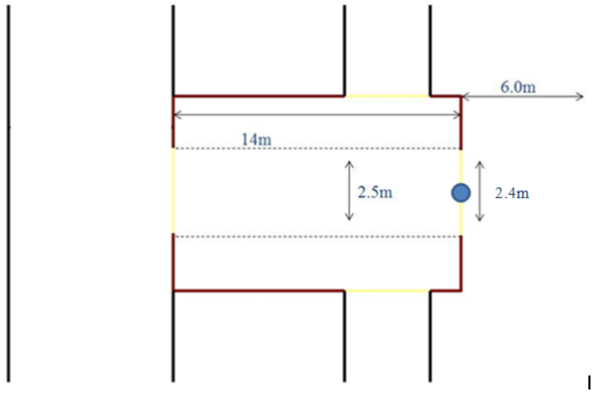


Figure 6: 0m stand-off configuration.

In order to ensure the consistency of the population density within the arch, TS1 also 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 20/15 participants to produce the desired population densities (see Figure 8). 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 7).

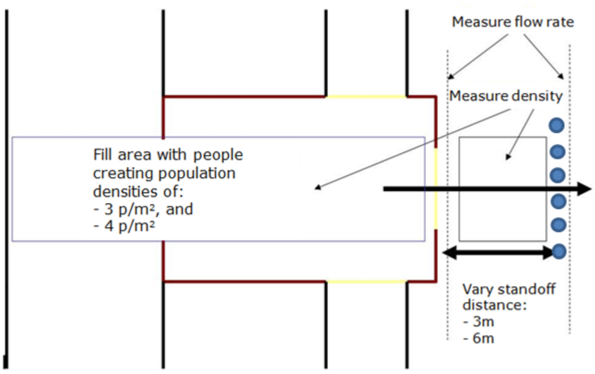


Figure 7: TS 1 configuration.

Similarly, a location also had to be prepared for the TS2 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 TS2 were performed with the BA present and without a BA.

TS2 presented the participants with four bollards with approximately 4m (4.05m) between the inner surfaces of the outer bollards in the array), providing 3.6m of effective space through which to move. TS2 required six sections to be marked off, two after the BA and four before the BA. Each section measured 4m x 1.25m. Each section was again filled with 20/15 participants to produce the desired population densities (see green area in Figure 8). These marked out sections allowed a range of measurements and calculations to be made see Figure 9).

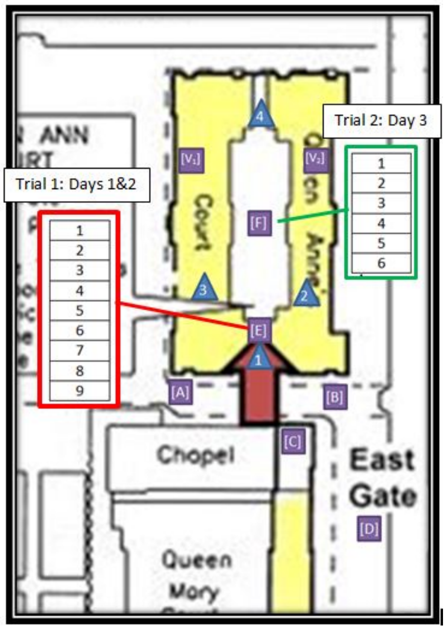


Figure 8: Section system used in TS1 and TS2.

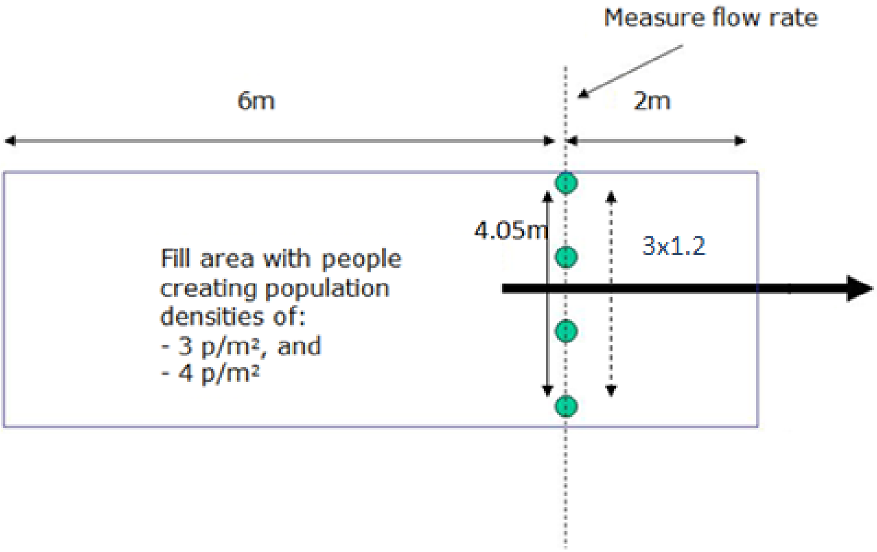


Figure 9: TS 2 configuration.

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 was appropriate. They then prepared the site for the three trial dates as shown in Figure 10 (where TS1 preparations are shown) and Figure 11 (where TS2 preparations are shown).

Figure 10: TRL staff preparing the BA and flooring set-up for TS1.

Figure 11: The TS2 configuration prepared by TRL during Day 3.

2.3.1.2 HUMAN RESOURCES

During the trials a number of staff members 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 4).

Table 4: Example role description.

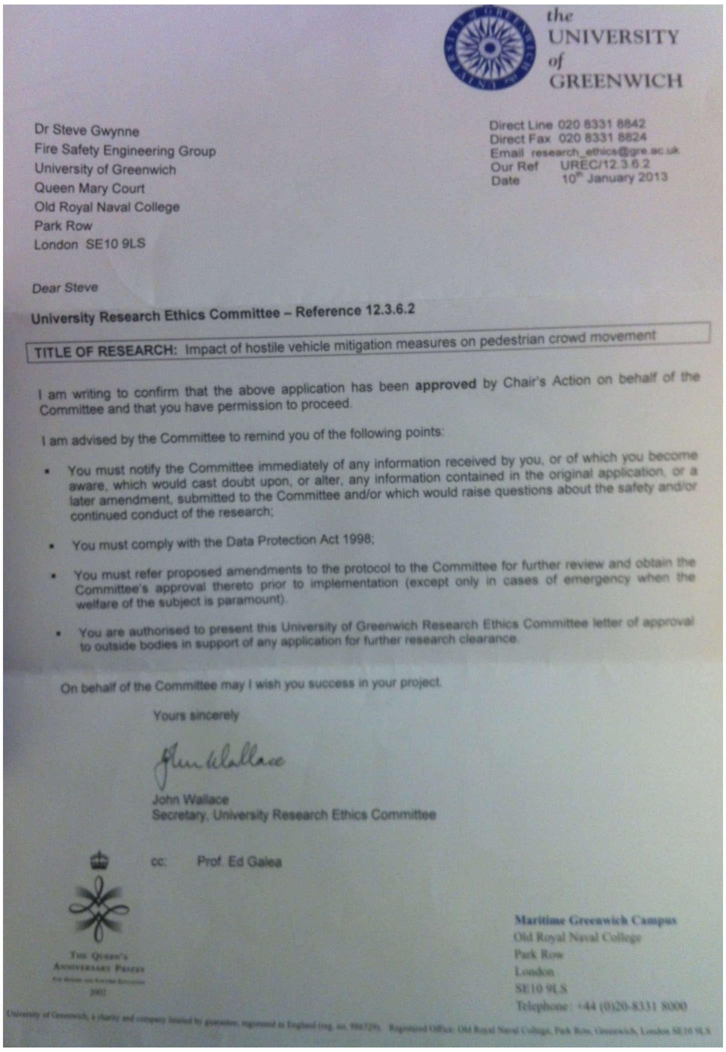
STAFF	ROLE
EG	Coordinator
AH	People Management
MP	People Management
DC	Camera / Resources
AV	Camera / Resources
XH	Camera / Resources
SD	Camera / Resources
LH	People Management / Administration
KJ	Administration
V	People Management
A	People Management
SG	People Management

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. An example of the timeline (which evolved throughout the preparation and execution of the trials) is shown in ANNEX B: PLANNING TIMELINE.

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 REC (Research and Ethics Committee) 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 (see Figure 12).



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Direct Line 020 8331 8842
Direct Fax 020 8331 8824
Email research_ethics@gre.ac.uk
Our Ref UREC/12.3.6.2
Date 10th January 2013

Dear Steve

University Research Ethics Committee – Reference 12.3.6.2

TITLE OF RESEARCH: Impact of hostile vehicle mitigation measures on pedestrian crowd movement

I am writing to confirm that the above application has been **approved** by Chair's Action on behalf of the Committee and that you have permission to proceed.

I am advised by the Committee to remind you of the following points:

- You must notify the Committee immediately of any information received by you, or of which you become aware, which would cast doubt upon, or alter, any information contained in the original application, or a later amendment, submitted to the Committee and/or which would raise questions about the safety and/or continued conduct of the research;
- You must comply with the Data Protection Act 1998;
- You must refer proposed amendments to the protocol to the Committee for further review and obtain the Committee's approval thereto prior to implementation (except only in cases of emergency when the welfare of the subject is paramount).
- You are authorised to present this University of Greenwich Research Ethics Committee letter of approval to outside bodies in support of any application for further research clearance.

On behalf of the Committee may I wish you success in your project.

Yours sincerely

John Wallace
Secretary, University Research Ethics Committee

cc: Prof. Ed Galea

The Queen's Anniversary Prizes
2002

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Telephone: +44 (0)20-8331 8000

Figure 12: Notification of successful REC submission.

In addition to the REC submission, a number of key tasks needed to be completed in preparation for the trials. These are outlined in steps 1-9 in Table 5. 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. A more detailed description of the registration and administration activities is outlined in ANNEX B: PLANNING TIMELINE.

Table 5: Administrative Schedule.

	Activity	**Date**
1	News Release Issued	08/02/13 sent to CPNI for approval
2	Advertisement placed	Week of 11/02/13
3	Responses Received: • E-mail – [AS] / [KJ] • Phone – [KJ]	
4	Responses Assessed: • If Responses < 75% of total requirement, send email to all staff and students requesting volunteers.	Evaluate on 25/02/13
5	Each day after advert, [KJ] to evaluate number of people registered and report by email to [EG]	
6	[XH] to sort out participants into appropriate trial days once we have at least 100 people registered	
7	Confirmation sent out to participants indicating trial days [KJ].	Ideally this should be done within a week of registering, but must be before 28/02/13
8	Set of participants produced, individual numbers assigned, omissions compensated through using buffer group [SG].	Ideally before 01/03/13
9	If the number of confirmed registrants falls below 145 then we may need to (a) reduce number of trial days or (b) run additional repeat trials with fewer conditions e.g. remove the 4 p/m^2 trial or remove the 6m standoff	07/03/13
10	Arrivals are met and taken to cafeteria [AH/MP]	Day of trial
11	Processed – documentation completed, hat provided [KJ/LH]	Day of trial
12	# from hat recorded on documentation for any changes [KJ]	Day of trial
13	Complete groups are taken to holding area where they are kept until the beginning of the trial [AK/V].	Day of trial
14	[SG] sends off groups to pen, telling person accompanying them [AF] which section to place them in.	Day of trial
15	[SG] accompanies final group to be used in the current trial and then follows them through	Day of trial

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 five 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 of the trials: TS1 (Exit flow trials) and TS2 (Bollard flow 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 trial.
- 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 configuration, 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. Three different Bollard Arrays (BA) were positioned in the path of the participants at stand-offs of 0m, 3m and 6m.The movement of participants was recorded using 5 cameras (see Figure 13).This approach was used during the first two days of trials that were conducted over the first weekend 16th and 17th of March.

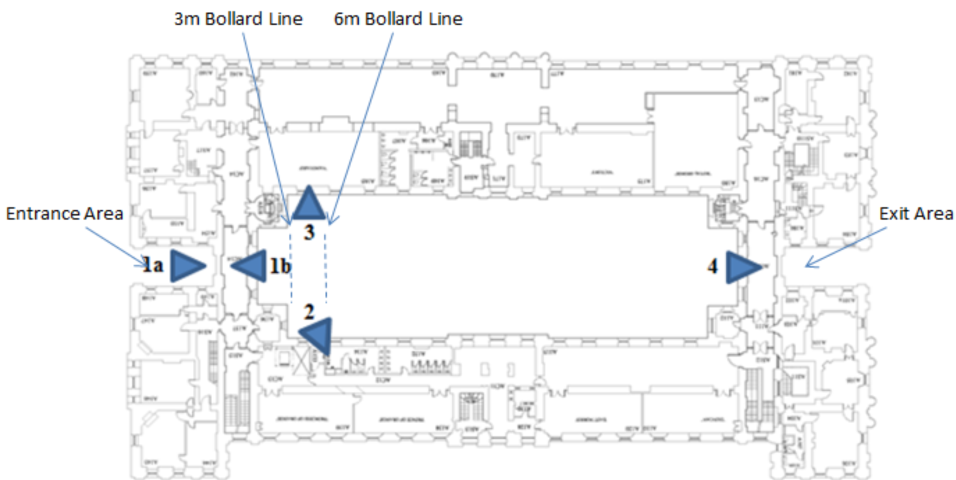


Figure 13: TS1: Exit Flow Trials

The five camera positions used during TS1 are shown in Figure 14 and the views captured by the video cameras are shown in Figure 15 in relation to several trial examples.

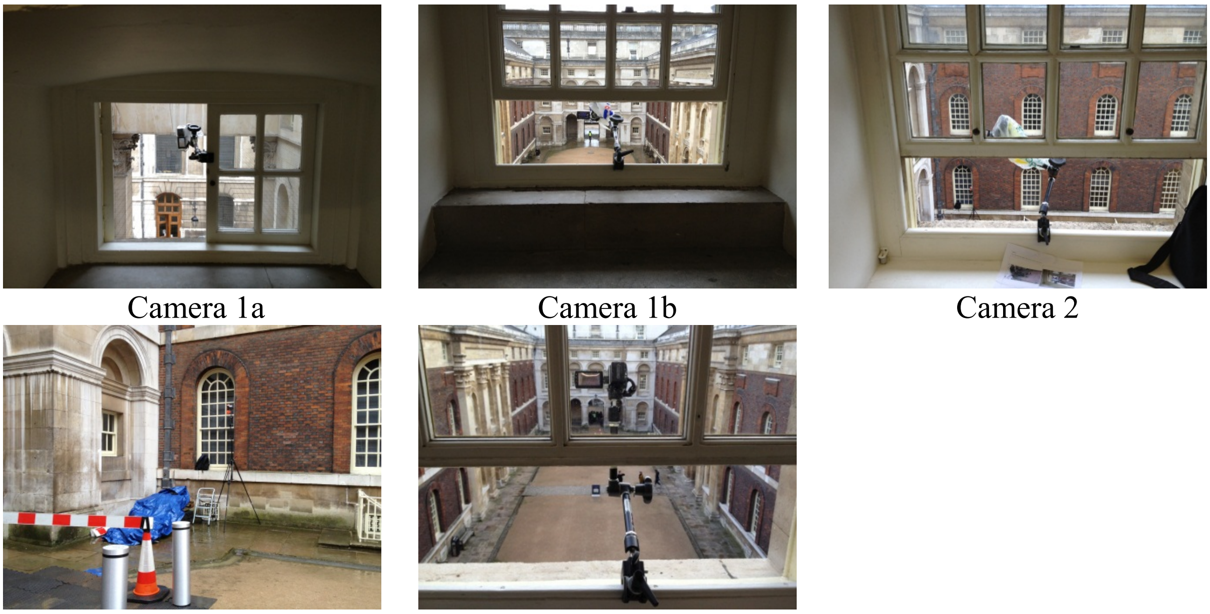


Figure 14: TS1: Camera Positions employed.

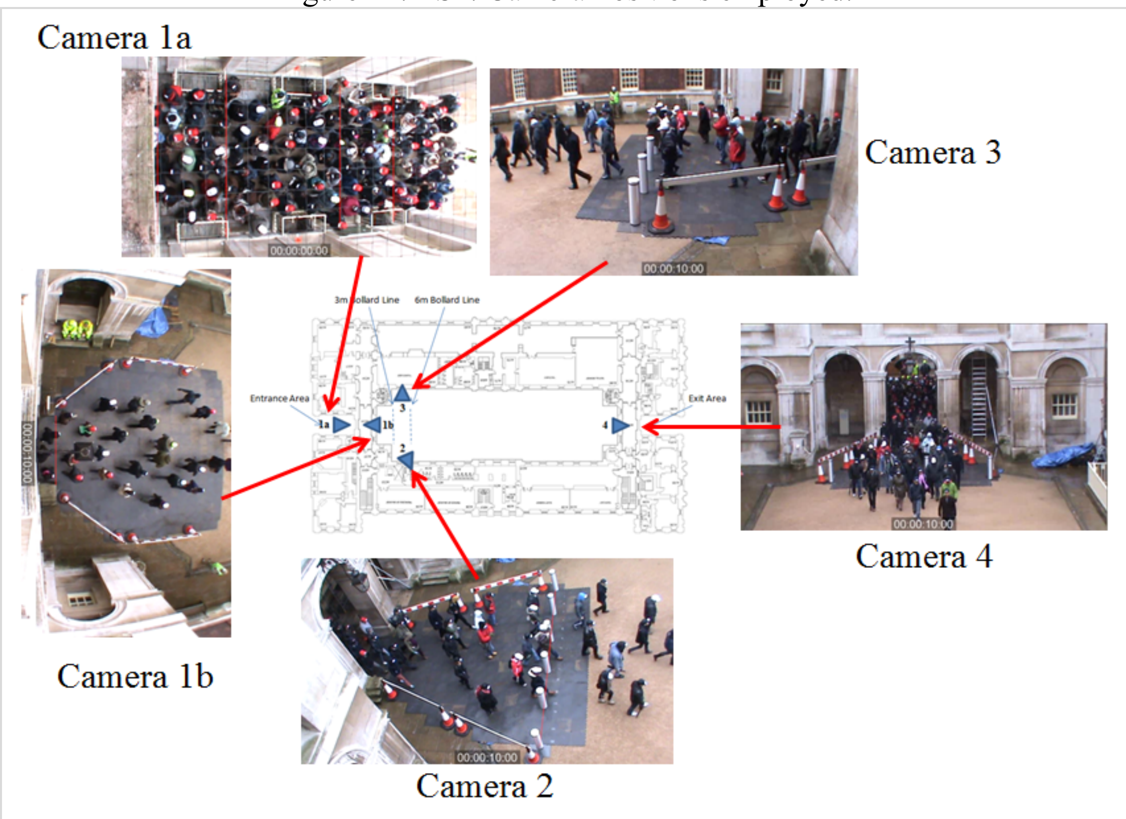


Figure 15: TS1: Exit Flow Trials – Camera Views

In the TS2 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 in four locations.

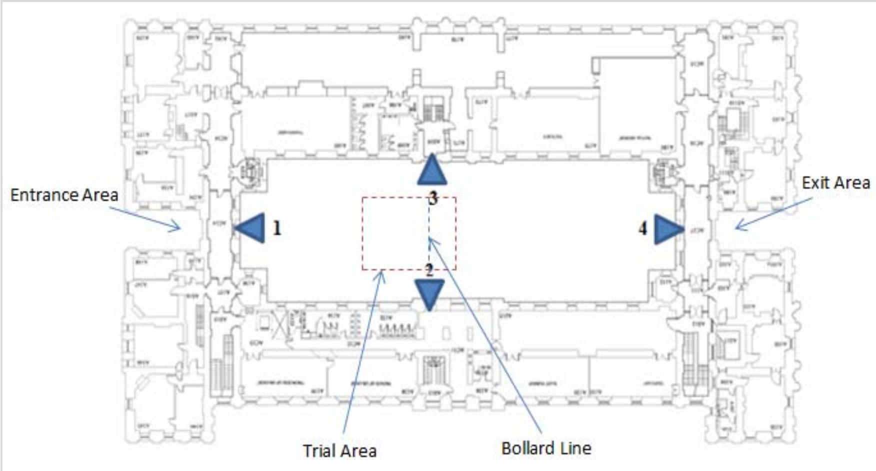


Figure 16: TS2: Bollard Flow Trials.

The four camera positions used during TS2 are shown in Figure 17.


Camera 1


Camera 2


Camera 3


Camera 4

Figure 17: TS2: Camera Positions employed.

The views captured by the video cameras from these positions are shown in Figure 18 in relation to several trial examples.

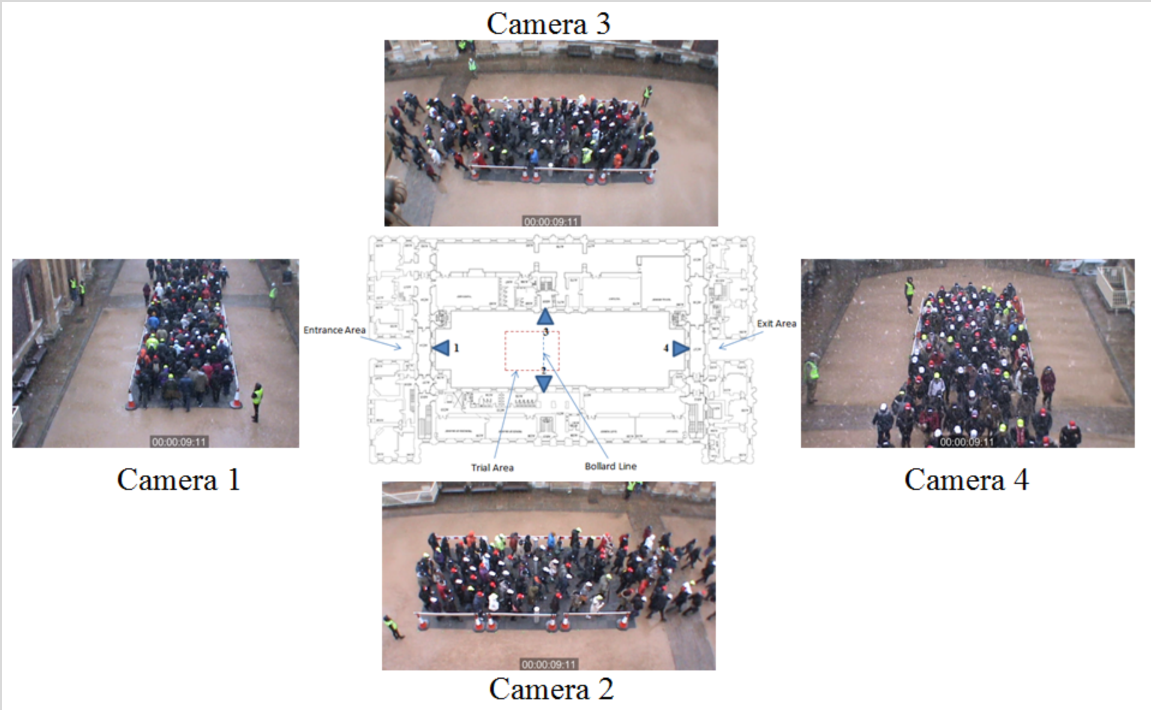


Figure 18: TS2: Bollard Flow Trials– Camera Views

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 day to cover their travel and incidental costs.

In order to ensure that sufficient numbers were available, a target number of recruits was 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 and 120 were needed for TS2. In addition, a 10% buffer population was also recruited – producing an overall participant population of 528 (i.e., 198 + 198 + 132). At the end of the recruitment process, 634 participants had registered and identified 1528 trial-days that in which they could participate; i.e. individuals were able to register for more than one day. 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. 630 participants were invited to participate in the trials Of the 630 participants invited to take part in the trials, 458 participants actually attended the trials.

The actual number of attendees for each of the days is shown in Table 6 and Table 7 (also see ANNEX G: PARTICIPANT DETAILS). On Day 1 approximately 25% of the registered volunteers failed to attend. However, during the trials, only two volunteers withdrew from the trials after only participating for about an hour on Day 1.

Table 6: Attendees for each day of the trial.

	Participants attended	Breakdown of attendees				
		Male	**Female**	**18-30**	**31-50**	**51+**
Day 1: TS1	149	79	70	60	58	31
Day 2: TS1	170	76	94	89	51	30
Day 3: TS2	139	72	67	76	38	25

Table 7: Attendees that dropped out during the trials.

	Drop-outs during trial				
	Male	**Female**	**18-30**	**31-50**	**51+**
Day 1: TS1	1	1	1	1	0
Day 2: TS1	0	0	0	0	0
Day 3: TS2	0	0	0	0	0

Although different from the number of attendees originally stating that they would participate, the number of people attending 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 6m 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. Following the large drop-out rate for Day 1, additional participants were recruited for Day 2 and Day 3 from both the reserve list and from those attending Day 1 as it was decided that a buffer of 10% was not sufficient. Given this, the participant population was allocated to the trials as shown in Table 8-Table 10.

Table 8: Day 1 Participation

Trial #	Trial Type	Actual # Participants	Expected # Participants
1	6m Bollards, 4p/m^2	149	180
2	6m Bollards, 3 p/m^2	134	135
3	6m Bollards, 4 p/m^2	149	180
4	6m Bollards, 3 p/m^2	123	135
5	6m Bollards, 4 p/m^2	140	180
6	6m Bollards, 3 p/m^2	135	135
7	No Bollards, 4 p/m^2	140	180
8	No Bollards, 3 p/m^2	135	135
9	No Bollards, 4 p/m^2	140	180
10	No Bollards, 3 p/m^2	135	135
11	No Bollards, 4 p/m^2	140	180
12	No Bollards, 3 p/m^2	135	135

Table 9: Day 2 Participation

Trial #	Trial Type	Actual # Participants	Expected # Participants
13	3m Bollards, 4 p/m^2	160	180

14	3m Bollards, 3 p/m^2	135	135
15	3m Bollards, 4 p/m^2	169	180
16	3m Bollards, 3 p/m^2	136	135
17	3m Bollards, 4 p/m^2	169	180
18	3m Bollards, 3 p/m^2	135	135
19	0m Bollards, 4 p/m^2	169	180
20	0m Bollards, 3 p/m^2	135	135
21	0m Bollards, 4 p/m^2	169	180
22	0m Bollards, 3 p/m^2	135	135
23	0m Bollards, 4 p/m^2	170	180
24	0m Bollards, 3 p/m^2	135	135
B1	6m Bollards, 4 p/m^2	159	180
B2	6m Bollards, 3 p/m^2	135	135
B3	6m Bollards, 4 p/m^2	169	180
B4	6m Bollards, 3 p/m^2	134	135
B5	No Bollards, 4 p/m^2	170	180
B6	No Bollards, 3 p/m^2	135	135
B7	No Bollards, 4 p/m^2	168	180
B8	No Bollards, 3 p/m^2	136	135

Table 10: Day 3 Participation

Trial #	Trial Type	Actual # Participants	Expected # Participants
1	Bollards, 4p/m^2	130	120
2	Bollards, 3p/m^2	90	90
3	Bollards, 4p/m^2	130	120
4	Bollards, 3p/m^2	91	90
5	Bollards, 4p/m^2	136	120
6	Bollards, 3p/m^2	88	90
B1	Bollards, CW, 4p/m^2	113 + 16	NA
B2	Bollards, CW, 4p/m^2	115 + 16	NA
7	No Bollards, 4p/m^2	134	120
8	No Bollards, 3p/m^2	88	90
9	No Bollards, 4p/m^2	135	120
10	No Bollards, 3p/m^2	90	90
11	No Bollards, 4p/m^2	135	120
12	No Bollards, 3p/m^2	90	90
B3	No Bollards, CW, 4p/m^2	114 +16	NA
B4	No Bollards, CW, 4p/m^2	113 +16	NA

B5	No Bollards, CW, 3p/m^2	91 +16	NA
B6	No Bollards, CW, 3p/m^2	87 +16	NA

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 will be an assessment of the following:

Trial Series 1:

- The flow rates produced leaving the 'station' exit given the presence/absence of bollards – *the impact of bollards on the flow leaving the station given different initial population densities.* This is measured in persons per minute.
- The unit flow rates produced leaving the 'station' exit given the presence/absence of bollards – *the impact of bollards on the unit flow rate produced when participants were leaving the station given different initial population densities.* This is measured in persons per metre of available width per minute (or per second).
- The flow rates produced at the bollard location outside of the station given the presence/absence of bollards – *the impact of bollards on the eventual flow reached as the population is moving away from the station given different initial population conditions.* 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 within a station.* This is measured in persons per metre squared.
- The population densities produced inside the 'station' exit 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.
- Use of the routes available between the bollards in the bollard array. This is referred to as gap analysis in the rest of this document.
- Qualitative description of pedestrian flows - *the impact of bollards on the general flows at and around the bollard array.*

Trial Series 2:

- The flow rate produced at the bollard location given the presence/absence of the bollard array. This is measured in persons per minute.
- The flow rate produced at the end location, 3.76m beyond the bollard array, given the presence/absence of the bollard array. This is measured in persons per minute.
- The unit flow rate produced at the bollard location given the presence / absence of the bollard array. This is measured in persons per minute per metre width.
- Qualitative description of pedestrian flows - *the impact of bollards on the general flows at and around the bollard array.*

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

(1) Three (core) trial runs are reported for each of the test cases examined.

(2) The steady (peak) flow conditions are reported with the initial and final time period excluded.

The first data reduction was performed in order to exclude outlier results. A by-product of this was that the number of trials examined in each case and subsequently reported in the body of the report (three trials) was the same throughout. Although not the intention of the data reduction, this does provide a more consistent basis for the analysis. It is therefore felt that by focusing on the three 'median' trials that we have better accounted for the impact of fatigue/resting and participant distractions. The process by which these outliers were excluded is described in the first results presented. All subsequent results reflect the set of trials with the outliers removed.

The discounted outlier trials are described in Table 11.

Table 11: Discounted outlier trials.

Day	Trial	Init. Density (p/m^2)	BA	Description
1	11	4	N	SLOWEST RUN. Took place at 13:00, 11/12 trials that day, and the first after a 20 minute rest break
2	B5	4	N	FASTEST RUN. Took place at 12:49, 17/20 trials that day, and the first after an 18 minute rest break.
1	3	4	6	SLOWEST RUN. Took place at 10:00, 3/20 trials that day, the third trial in a sequence of three which was followed by a 30 minute rest break.
2	B3	4	6	FASTEST RUN. 12:06, 15/20 trials that day, third of a four trial series between lunch and an 18 minute rest break.
1	8	3	N	SLOWEST RUN. Took place at 12:05, 8/12 trials that day, second of a four trial series between lunch and a 20 minute rest break
2	B8	3	N	FASTEST RUN. Took place at 13:15, 20/20 trials that day, fourth of a four trial series between a rest break and the end of the day.
1	2	3	6	SLOWEST RUN. Took place at 09:37, 2/20 trials that day, the second trial in a sequence of three between the start of the day and a 30 minute rest break.
2	B2	3	6	FASTEST RUN. 11:58, 14/20 trials that day, second of a four trial series between lunch and an 18 minute rest break.

The second data reduction was performed to account for (a) the initial time period where the flow rate 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 rate 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 (b).

It is felt that the resultant data-sets produced after these two data-reduction exercises undertaken are more reliable, more representative and provide a more consistent indication of the conditions produced during the trials.

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) There was a slight difference in the barrier positioning between several of the trials. Comparing the Day 1 and Day 2 6m setup, the Day 2 setup is more consistent with the arrangement used for the 3m and 0m bollard arrangement. This can be seen by comparing Figure 19 and Figure 20. While this might have affected the movement of the participants, in this instance it did not, given the tendency for the participants to progressively fan out as they neared the BA rather than immediately fanning out on leaving the exit. This behaviour was consistent throughout the trials. This became apparent during the analysis and therefore the results were kept as this factor did not unduly affect the results produced.

Figure 19: Day 1 6 m setup

Figure 20: Day 2 6m Setup

(2) 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. In reality, 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 or local conditions). 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 TS1, while the target was directly ahead of the participants, the participants could fan out and use the entire width of the BA. Indeed, 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 was not tested in these trials it may warrant further analysis in future trials.

(3) 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 was being monitored or measured.

(4) The smallest BA stand-off distance examined was 3m (a single bollard was placed at the centre of the exit however a single bollard does not constitute a BA). It is thus not possible to determine the impact on exit flows of a BA at stand-off distances between

0m and 3m. As this aspect was not 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 all three of these trials the weather was inclement – either involving low temperatures and light rain (Day 1/2) or low temperatures and light snow (Day 3). This certainly may have influenced performance, although the exact manner of this influence is difficult to assess. However, the weather was consistently inclement throughout the various trials and so one experimental scenario would not have unduly been affected. In addition, the inclement conditions are representative of UK weather to which pedestrians might be exposed on leaving stations at certain times of the year.
(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 train station was not used during the trials. Although the configuration approximated the exit route out from a station, it did not have the appearance of a station. The impact of this upon performance is unknown, although it would have been consistent throughout the trials.
(3) The participants occasionally carried small pieces of baggage; e.g., handbags, umbrellas, books, etc. In reality, pedestrians at rail and underground stations may occasionally have large pieces of luggage; e.g., brief cases, suitcases, pushchairs, etc. This was not accounted for in these trials. The presence of luggage is thought to potentially be of greatest significance in the TS1 0m trials and the TS2 trials were the unit flow rate effect was noticed. In these cases it may be important to examine the impact of participants carrying more luggage and possibly different types of luggage. As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

2.4 PILOT STUDY

A pilot study was conducted on the 1st and 2nd February 2013. Over this period the construction, construction time, data collection and participant movement were examined to ensure that the conditions were representative and manageable. This involved 20 FSEG staff to act as participants and also to adopt the roles expected of them during the trials. In addition, two TRL staff members were present to prepare the spatial configuration.

The pilot study provided much important feedback that directly influenced the performance of the trials:

(1) TRL determined that a different approach to the flooring underlay was required.
(2) Camera positions were adjusted to maximise the data captured.
(3) The participant route was modified to make the process more efficient.

(4) Changes were made to registration process based on table-top examination regarding the efficiency of the planned approach.

2.5 ADDITIONAL TRIALS

On Days 2 and 3 of the trials, additional trials were made possible by efficient participant management and turnaround times. On Day 2 this meant additional runs for existing trial conditions. On Day 3 additional trial conditions were examined. This allowed the impact of a cross flow of pedestrians upon the primary flow of pedestrians to be examined. This was examined both with and without the BA. This was to examine how the cross-flow interacted with the disruption produced by the BA and also to compare the impact of the presence of a cross-flow with the impact of the presence of the BA alone. The cross walkers (through which the main flow of participants attempted to pass) were spaced out with a starting line density of 1.11 p/m in each line, just beyond the Endline, and were moving at an initial flow rate (before trial started) of 60 ppm. The cross walkers were instructed to walk around in a loop while trying to maintain this spacing and flow rate. The trial conditions are shown in Figure 21.

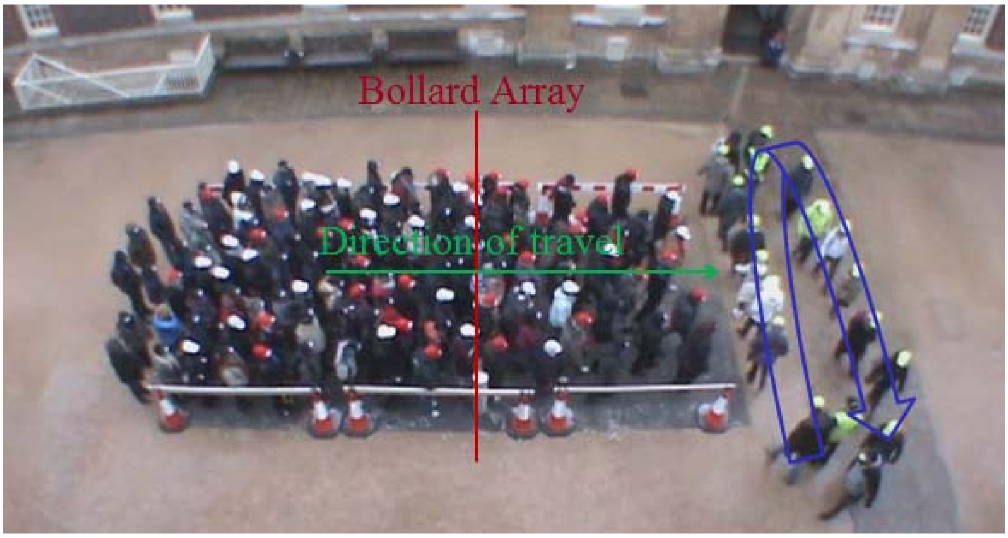


Figure 21: TS2 trial conditions involving cross-flow.

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 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 rate at exit (or other specified location), flow rate at bollards, density at bollards, and gap usage.

Each type of data collected is now described.

3.1 DENSITY MEASUREMENTS:

In TS1 population densities were measured in the holding area and at the BA line. In TS2, densities were measured at the BA line and at the Endline.

3.1.1 TS1: INITIAL DENSITIES IN HOLDING AREA

The initial densities were critical as they represented a controlled variable in the experimental condition. Two 5m^2 areas were marked out in red over the video near the front and rear of the queuing participants (see Figure 22). 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 22, the trial condition required 4 p/m^2 starting density and there are 20 people in each area.

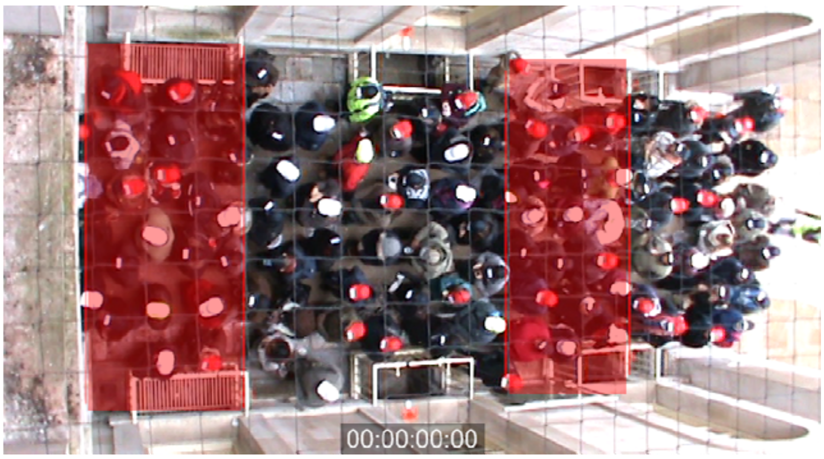


Figure 22: Example footage from initial density analysis.

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 previous 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 23 and Figure 24).

a) Camera 1b No BA at 6m (Day 2 setup)

b) Camera 2 No BA at 6m (Day 2 setup)

c) Camera 1b 6m BA (Day 2 Setup)

d) Camera 2 6m BA (Day 2 Setup)

e) Camera 1b No BA at 6m (Day 1 Setup)

f) Camera 2 No BA at 6m (Day 1 Setup)

g) Camera 1b 6m BA (Day 1 Setup)

h) Camera 2 6m BA)Day 1 Setup)

Figure 23: Example footage from density analysis at 6m.

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 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 6m and 3m BA stand-off positions.

a) Camera 1b No BA at 3m (Day 2 Setup) b) Camera 2 No BA at 3m (Day 2 Setup)

c) Camera 1b No BA at 3m (Day 1 Setup) d) Camera 2 No BA at 3m (Day 1 Setup)

e) Camera 1b 3m BA (Day 2 Setup) f) Camera 2 3m BA (Day 2 Setup)

Figure 24: Example footage from density analysis at 3m.

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 1b 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 23 for 6m and Figure 24 for 3m. It should be noted that due to the narrower setup of the trials conducted on Day 1, only the central region B can be compared when using these trials as regions A and C lie mostly outside the barriers, see Figure 24 (c).

The density around the bollard for the 0m trials was assumed to be that of the starting conditions.

3.1.3 TS2: GENERAL DENSITIES AT BOLLARD ARRAY AND ENDLINE

Densities were also calculated during TS2 – around the BA line and 3.76m beyond this point around the Endline (the green lines in Figure 25). Lines were overlaid on the video footage, 1m either side of the green lines, defining the areas at ground level, using the floor tiles as a guide (the red lines in Figure 25). The area of these regions around the BA line (when no BA present) and the Endline was $8.04m^2$. When bollards were present at the BA line the total area of the bollards or part of bollards was subtracted to give the available area of $7.92m^2$. The density within these areas was measured at 3 second intervals for the trials with a starting density of $4p/m^2$ and at 2 second intervals for the $3p/m^2$ trials. A shorter time step was required for the $3p/m^2$ trials given that the trials took less time to complete due to having fewer people. This allowed the density to be established and then compared between trial conditions.

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 2 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 25 shows an example of this analysis; a) without cross-walkers and b) with cross-walkers.

a) Camera 2 TS2 b) Camera 2 TS2 with cross walkers

Figure 25: Density measurement in TS2 (Camera 2).

3.2 TS1: GAP USAGE AT BOLLARD ARRAY LOCATION

The number of people using each gap during each of the 6m and 3m trials over the entire trial period was counted in order to measure how the population spread out during the trials. The gaps available were numbered 1 to 5 (from left to right within the BA, see Figure 26). The examination of the use of these gaps is referred to throughout the discussion of TS1 trials as gap analysis.

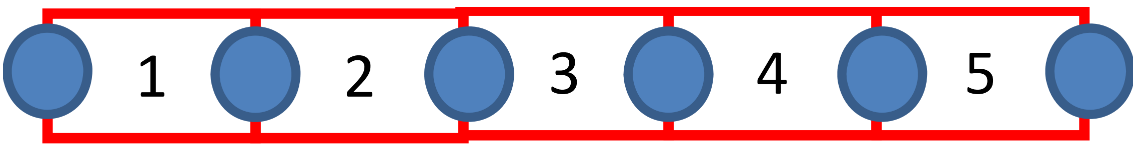


Figure 26: Numbering of the gaps within the BA.

3.3 FLOW RATE MEASUREMENTS

In TS1, flow rate measurements were conducted at the exit point and at the BA position for the 0m, 3m, 6m and 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.

In TS2, flow rates were measured at the BA line and at the end line. These trials were completed in less time than the TS1 trials given the reduced number of people involved. This meant that the time period used to extract results from the video footage was reduced to ensure sufficient data points. During these trials the time interval for the 4p/m^2 trials was 3.0 seconds, while the time interval for the 3p/m^2 trials was 2.0 seconds.

3.3.1 TS1: EXIT FLOW RATES

To measure the flow rate at the exit, a red line was superimposed on the video footage at ground level and along the start line. This line passed through where the bollard would be at 0m distance and was used whether or not the BA was present (see Figure 27). The number of people that passed the superimposed red line within each 5 second period was counted using only the view from Camera 1b. 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.

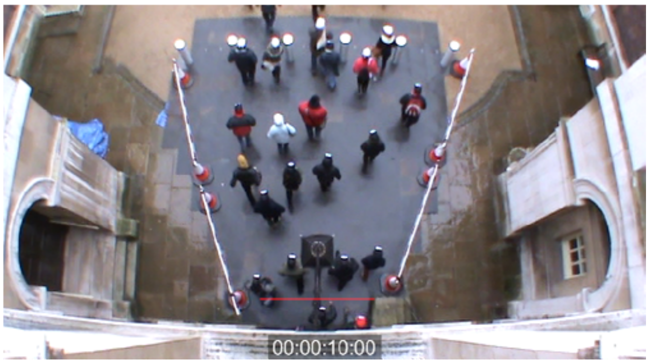


Figure 27: Example footage from exit flow analysis (Camera 1b).

3.3.2 TS1: BA FLOW RATES

The flow rate was also measured at the 3m and 6m stand-off positions. A line was superimposed on the video footage across the full width of the enclosed space at ground height, either at 3m or 6m distance, along the line of the BA or where the BA would be in the trials where no bollards were present. The number of people that had passed the superimposed red line within each 5 second period was counted. Two camera views (Camera 1b and Camera 2) were required when measuring the flow rate at the 3m line (see Figure 28) while Camera 2 was used when measuring the flow rate at the 6m line (see Figure 29).

a) Camera 1b: 3m No BA b) Camera 2: 3m No BA

c) Camera 1b: 3m BA d) Camera 2: 3m BA

Figure 28: Example footage from bollard flow analysis at 3m.

a) Camera 2: 6m No BA (Day 2 Setup) b) Camera 2: 6m BA (Day 2 Setup)

c) Camera 2: 6m No BA (Day 1 Setup) d) Camera 2: 6m BA (Day 1 Setup)

Figure 29: Example footage from bollard flow analysis at 6m.

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

3.3.3 TS2: BA AND ENDLINE FLOW RATES

To measure the flow rate at the BA and Endline, lines were superimposed on the video footage at ground height, at the BA location (whether it was present or not) and 3.76m beyond this point – 1m in from the end of the artificial flooring (the green lines in Figure 25). This was selected to provide the maximum distance beyond the BA location that still enabled a consistent and accurate reading to be taken.

The number of people that had passed the superimposed green line within each time interval was counted. This was done for both the BA line and the Endline (with the same position of lines used for the TS2 trials with cross walkers). A person was counted if at least half of their body footprint had crossed the green line during the time interval. When measuring the flow rate at the Endline particular consideration of the perspective of the camera angle was required.

3.3.4 TS2: BA AND ENDLINE FLOW RATES WITH CROSS WALKERS

For the TS2 trials, where cross walkers were used, in addition to the flow rates at the BA Line and Endline, the flow rate of the cross walkers was measured in two places (see the horizontal green lines in Figure 25(b)). The cross walkers (through which the main flow of participants attempted to pass) were spaced out with a starting line density of 1.11 p/m in each line, just beyond the Endline, and were moving at an initial flow rate (before trial started) of 60 ppm. The cross walkers were instructed to walk around in a loop while trying to maintain this spacing and flow rate (see Figure 30).

Figure 30: TS2 Trial setup with cross walkers (Camera 2).

The number of cross walkers that passed each line was then counted during each time interval in order to monitor the flow of cross walkers. A cross walker was counted if at least half of their body footprint had passed line during the time interval. This was done using Camera 2 and careful consideration of the perspective view was required.

There were no cross walker trials conducted with the BA present at 3p/m^2 due to the adverse weather conditions at that time.

3.4 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 rate at the exit (or Endline), flow rate at BA, Gap usage and BA density analysis 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.

4 RESULTS

In these sections the results produced during the TS1 and the TS2 experimental trials are presented.

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 rate measured at the BA Line.
- Core trials – set of trials excluding those with lowest and highest flow rates.
- * - An asterisk at the end of a series name in the graphs denotes Day 1 narrow setup
- CW – Cross Walkers, used in reference to the additional trials conducted for TS2. The term describes the sub-population that walked across the face of the on-coming main flow.
- Endline – A line 3.76m beyond bollard array in TS2.
- Exit Flow – Flow rate 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
    - For TS1 and TS2 the definition of peak flow is that which begins with the second non-zero flow time period, and concludes with the penultimate non-zero flow time period.
    - For TS2 with cross-walking an additional caveat was included if the flow tailed off but still met the above criteria; If the flow dropped below 30% of the highest flow level in the peak period, then the period would be truncated at this point

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:

[Density]_[Bollard Array Presence]_[Stand-Off distance]_[Trial Type]

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

[3|4]_[BA|NoBA]_[0m|3m|6m]_[TS1|TS2|TS2_CW]

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

4.2.1 INITIAL POPULATION 4P/M^2 – 6M BOLLARD ARRAY LOCATION

The results produced during the 4_NoBA_TS1 trials are initially presented and discussed. This is followed by a discussion of the 4_BA_6m_TS1 trials, along with a justification for focusing the analysis on the core trials and the peak time periods.

4.2.1.1 NoBA BASE RESULTS – 4p/m^2

The NoBA trials are referred to throughout the section describing the TS1 results produced in trials with an initial density of 4p/m^2. Furthermore, different combinations of the data are explored in which results from outlier trials are removed. An overview of the results produced is presented in Table 12 and Table 13. Presented in Table 12 are the average exit flows during peak periods for TS1 for the 4 p/m^2 initial density. The presented results are based on data collected from; all 5 trials, 4 trials, in which the slowest data-set is removed and 3 trials in which the slowest and fastest data-sets are removed.

Table 12: TS1: Exit flows for NoBA trials at 4p/m^2.

Scenario	Flow (ppm) at Exit
4_NoBA_TS1 (5 trials)	245.8 [230.0 – 258.0]
4_NoBA_TS1 (slowest trial removed - 4 trials)	249.8 [242.0 – 258.0]
4_NoBA_TS1 (slowest and fastest trials removed - 3 trials)	247.1 [242.0 – 252.0]

Presented in Table 13 are the exit flows for each of the TS1 NoBA trials for the 4 p/m^2 initial density presented in 5 second time periods during the peak period. Also presented is the average peak period flow.

Table 13: TS1 - Exit flow during peak period measured in 5 sec time intervals for the 4p/m^{2}trials with NoBA.

4_NoBA_TS1	Peak period flow (ppm) Time interval (sec)						Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial B5	288	252	276	276	228	228	258.0
Trial B7	288	252	264	252	228	228	252.0
Trial 7	276	264	216	264	216	216	242.0
Trial 9	300	240	228	240	228	--	247.2
Trial 11	240	228	228	264	228	192	230.0

The results presented in these two tables are referred to frequently throughout the following discussion.

4.2.1.2 ORIGINAL EXIT FLOW TRIALS

The first analysis reflects the full set of trials for the 4p/m^2 condition (see Figure 31). The flow rates produced where the bollards were present (BA) and where they were absent (NoBA) are shown in Figure 32 and Figure 33 respectively.

Figure 31: Overview of TS1 6m BA trial day 1 configuration.

As can be seen from Figure 32 and Figure 33, the flow conditions in each of the trials were broadly similar, with each set of trials producing broadly similar trends in exit flows; i.e. the five NoBA trials were broadly similar and the five 6m BA trials were broadly similar.

As discussed previously (see Section 2.3.3), it is apparent that the initial and final time periods produced variable results that were not representative of the desired steady state flow, for the reasons given. The rest of the detailed analysis presented focuses upon these peak time periods, with the inclusion of the non-peak periods primarily made only for comparison.

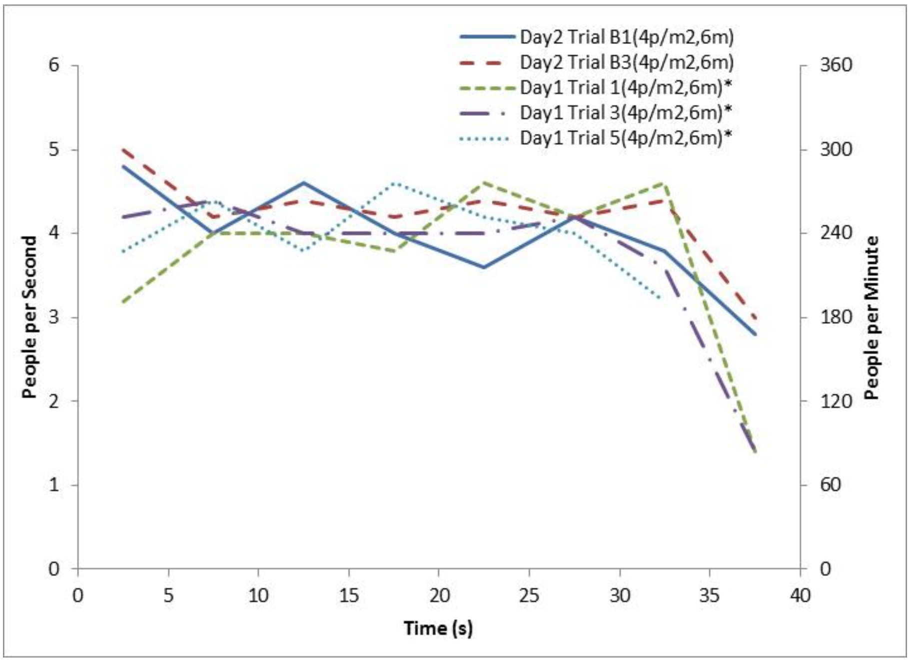


Figure 32: TS1 – Exit flow rate measured in 5 sec intervals for the five 6m BA 4 p/m^2 trials.

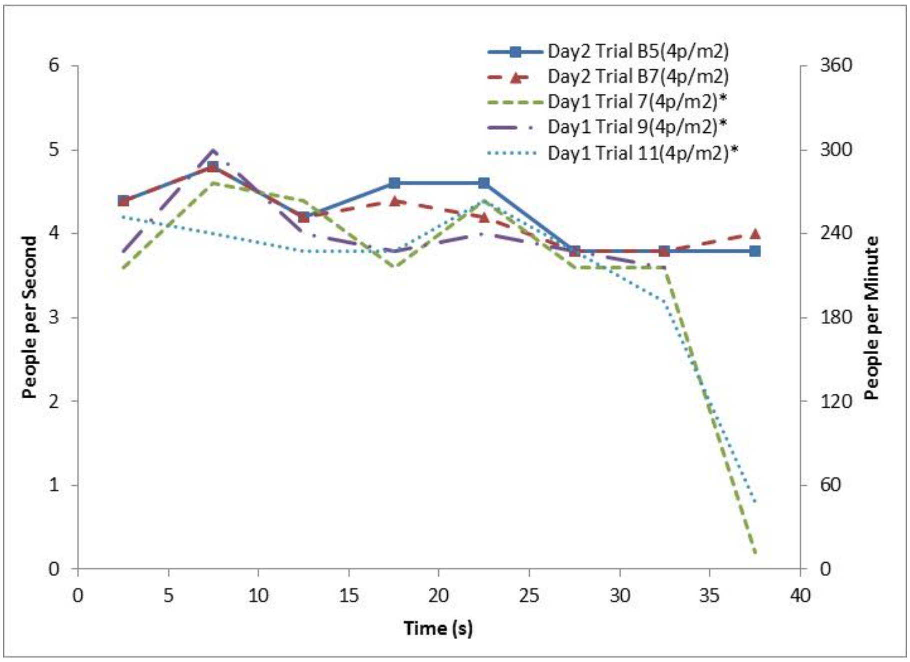


Figure 33: TS1 – Exit flow rate measured in 5 sec intervals for the five NoBA 4 p/m^2 trials

The curves for the remaining peak flow conditions, once these two (non-peak) time periods are removed, are shown in Figure 34 and Figure 35, representing the 6m BA and NoBA conditions.

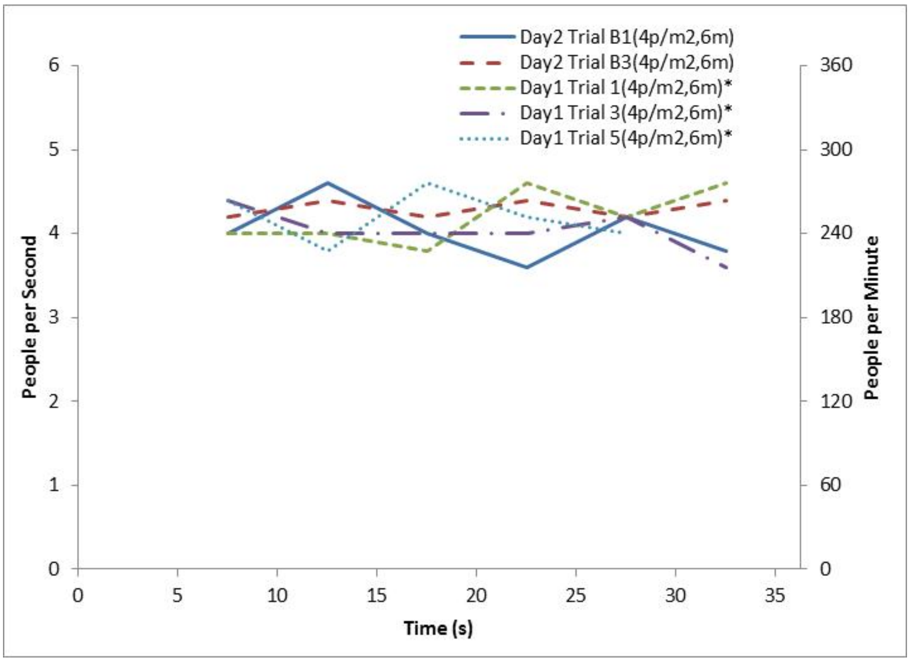


Figure 34: TS1 - Peak exit flow rate measured in 5 sec intervals for the five 6m BA 4 p/m^2 trials

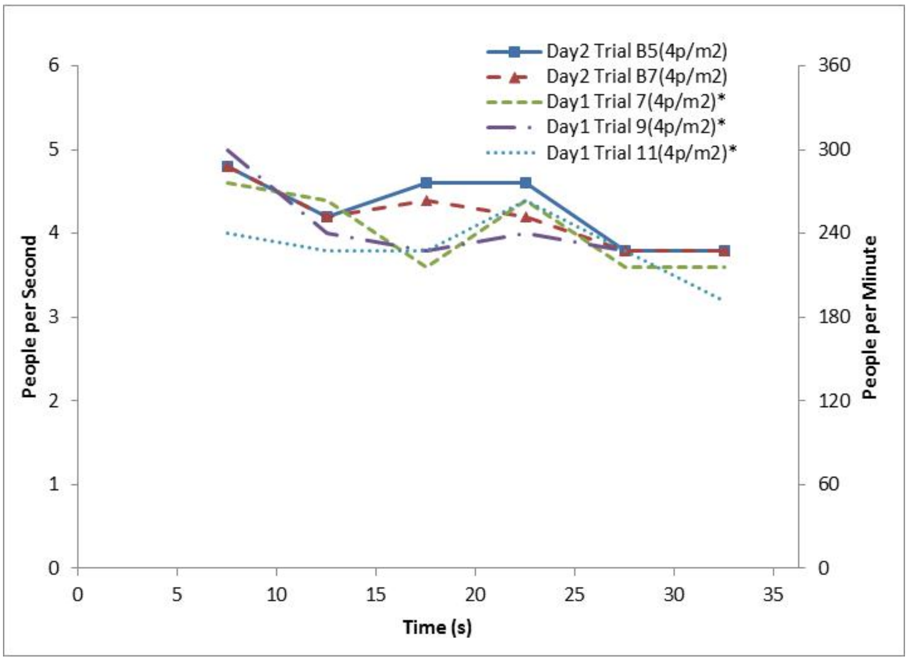


Figure 35: TS1 - Peak exit flow rate measured in 5 second intervals for the five NoBA trials

It is also instructive to compare the average peak flow curves for the Day 1 and Day 2 trials. From Figure 36 and Figure 37 it is apparent that the conditions and the subsequent results produced were qualitatively consistent allowing them to be combined where necessary.

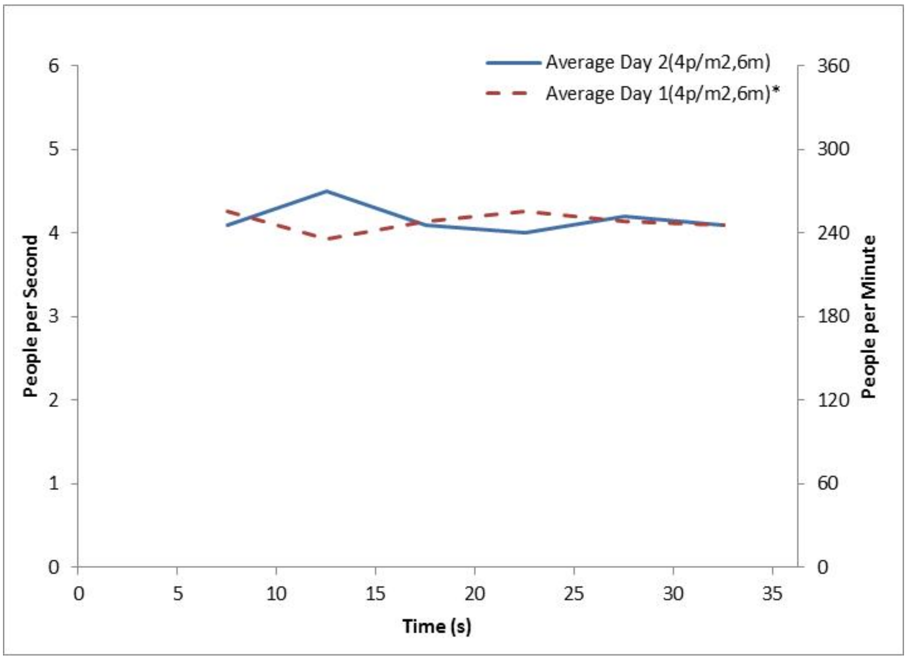


Figure 36: TS1 - Average exit peak flow rate measured in 5 second intervals for the 6m BA 4 p/m^2 trials for day 1 and day 2

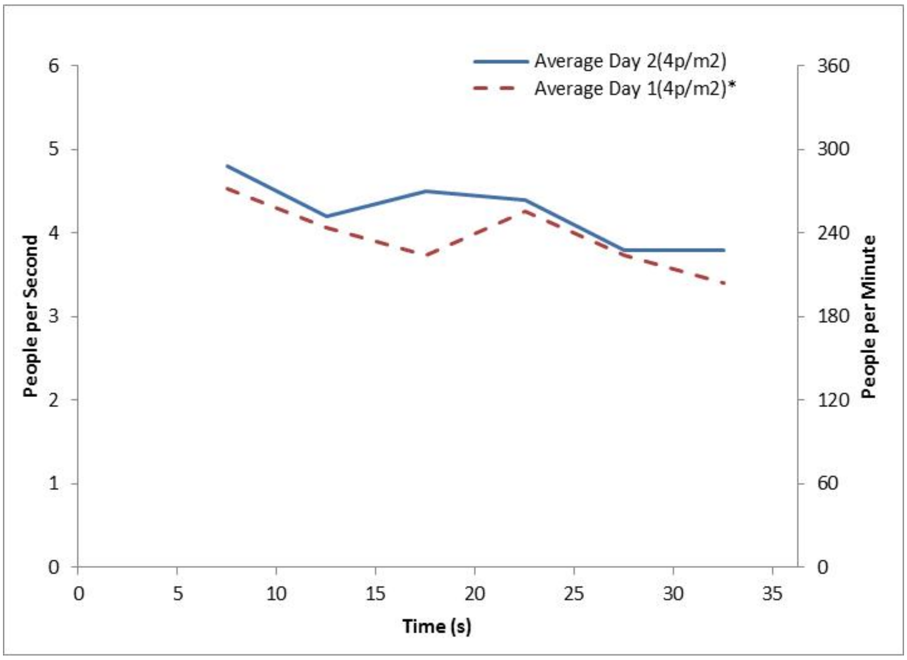


Figure 37: TS1 - Average exit peak flow rate measured in 5 sec intervals for the NoBA 4 p/m^2 trials for day 1 and day 2

Table 14 compares the peak flow results at the exit, with an initial density of 4p/m^2 for trials with NoBA and with the 6m BA trials. The results show that across five trials, the 6m BA case produced flow rates that were, on average, 1.4% greater (with a range of -3.5% to +7.7%) than the equivalent NoBA case. The NoBA trials produced an average flow rate of 245.8ppm (with a standard deviation of 10.65 and a range of -6.4% to +4.9%) while the 6m BA case produced an average flow rate of 249.2ppm (with a standard deviation of 7.01 and a range of -2.9% to +3.5%).

Table 14: TS1: Average Exit flow rates using data from all 5 trials at 4p/m^2.

	Flow (ppm) at Exit
4_NoBA_TS1	245.8 [230.0 – 258.0]
4_BA_6m_TS1	249.2 [242.0 – 258.0]

The difference in average peak exit flows between the 6m BA and NoBA cases is 3.4 ppm or 1.4%. This difference in exit flow rates is small and, as shown in Figure 38, during the peak flow period, the NoBA and BA trials fluctuate in the flow levels produced, with them alternating in producing marginally higher results than the other.

It is noted that the difference in average exit flow rates between the two sets of conditions is lower than the trial by trial variability within the series of NoBA trials and the 6m BA trials. In addition it can be seen from the standard deviations that the NoBA case generated a greater variability than the 6m BA case.

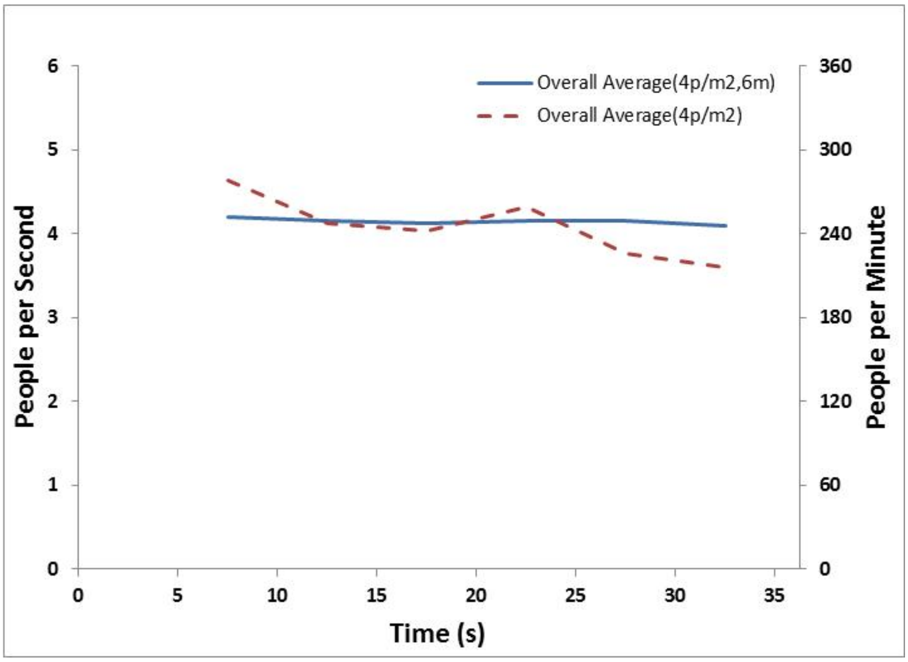


Figure 38: TS1 -Average exit peak flow rate measured in 5 second intervals for both the 6m BA and NoBA trials

Table 15 shows the ranking of the two sets of trials according to the flow rates produced. From Table 15 it can be seen that in 48% of the comparisons, BA trials produced higher flow rates; in 32% of the comparisons they produced lower flow rates and in 20% of the comparisons they produced equal flow rates. This indicates that, overall, the presence of bollards resulted in a *modest increase* in flow rate at the exit.

Table 15: TS1: Trial Ranking for Exit flow trials at 4p/m^2 with 6m BA.

4_6m_BA_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1 Trials	Equal to 4_NoBA_TS1Trials
Trial B1	1	3	1
Trial B3	4	0	1
Trial 1	3	1	1
Trial 3	1	3	1
Trial 5	3	1	1
Total	12	8	5

Table 16 and Table 17 include the average flow rate at the exit within each 5 second interval of the peak flow period for each of the 6m BA and NoBA trials. The data in these tables has then been used to calculate the overall average exit flow rate. Variability is apparent in both conditions over the time intervals examined.

Table 16: TS1: Exit flow during peak period measured in 5 sec time intervals for the 4p/m^2 trials with 6m BA.

4_6m_BA_TS1	Peak period flow (ppm) Time interval (sec)						Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial B1	240	276	240	216	252	228	242.0
Trial B3	252	264	252	264	252	264	258.0
Trial 1	240	240	228	276	252	276	252.0
Trial 3	264	240	240	240	252	216	242.0
Trial 5	264	228	276	252	240		252.0
Average (ppm)	252.0	249.6	247.2	249.6	249.6	246.0	249.2

Table 17: TS1: Exit flow during peak period measured in 5 sec time intervals for the $4p/m^2$ trials with NoBA.

4_NoBA_TS1	Peak period flow (ppm) Time interval (sec)						Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial B5	288	252	276	276	228	228	258.0
Trial B7	288	252	264	252	228	228	252.0
Trial 7	276	264	216	264	216	216	242.0
Trial 9	300	240	228	240	228	--	247.2
Trial 11	240	228	228	264	228	192	230.0
Average (ppm)	278.4	247.2	242.4	259.2	225.6	216.0	245.8

Figure 39 shows the results of the average and range of the average peak flow rates produced over the five NoBA and 6m BA trials. This shows that the 6m BA trials produced numerically higher average exit flow rates than the NoBA trials, but that the difference in the averages was significantly less than the variability within each NoBA and 6m BA trials.

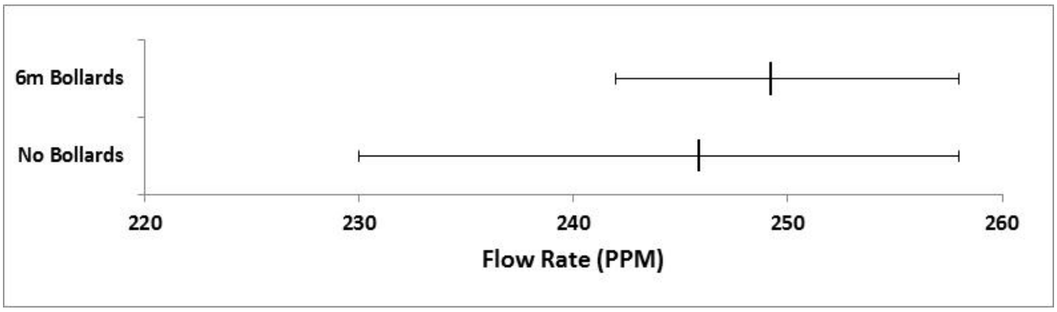


Figure 39: TS1 – Average and range of peak exit flow rates for the 6m BA and NoBA 4 p/m^2 trials.

Key Findings: There is little difference between the results produced by the trials with no bollards (NoBA) and those with the 6m bollards present (BA), with the latter producing 1.4% higher exit flow rates than the trials with no bollards present.

4.2.1.3 INCREMENTAL REMOVAL OF DATA (slowest data removed)

It is apparent from Figure 34 and Figure 35 that in both the NoBA and 6m BA trials there is a degree of spread in the results. To reduce this variability, the outlier trials that produced the slowest and fastest average flow rates during this peak period were incrementally removed. The results of this process are now briefly described.

Table 18 shows the NoBA peak flow results at the exit, with an initial density of 4p/m^2 for the NoBA compared with the 6m BA trials. In this instance, the slowest of each of the NoBA and 6m BA trials have been removed before analysis is performed (see Figure 40).

Table 18: TS1:Average exit flow for peak period at 4p/m^2 with lowest flow rate removed (data from 4 trails).

	Flow (ppm) at Exit
4_NoBA_TS1	249.8 [242.0 – 258.0]
4_BA_6m_TS1	251.0 [242.0 – 258.0]

The NoBA case produced an average flow rate of 249.8ppm (with a standard deviation of 6.82 and a range of -3.1% to +3.3%) while the 6m BA case produced an average flow rate of 251.0ppm (with a standard deviation of 6.63 and a range of -3.6% to +2.8%).

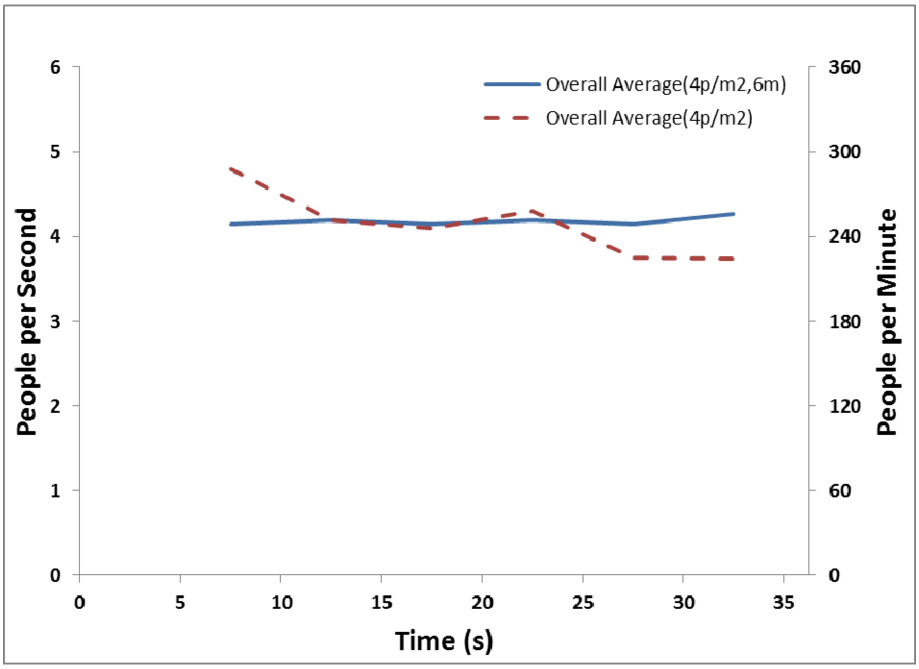


Figure 40: TS1 - Average peak flow rate at 5 second intervals for both the 6m BA and NoBA trials, 4 cases (slowest case removed)

The difference in average peak exit flows between the 6m BA and NoBA cases is 1.2 ppm or 0.5%. This difference in exit flow rates is small and as shown in Figure 40, during the peak flow period, sometimes the NoBA case produces marginally greater flow rates than the 6m BA case and sometimes it produces marginally lower flow rates. It is noted that the difference in average exit flow rates between the two sets of conditions is lower than the trial by trial variability within the series of NoBA trials and the 6m BA trials. In addition it can be seen from the standard deviations that the two cases have very similar variability in resulting flow and identical ranges. The 6m BA average flow rate was higher than two of the four individual NoBA results and lower than the other two.

Table 19 shows the ranking of the two sets of trials according to the flow rates produced. From Table 19 it can be seen that in 44% of the comparisons, the 6m BA trials produced higher flow rates; in 31% of the comparisons they produced lower flow rates and in 25% of the comparisons they produced equal flow rates.

Table 19: TS1: Trial Ranking for Exit flow trials at 4p/m^2 with 6m BA (slowest trial removed).

4_BA_6m_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1 Trials	Equal to 4_NoBA_TS1 Trials
Trial 1	2	1	1
Trial 5	2	1	1
Trial B1	0	3	1
Trial B3	3	0	1
Total	7	5	4

This indicates evidence that overall, the presence of bollards at the 6m stand-off position resulted in a modest increase in flow rate at the exit. Table 19 should be compared with Table 15 where the ranking of the trials is seen to be broadly comparable.

Table 20 shows for the 6m BA trials, with the slowest trial removed the average flow rate at the exit within each 5 second interval of the peak flow period. This can be compared with Table 21where the equivalent NoBA results are presented. The data in Table 20 and Table 21 have then been used to calculate the overall average flow rate. Comparing these results with those in Table 16, it is apparent that there is only a modest change in average peak flow produced (representing a 0.7% in comparison with the value for the full five trials)

Table 20: TS1: Peak flow according to time intervals for exit flow trials at 4p/m^2 with 6m BA (slowest trial removed).

4_BA_6m_TS1	Peak period flow (ppm) Time interval (sec)						Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 1	240	240	228	276	252	276	252.0
Trial 5	264	228	276	252	240	--	252.0
Trial B1	240	276	240	216	252	228	242.0
Trial B3	252	264	252	264	252	264	258.0
Average (ppm)	255.0	243.0	249.0	258.0	249.0	252.0	251.0

Table 21: TS1: Peak flow according to time intervals for exit flow trials at 4p/m^2 with NoBA (slowest trial removed).

4_NoBA_TS1	Peak period flow (ppm) Time interval (sec)						Average (ppm)
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 7	276	264	216	264	216	216	242.0
Trial 9	300	240	228	240	228		247.2
Trial B5	288	252	276	276	228	228	258.0
Trial B7	288	252	264	252	228	228	252.0
Average (ppm)	288.0	252.0	246.0	258.0	225.0	224.0	249.8

Figure 41 shows the results of the average and range of the average peak flow rates produced over the four NoBA and 6m BA trials with the slowest trial having been removed. Comparing this with the data from the full set of trials (see Figure 39), the decrease in the spread of results is apparent, with only a modest numerical impact on the average flow produced. The difference between the averages is still considerably less than the spread in the trial results for each case.

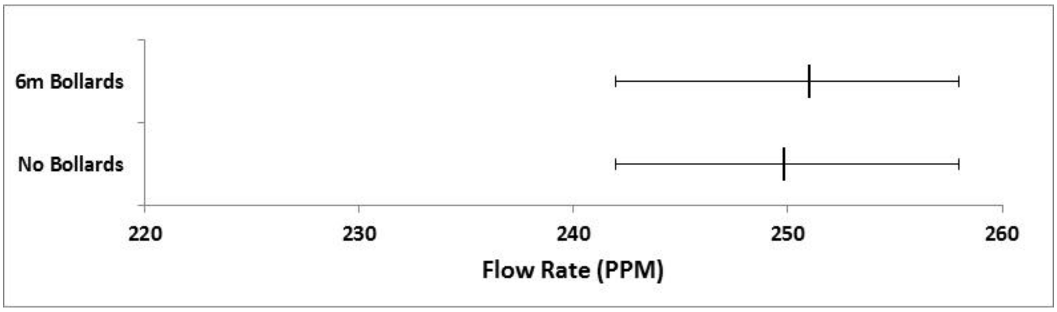


Figure 41: TS1: Average and range of peak exit flow rates for the 6m BA and NoBA 4 p/m^2 trials (slowest trial removed).

Key findings: The findings for this analysis are similar to the analysis for the full-set of trial data; i.e., that there is little numerical difference between the NoBA and 6m BA trials at 4p/m^2, with the 6m BA trials producing 0.5% higher flow rates.

The analysis is continued with the trial producing the highest average peak flow removed. This was again performed in order to decrease the impact of trial outliers.

4.2.1.4 CORE EXIT FLOW (fastest and slowest data removed)

Table 22 shows the comparison between flow rates produced in the peak time periods at the exit for the NoBA and 6m BA trials, with an initial density of 4p/m^2 (see Figure 31). In this case the fastest and slowest of each of the NoBA and 6m BA trials have been removed before analysis is performed (see Section 4.2.1.3). This should be considered the **core** data for analysis. As mentioned, this core data will be addressed in the body of the report while the complete data-sets will be presented in the associated appendices, unless specifically stated otherwise.

The results in Table 22 show that the 6m BA trials produced exit flow rates that were on average 1.6 ppm or 0.6% greater than the equivalent NoBA case. The NoBA case produced an average flow rate of 247.1ppm (with a standard deviation of 5.00 and a range of -2.1% to +2.0%), while the 6m BA case produced an average flow rate of 248.7ppm (with a standard deviation of 5.77 and a range of -2.7% to +1.3%).

Table 22:TS1: Exit Flow for peak period at initial density of 4p/m^2.

Scenario	Flow (ppm) at Exit
4_NoBA_TS1 (3 run)	247.1 [242.0 – 252.0]
4_BA_6m_TS1 (3 run)	248.7 [242.0 – 252.0]

This difference in exit flow rates is small and as shown in Figure 42, during the peak flow period, the NoBA trials and the 6m BA trials alternate in producing marginally greater flow rates. It is noted that the difference in average exit flow rates between the two sets of conditions is smaller than the trial by trial variability within the series of NoBA trials and the 6m BA trials. In addition it can be seen from the standard deviations that the two cases have very similar variability in the resulting flow and identical ranges. The 6m BA average flow rate was higher than two of the three individual NoBA results and lower than the other one.

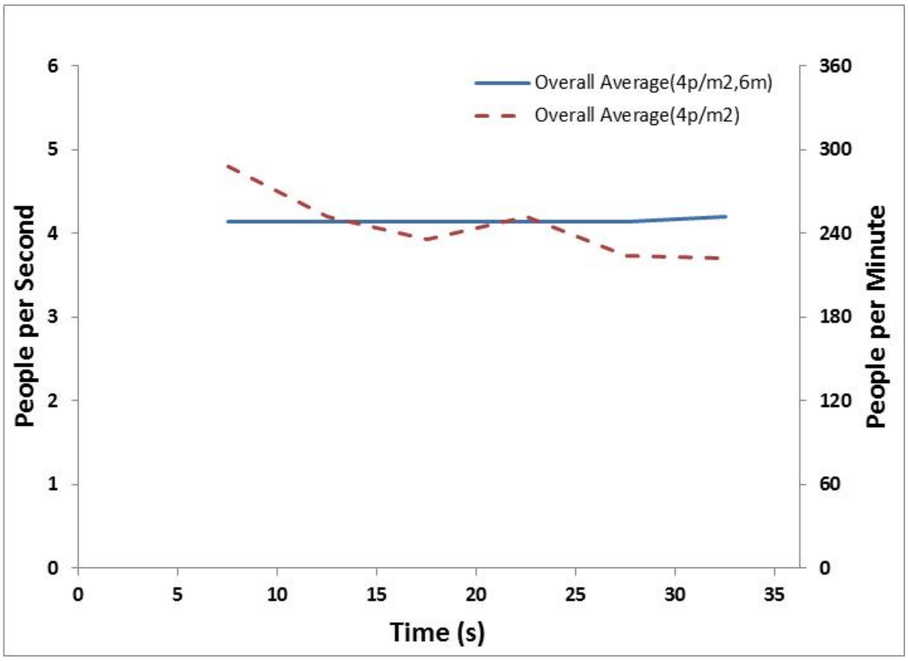


Figure 42: TS1 – Average exit peak flow rate measured in 5 second intervals for both the 6m BA and NoBA core trials.

The individual trials have been ranked according to the flow rates produced. From Table 23 it can be seen that in 44% of the comparisons, the 6m BA trials produced higher flow rates; in 22% of the comparisons they produced lower flow rates and in 33% of the comparisons they produced equal flow rates. This suggests that overall, the presence of bollards resulted in a modest **increase** in flow rate at the exit.

Table 23: TS1: Ranking of trials (slowest and fastest trials removed).

4_BA_6m_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1 Trials	Equal to 4_NoBA_TS1 Trials
Trial 1	2	0	1
Trial 5	2	0	1
Trial B1	0	2	1
Total	4	2	3

Table 24 (and Figure 43) and Table 25 (and Figure 44) show the average flow rate produced at the exit within each 5 second interval of the peak flow period for each of the core 6m BA and NoBA trials respectively. The data in these tables has then been used to calculate the overall average flow in persons per minute.

Table 24: TS1: Peak flow per time interval for core trials with 6m BA.

4_BA_6m_TS1	Peak flow (ppm)						Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 1	240	240	228	276	252	276	252.0
Trial 5	264	228	276	252	240	--	252.0
Trial B1	240	276	240	216	252	228	242.0
Average (ppm)	248.0	248.0	248.0	248.0	248.0	252.0	248.7

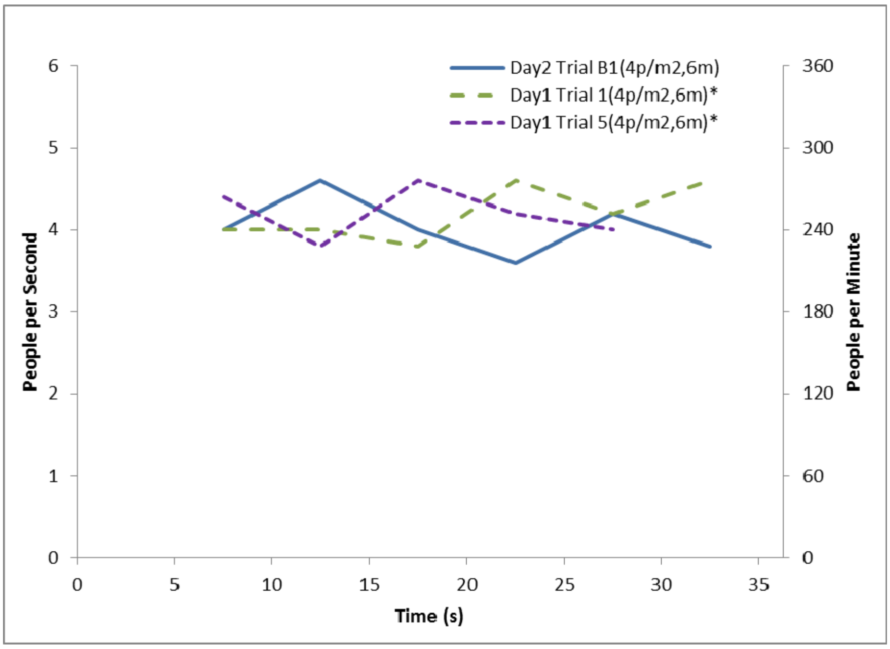


Figure 43: TS1 - Peak exit flow rate measured in 5 second intervals for the three 6m BA trials.

It is apparent that, although not identical, the two sets of results are broadly consistent.

Table 25: TS1: Peak flow per time interval for core trials with NoBA.

4_NoBA_TS1	Peak period flow (ppm)						Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 7	276	264	216	264	216	216	242.0
Trial 9	300	240	228	240	228	--	247.2
Trial B7	288	252	264	252	228	228	252.0
Average (ppm)	288.0	252.0	236.0	252.0	224.0	222.0	247.1

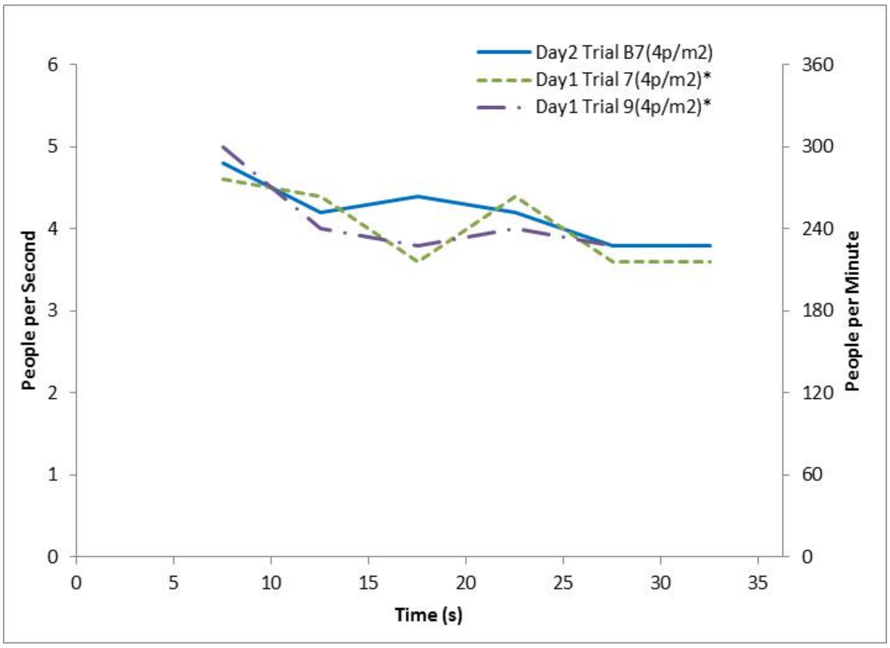


Figure 44: TS1 - Peak exit flow rate measured in 5 second intervals for the three NoBA trials

The quantitative and qualitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 42. For comparison, the flow rates produced across the entire trial (including non-peak times) are also provided in Figure 45. From these figures the similarity in the exit flows for the two conditions (NoBA and 6m BA) is apparent.

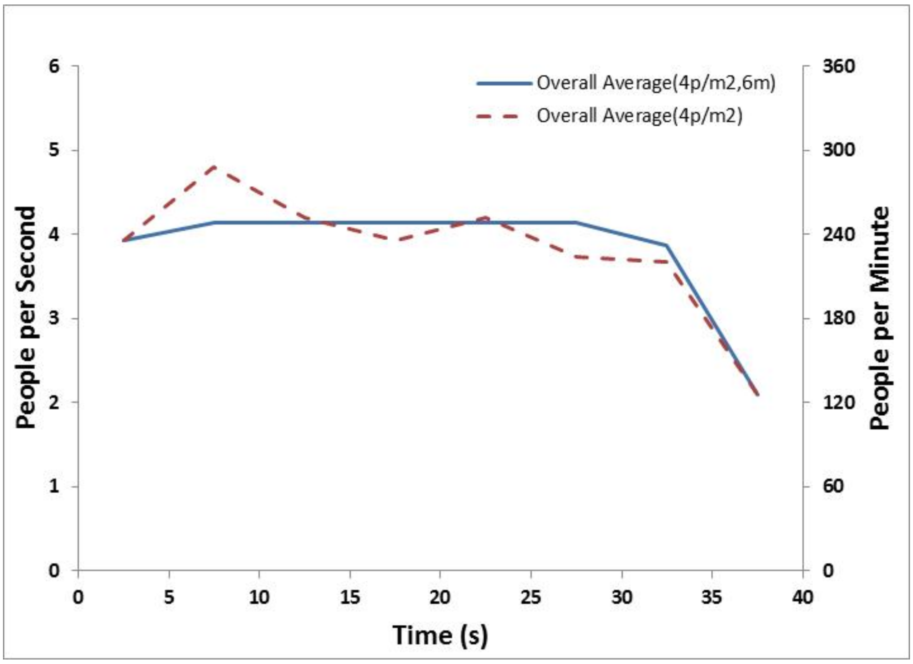


Figure 45: TS1 – Average exit flow rate measured in 5 second intervals for both the 6m BA and NoBA trials – Entire Duration.

Figure 46 shows the average and range of the average peak flow rates produced over the three NoBA and 6m BA trials with the slowest and fastest trials having been removed. Comparing this with the data from the full set of trials (see Figure 39), the decrease in the spread of results is apparent, with only a modest numerical impact on the average flow produced. The difference between the averages is still less than the spread in the trial results for each case. Furthermore, it is apparent that the range in average exit flow rates for the two sets of trial conditions is identical.

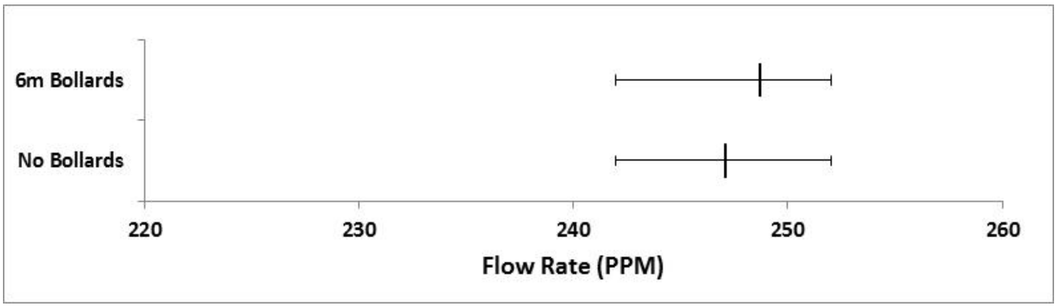


Figure 46: TS1: Average and range of peak exit flow rates for the core 6m BA and NoBA 4 p/m^2 trials.

Key Finding – 4_BA_6m_TS1: The core trials with the 6m bollards present produced average flow rates at the exit that were 0.6% higher than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 6m from the exit compared to the case in which there was no bollard array present.**

4.2.1.5 BOLLARD FLOW

The peak flows at the position of the BA for an initial population density of 4p/m^2 for the NoBA and the 6m BA trials for the core data (i.e. fastest and slowest removed) are presented in Table 26. In the case of the NoBA trials, Table 26 shows that the 6m BA case produced flow rates that were on average 0.1% greater (with a range of -1.6% to +3.3%) than the equivalent NoBA case. The NoBA case produced an average flow rate of 246.2ppm (with a standard deviation of 6.85 and a range of -3.2% to +1.7%) while the 6m BA case produced an average flow rate of 246.4ppm (with a standard deviation of 6.65 and a range of -1.9% to +3.1%). The average flow rates at the position of the BA are almost identical.

Table 26: TS1 -Flow rates at the position of the Bollard Array for the 6m BA trials with a population density of 4p/m^2.

Scenario	Flow (ppm) at BA
4_NoBA_TS1 (3 run)	246.2 [238.3 – 250.3]
4_BA_6m_TS1 (3 run)	246.4 [241.7 – 254.0]

The average flow rate produced during the 6m BA trials was higher than one of the three individual NoBA results and lower than two. The individual trials have been ranked according to the flow rates produced. From Table 27 it can be seen that in 56% of the comparisons, the 6m BA trials produced higher flow rates; in 44% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates. This suggests that overall, the presence of bollards resulted in little difference in the flow rate produced at the Bollard Array.

Table 27: TS1: Ranking of BA trial results.

4_BA_6m_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1 Trials	Equal to 4_NoBA_TS1 Trials
Trial 1	1	2	0
Trial 5	3	0	0
Trial B1	1	2	0
Total	5	4	0

Table 28: TS1: Peak flow per time interval at BA for core trials with 6m BA.

	Peak period flow (ppm)							Average (ppm)
	Time since trial start (5s intervals)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Trial 1	204	252	228	252	252	276	240	243.4
Trial 5	240	264	228	288	240	264		254.0
Trial B1	276	216	300	252	192	264	192	241.7
Average (ppm)	240.0	244.0	252.0	264.0	228.0	268.0	216.0	246.4

Table 29: TS1: Peak flow per time interval at BA for core trials with NoBA.

	Peak period flow (ppm)							Average (ppm)
	Time since trial start (5s intervals)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Trial 7	240	276	288	204	240	216	204	238.3
Trial 9	252	288	252	204	288	216		250.0
Trial B7	288	252	264	276	252	216	204	250.3
Average (ppm)	260.0	272.0	268.0	228.0	260.0	216.0	204.0	246.2

Table 28 and Table 29 show the average flow rate produced at the BA within each 5 second interval of the peak flow period for each of the 6m BA and NoBA trials. The data has then been used to calculate the overall average flow in persons per minute. It is apparent that the average flow rates produced in the BA 6m trials (246.4 ppm) are similar to those produced during the NoBA trials (246.2ppm).

Comparing the flow rates at the BA line (Table 26) with those at the exit (Table 22) suggests that the average flow rate at both locations, for both sets of conditions, are broadly similar. This might indicate a number of things including (1) the BA conditions did not feedback to the exit given the 6m stand-off, or (2) the presence of the BA at 6m had little impact on the conditions present (see Section 4.2.1.7).

The quantitative and qualitative similarity between the flow rates produced is more apparent when examining Figure 47.

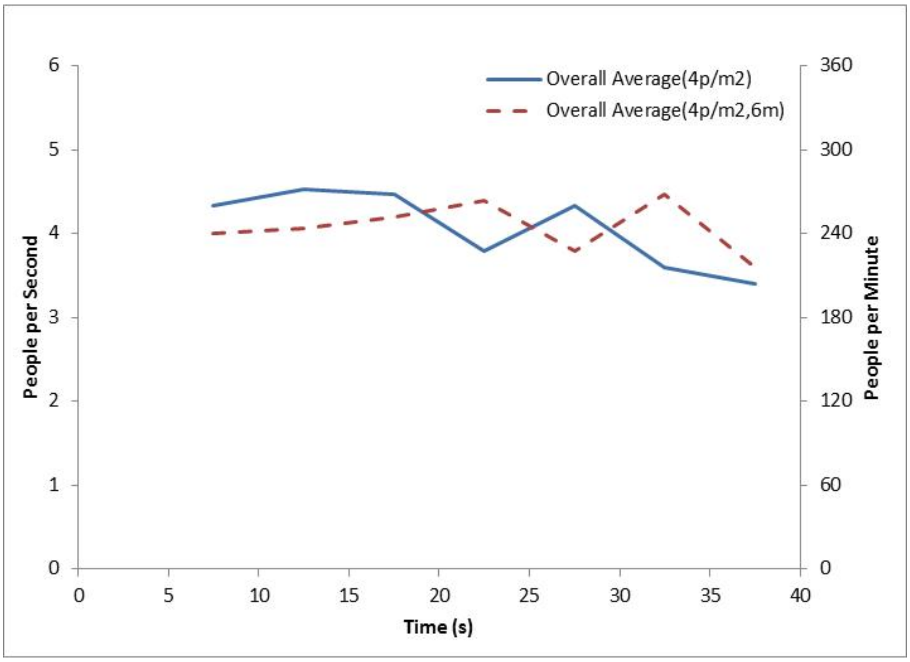


Figure 47: TS1 – Average BA peak flow rate measured in 5 second intervals for the 6m BA and NoBA trials

Figure 48 shows the results of the average and range of the peak flow rates produced during the core NoBA and 6m BA trials at the BA location. This shows that there is little difference in average flow rates produced (246.2 and 246.4), but that both the minimum and maximum values of the flow rates produced at the 6m BA were larger than when the BA was absent

(241.7-254.0ppm as opposed to 238.3-250.3ppm). Furthermore, the difference between the averages is less than the spread in the trial results for each case.

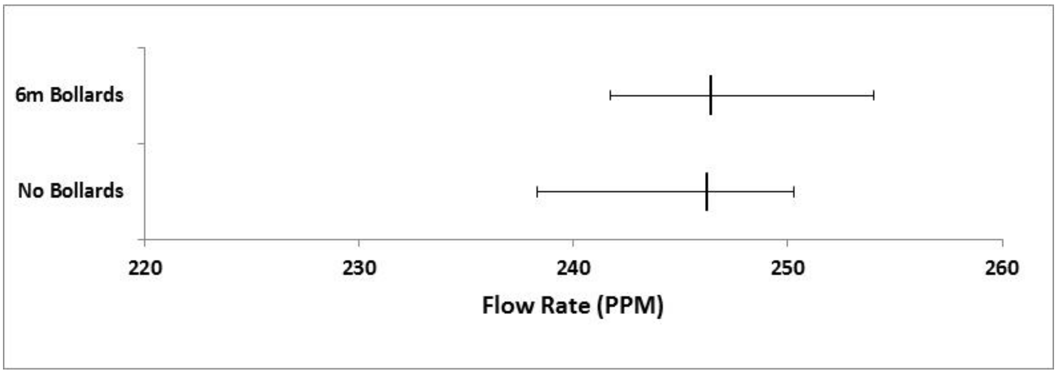


Figure 48: TS1 – Average and range of peak exit flow rates for the core 6m BA and NoBA 4 p/m^2 trials.

Key Finding - 4_BA_6m_TS1: There is no appreciable difference in the flow rates at the bollard line produced during the NoBA and 6m BA trials at 4p/m^2, with the latter producing 0.1% higher flow rates. The results produced do not demonstrate a clear numerical difference between the conditions examined. **The results suggest that there is no appreciable difference in the average flow rate 6m from the exit that would be produced if a bollard array was located at this position compared to the case in which there was no bollard array present.**

4.2.1.6 GAP ANALYSIS

The manner in which the participants made use of the various gaps between the BA was examined (with the gaps numbered 1-5, see Figure 26). The average gap usage over the entire set of trials (5 trials), for the case where the slowest trial is removed (4 trials) and for the case with the fastest and slowest trials removed (3 trials) is presented in Table 30 and Figure 49. The average gap usage was determined using a weighted average which was dependent on the number of people in each trial. In addition, for trials in which the BA was not present (NoBA trials), the number of people passing through the regions where the gaps would have been located had a BA been present were also counted. This allowed a comparison to be made between the degree the participants spread out in the BA and NoBA trials.

From this analysis it is clear that the participants do not spread out to equally use the entire available width of the BA. The participants are focused on using the central gap and the gaps either side of the centre, with very little usage of the gaps at the extremities (i.e., 1 and 5). This is because the target for the participants is at the opposite end of the courtyard; i.e., directly ahead of them. However, as gaps 2, 3 and 4 attract heavy usage it is clear that participants are prepared to spread out or diffuse as they pass through the courtyard onto their target destination, at least to some degree. Furthermore, even gaps 1 and 5 in the extremities of the BA attract some usage. This may have been due to the individuals making a deliberate choice to use alternate routes, or them spilling over into less crowded adjacent gaps due to congestion. However, it is noted that the gap usage is symmetrical, with one side typically not being favoured over another side.

It is apparent that as the trials are incrementally removed, as described previously, the gap usage subtly changes, although these changes do not affect any conclusions that might be drawn. It is noticeable that the removal of the fastest trial produced a greater use of the central gap with a corresponding significant decrease in the gap usage in the extremities. This suggests that the fastest trial may have been a result of a more balanced use of the gaps available in the BA leading to the population spreading out more between the gaps available; i.e., they were more able to move at their desired speed.

Table 30: TS1: Percentage of participants using the available gaps between bollards given the sets of 6m BA trials examined.

4_BA_6m_TS1	% Gap Usage				
# Trials	1	2	3	4	5
5 (all trial data used)	8.0	25.7	34.2	25.3	6.8
4 (slowest removed)	7.8	25.4	34.7	25.0	7.1
3 (fastest and slowest removed)	6.7	25.2	36.4	25.7	6.0

In all of the cases examined, the central routes available were used by a greater proportion of the population (see Figure 49).

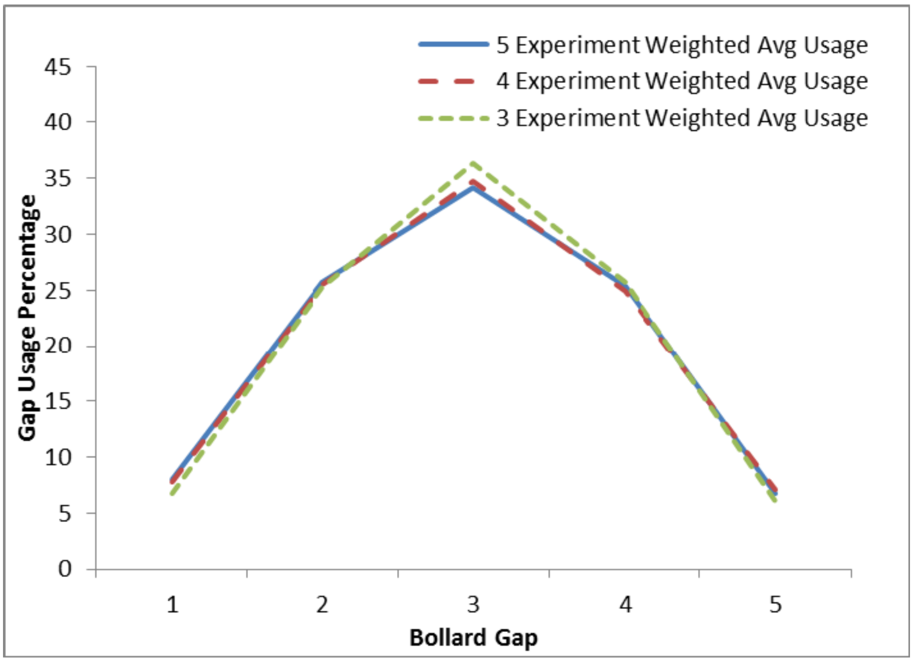


Figure 49: TS1 - Percentage of participants using the available gaps between bollards for the 6m BA trials.

It should be remembered that these trials were designed to represent only a section of an actual array and that in reality pedestrian route selection might be influenced by a larger number of potential pedestrian objectives leading to a more distributed use of the BA available. This might produce a more distributed use of the gaps available – leading to more of a multi-modal curve.

If the BA and NoBA trials are compared, we note that the "gap" usage at the 6m BA line is quite similar (see Figure 50). In particular, the use of the gaps in the extremities (gaps 1 and 5) is identical. However, the central three gaps are more uniformly utilised in the NoBA case than in the BA case suggesting that more people are channelled into the central gap with the BA present.

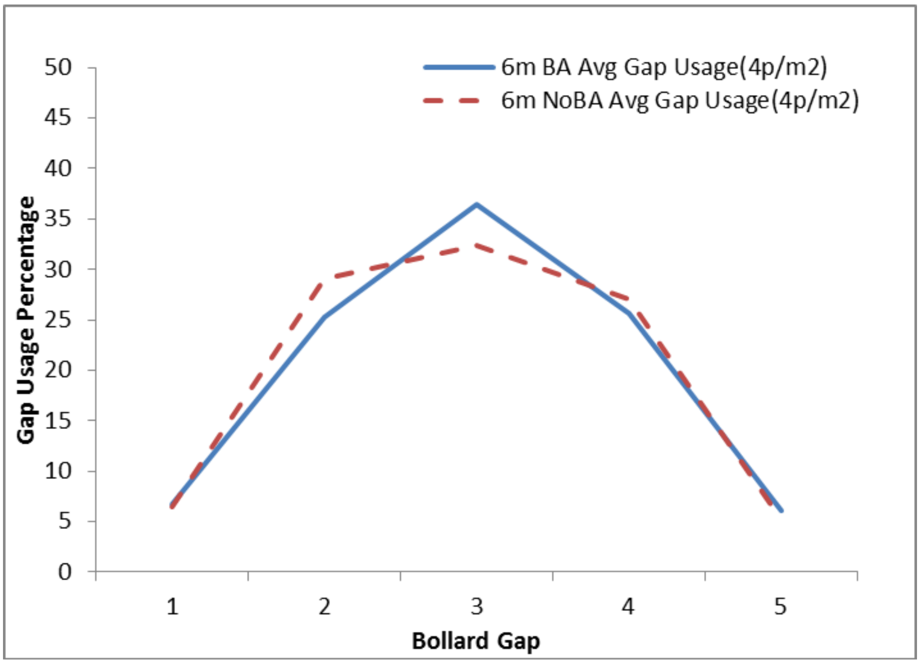


Figure 50: TS1 - Percentage of participants using the available gaps at the 6m BA line for the BA and NoBA trials.

Key Findings - 4_BA_6m_TS1: Participants disproportionately favoured the central gaps of the 6m BA. In the NoBA trial, participants were more evenly distributed over the three central gaps then in the BA trial; however, there was no appreciable difference in the use of the extreme gaps in either trial.

4.2.1.7 DENSITY ANALYSIS

The densities recorded at the BA location during the 6m BA and NoBA trials are shown in Table 31 to Table 33. Presented in Table 31 and Table 32 are the densities calculated using the entire BA area as described in Section 3.1.2. Using this approach generates quite low densities since, as shown in Section 4.2.1.6, not all of the space was fully utilised during the trials. The densities generated using this approach will therefore be unrepresentative of the actual population densities experienced by participants as they passed through the BA location and will be considerably less than that actually experienced (as the area is considerably greater than that used). Nevertheless, from these tables it is noted that the density at the BA line is considerably less than that within the holding area. The reason for this reduction in density is twofold. Firstly, as was already mentioned, the density presented in these tables is not truly representative of the density experienced by the population. Secondly, the fixed size population is spread out over a much larger area; i.e. the space between the exit and the BA line. Because of this we would expect the population density at the BA to be considerably less than the initial population density in the holding area.

The average density at the BA line for the 6m BA was 0.49 p/m^2 and for the NoBA 0.46 p/m^2. These values are very similar. Given that the average flow rates at the BA line are similar, it appears reasonable that the average densities should also be similar (i.e. conditions and outcome are similar). Note that these densities were determined each 5 seconds and so do not represent a continuous measure of density, but rather a snap shot of the density over time.

Table 31: TS1 – Densities at the 6m BA for the 4p/m^2 initial density

4_BA_6m_TS1	**Time (sec)**							**Average (p/m^2)**
	10	**15**	**20**	**25**	**30**	**35**	**40**	
Trial B1 (p/m^2)	0.45	0.45	0.63	0.36	0.63	0.63	0.36	0.50
Trial 1 (p/m^2)	0.54	0.45	0.45	0.54	0.63	0.54	0.18	0.48
Trial 5 (p/m^2)	0.54	0.54	0.36	0.63	0.63	0.45	--	0.53
Average (p/m^2)	0.51	0.48	0.48	0.51	0.63	0.54	0.27	**0.49**

Table 32: TS1 - Density at the 6m BA line (NoBA) for the 4p/m^2 initial density

4_NoBA_6m_TS1	**Time (sec)**							**Average (p/m^2)**
	10	**15**	**20**	**25**	**30**	**35**	**40**	
Trial B7 (p/m^2)	0.44	0.53	0.35	0.35	0.71	0.44	0.62	0.49
Trial 7 (p/m^2)	0.62	0.35	0.35	0.71	0.44	0.35	0.00	0.41
Trial 9 (p/m^2)	0.62	0.62	0.35	0.44	0.53	0.53	--	0.52
Average (p/m^2)	0.56	0.50	0.35	0.50	0.56	0.44	0.31	**0.46**

Also presented are the densities calculated for the three separate regions (Table 33 and Table 34), regions A and C which are in the extremities to the left and right of the BA and region B is located in the centre (the central three gaps) of the BA (see Section 3.1.2). As expected, the density in the central region (B) is considerably higher than that for the outer regions. However, it is still considerably smaller than that in the initial holding area. While this goes up to a maximum of 1.0 p/m^2 in the case of the 6m BA and 1.0 p/m^2 in the NoBA case it is still considerably less than the 4 p/m^2 of the initial holding area. This is due to the second of the two reasons provided above. Note that a single person in region A or C will produce a density of 0.44 p/m^2 while a single person in region B will produce a density of 0.15 p/m^2. Furthermore, as mentioned above, the density was measured every 5 seconds and so represents a snapshot view of the actual continuous density. As such this measurement is strongly sensitive to minor variations in the number of people using each gate at any one time and so may be unreliable as a true indication of the density. As the density in regions A and C are considerably smaller than 0.44 p/m^2, it suggests that there were long periods in which no participants were in the outer regions. It is worth noting that the same number of people used the extremities (region A and C) in both the BA and NoBA trials (see Figure 50).

Table 33: TS1 – Average density at the 6m BA line (NoBA) for the 4p/m^2 initial density measured in the three regions during the peak period

4_NoBA_6m_TS1	p/m^2
A	0.18
B	0.69
C	0.11

Table 34: TS1 – Average density at the 6m BA for the 4p/m^2 initial density measured in the three regions during the peak period

4_BA_6m_TS1	p/m^2
A	0.14
B	0.77
C	0.05

Key Findings - 4_BA_6m_TS1: The densities produced at the bollard array during the 4_BA_6m_TS1 trials and the 4_NoBA_TS1 trials are similar. However, both are lower than the initial population density of 4p/m^2 in the holding area due to the diffusion of the population.

4.2.2 INITIAL POPULATION 4P/M^2 – 3M BOLLARD ARRAY LOCATION

In the following section, the 4_BA_3m_TS1 trials are discussed and compared with the 4_NoBA_TS1 trials (see Figure 51).

Figure 51: Overview of configuration for BA 3m stand-off.

4.2.2.1 EXIT FLOW

The results in Table 35 show the flow rates produced at the exit with an initial density of 4p/m^2 for the NoBA as compared to the 3m BA cases. In this case the fastest and slowest NoBA trials have been removed before analysis is performed; i.e., the core results are presented.

Table 35: TS1: Exit Flow for peak period with 3m BA at initial density of 4p/m^2.

Scenario	Flow (ppm) at Exit
4_NoBA_TS1	247.1 [242.0 – 252.0]
4_BA_3m_TS1	245.5

	[236.6 – 260.0]

Table 35 shows that the 3m BA trials produced exit flow rates that were on average 0.6% lower than the equivalent NoBA trials (with a range of -2.6% to +1.4%). The NoBA trials produced an average flow rate of 247.1ppm (with a standard deviation of 5.00 and a range of -2.1% to +2.0%) while the 3m BA trials produced an average flow rate of 245.5ppm (with a standard deviation of 12.64 and a range of -3.6% to +5.9%).

The manner in which the exit flow rates vary with the BA placed at 3m from the exit can be seen in Figure 52. As can be seen from Figure 52 the flow conditions in each of the trials produced broadly similar trends in exit flows.

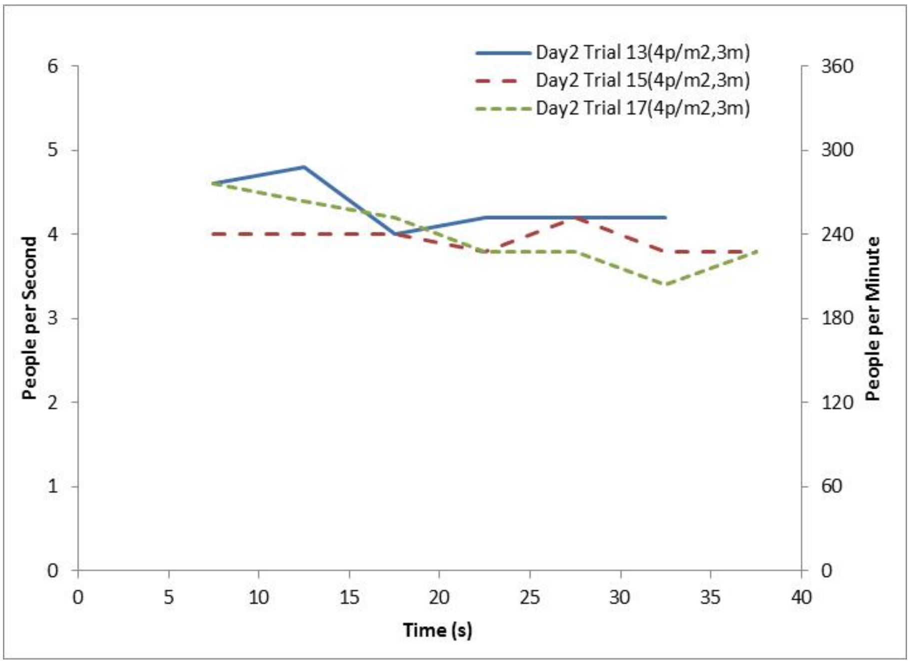


Figure 52: TS1 - Peak exit flow rate measured in 5 second intervals for the three 3m BA 4 p/m^2 trials

The difference in average peak exit flows between the 3m BA and NoBA cases is -1.6 ppm or -0.6%. This difference in exit flow rates is small and as shown in Figure 53, during the peak flow period, the NoBA and 3m BA trials alternate in producing marginally greater flow rates.

Table 36 shows the ranking of the individual runs for the 3m BA and the NoBA trials. From Table 36 it can be seen that in 33% of the comparisons, the presence of bollards at 3m produced higher flow rates; in 67% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates. This indicates that, overall, the presence of bollards at 3m resulted in a slight decrease in flow rate at the exit.

Table 36: TS1: Ranking of trials.

4_BA_3m_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1Trials	Equal to 4_NoBA_TS1Trials
Trial 13	3	0	0
Trial 15	0	3	0
Trial 17	0	3	0

Total	3	6	0

Table 37 shows the average flow rate produced at the exit within each 5 second interval of the peak flow period for each of the 3m bollard trials. The data has then been used to calculate the overall average flow in persons per minute. This can be compared with Table 25 to determine the manner in which the flow varied when the 3m BA was present and when there were no bollards present. It is apparent that the average flow rates produced in the 3m BA trials (245.5ppm) are similar to those produced during the NoBA trials (247.1ppm – see Table 25).

Table 37: TS1: Peak flow per time interval for the 3m BA.

4_BA_3m_TS1	Peak period flow (ppm)							Average (ppm)
	Time interval (sec)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Trial 13	276	288	240	252	252	252	--	260.0
Trial 15	240	240	240	228	252	228	228	236.6
Trial 17	276	264	252	228	228	204	228	240.0
Average (ppm)	264.0	264.0	244.0	236.0	244.0	228.0	228.0	245.5

The quantitative and qualitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 53. The progression of the flow rates appears approximately at the same level throughout, adopting the same downward trend as time advanced. It is noted that the difference in average exit flow rates between the two sets of conditions is lower than the trial by trial variability within the series of NoBA trials and the 3m BA trials. The standard deviations produced indicate more variability in the results for the 3m BA case than in the NoBA case. The 3m BA average flow rate was higher than one of the three individual NoBA results and lower than two.

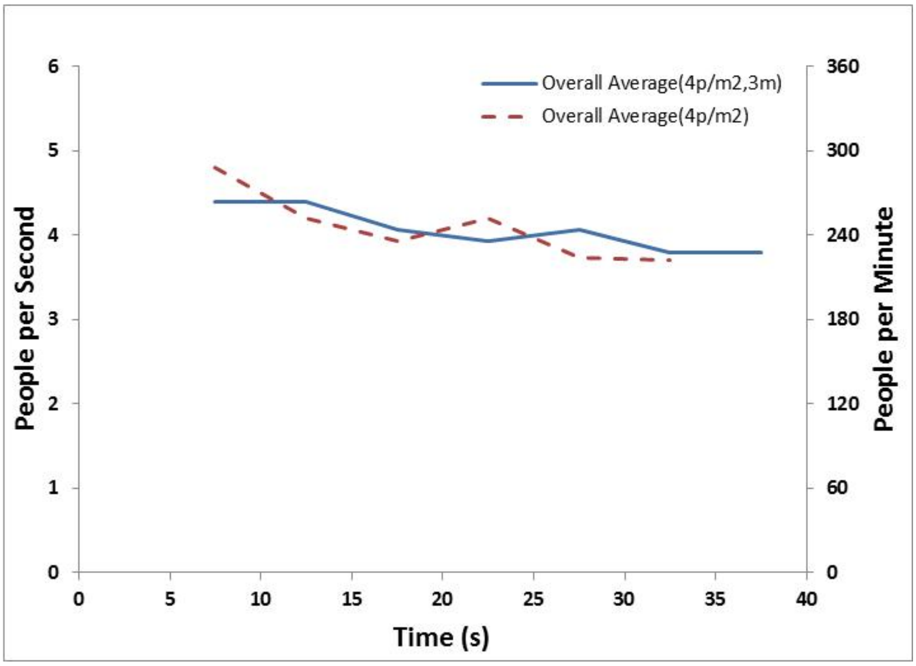


Figure 53: TS1 - Average exit peak flow rate measured in 5 second intervals for both the 3m BA and core NoBA 4 p/m^2 trials

Figure 54 shows the results of the average and range of the average peak flow rates produced over the core NoBA and the 3m BA trials. This shows that there was little difference between the average flow rate in the two cases (245.5ppm for the 3m BA and 247.1ppm for the NoBA case) with the 3m BA case producing a larger range of flow. The difference between the averages is still considerably less than the spread in the trial results for each case.

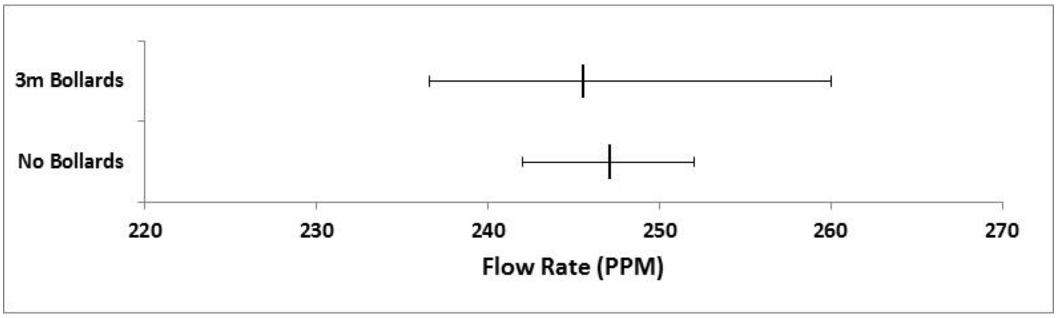


Figure 54: TS1- Average and range of peak exit flow rates for the core 3m BA and NoBA 4 p/m^2 trials.

Key Finding - 4_BA_3m_TS1: There is little difference between the flow rates at the exit produced in the NoBA and 3m BA trials at 4p/m^2, with the 3m bollard trials producing 0.6% lower flow rates. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 3m from the exit compared to the case in which there was no bollard array present.**

4.2.2.2 BOLLARD FLOW

Table 38 compares the flow rates produced during the peak periods at the BA line with an initial density of 4p/m^2 for the core data-sets of the NoBA trials (measured at the 3m line) and 3m BA trials.

Table 38: TS1 - Flow rates at the position of the Bollard Array for the 3m BA trials with a population density of 4p/m^2.

Scenario	Flow (ppm) at BA
4_NoBA_3m_TS1	248.7 [246.0 – 250.0]
4_BA_3m_TS1	243.4 [234.9 – 255.4]

The results in Table 38 show that the 3m BA case produced flow rates that were on average 5.3ppm or 2.1% lower (with a range of -2.6% to -1.1%) than the equivalent NoBA case. The NoBA case produced an average flow rate of 248.7ppm (with a standard deviation of 2.31 and a range of -1.1% to +0.5%) while the 3m BA case produced an average flow rate of 243.4ppm (with a standard deviation of 10.71 and a range of -3.5% to +4.9%).The flow rates produced during the two sets of trials are shown in Figure 55.

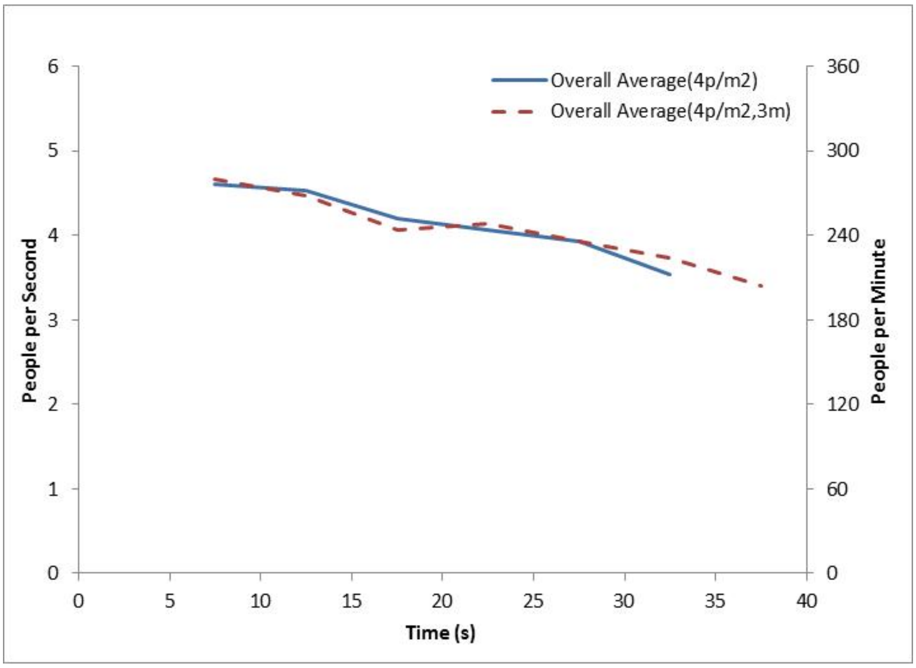


Figure 55: TS1: Average BA peak flow measured in 5 second intervals for the core 3m BA and NoBA trials

It should be noted that originally, the NoBA trial extended for another data-point. However, this only represented a single trial, as the others finished earlier. The original spike in the final data point for the NoBA trials was due to one trial still continuing into the 40 second time period. Given that the flow rate produced was high in comparison and unaffected by other more moderate flow rates it has been was omitted.

Comparing Table 38 with Table 35 it is apparent that the flow rates produced at the 3m line (with and without BA) are broadly comparable with the flow rate at the exit: for the NoBA case, 248.7ppm at the 3m BA line compared with 247.1ppm at the exit, for the 3m BA case, 243.4ppm at the 3m BA line compared with 245.5ppm at the exit.

Table 39 and Table 40 shows the average flow rate produced at the BA within each 5 second interval of the peak flow period for each of the 3m BA and NoBA bollard trials. The data has then been used to calculate the overall average flow in persons per minute. It is apparent that the average flow rates produced in the BA 3m trials (243.4 ppm) are similar to those produced during the NoBA trials (248.7ppm).

Table 39: TS1: Peak flow per time interval at BA for core trials with 3m BA.

	Peak period flow (ppm)							Average (ppm)
	Time since trial start							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Trial 13	252	312	276	240	252	252	204	255.4
Trial 15	264	240	204	264	228	240	204	234.9
Trial 17	324	252	252	240	228	180	204	240.0
Average (ppm)	280.0	268.0	244.0	248.0	236.0	224.0	204.0	243.4

Table 40: TS1: Peak flow per time interval at 3m BA line for core trials with No BA.

	Peak period flow (ppm)						Average (ppm)
	Time since trial start						
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 7	300	252	240	252	228	228	250.0
Trial 9	276	276	252	228	228	216	246.0
Trial B7	252	288	264	252	252	192	250.0
Average (ppm)	276.0	272.0	252.0	244.0	236.0	212.0	248.7

The 3m BA average flow rate was higher than one of the three individual NoBA results and lower than two. The individual trials have been ranked according to the flow rates produced. From Table 41 it can be seen that in 33% of the comparisons, the 3m BA trials produced higher flow rates; in 67% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates. This suggests that overall, the presence of bollards resulted in a lower flow rate at the BA line.

Table 41: TS1: Ranking of BA trial results.

4_BA_3m_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1 Trials	Equal to 4_NoBA_TS1 Trials
Trial 13	3	0	0
Trial 15	0	3	0
Trial 17	0	3	0
Total	3	6	0

Figure 56 shows the results of the average and range of the peak flow rates produced during the core NoBA and 3m BA trials at the BA. This shows that the average flow rate for the 3m BA trials falls outside of the flow range produced in the NoBA trials.

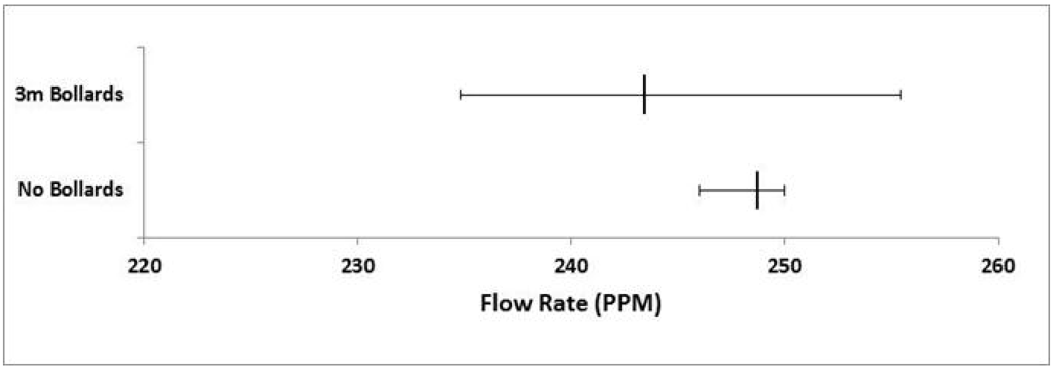


Figure 56: TS1 - Average and range of peak BA flow rates for the 3m BA and NoBA 4 p/m^2 trials

Key Finding - 4_BA_3m_TS1: There is a small difference between the flow rates produced at the BA line during the NoBA and 3m BA trials given that the average 3m BA trial falls below the entire range of the NoBA trials, with 3m BA producing 2.1% lower flow rates. Although suggestive, the results produced do not demonstrate a clear numerical difference between the conditions examined.

4.2.2.3 GAP ANALYSIS

The manner in which the participants made use of the various gaps between the BA was examined (with the gaps numbered 1-5, see Figure 26). This is shown in Table 42.

Table 42: TS1: Percentage of participants using the available gaps between bollards in the 3m BA trials at $4p/m^2$.

4_BA_3m_TS1: % Gap Usage				
1	**2**	**3**	**4**	**5**
3.6	28.7	37.3	27.1	3.2

In all of the cases examined, the central routes available (through gaps 2-4) were used by a greater proportion of the population (see Figure 57). The gap usage for the 3m BA trials is very similar to that for the 6m BA trials as shown in Figure 58. However, slightly more people used the gaps in the extremities for the 6m bollard trials compared to the 3m bollard trials. With the bollards placed further away from the exit, the participants have more opportunity to spread out in the 6m bollard trials and so more people make use of the far gaps.

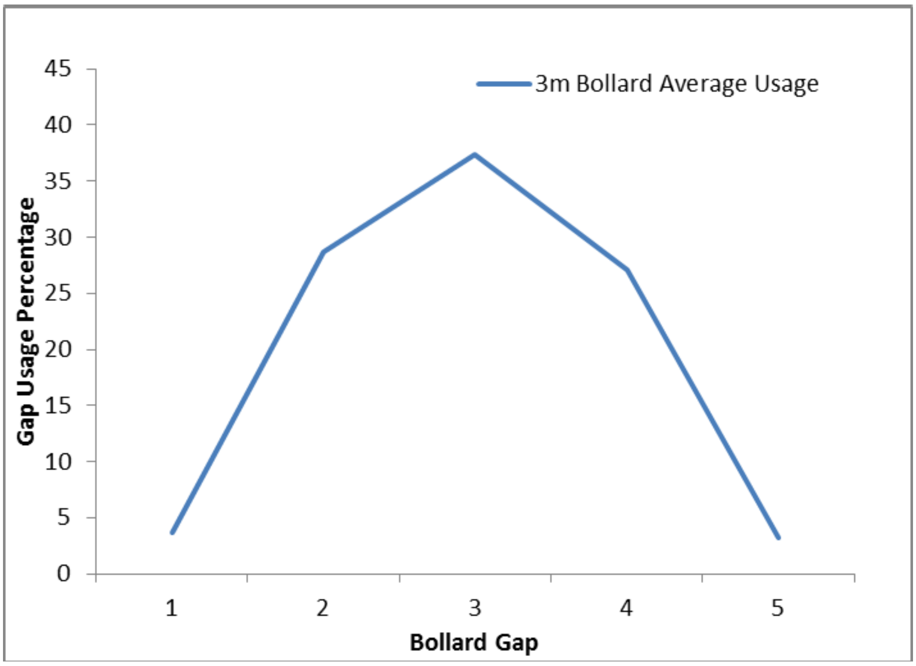


Figure 57: TS1 - Percentage of participants using the available gaps between bollards for the 3m BA trials.

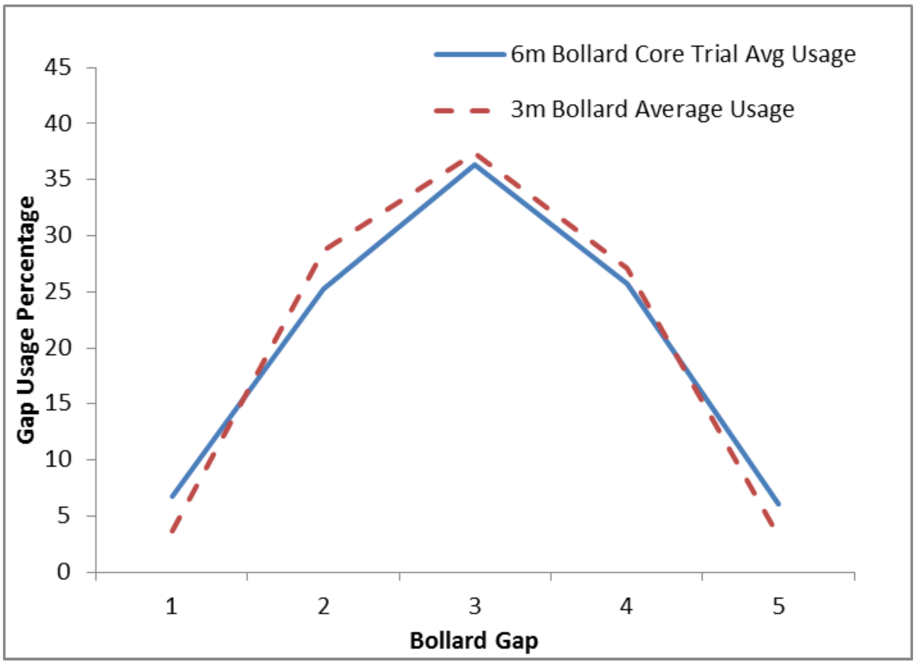


Figure 58: TS1- Percentage of participants using the available gaps between bollards given the sets of 6m BA and the 3m BA trials.

If the BA and NoBA trials are compared, we note that there are slight differences in the "gap" usage at the 3m BA line (see Figure 59). Slightly more people tended to use the gaps in the extremities and slightly fewer tended to use the central gap when the BA was present at 3m compared to NoBA at 3m.

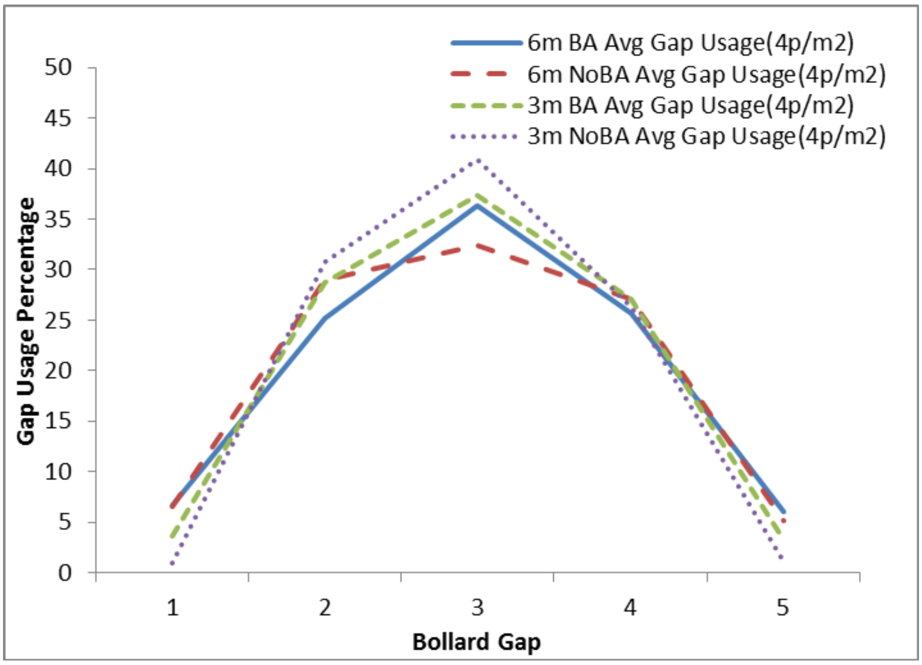


Figure 59: TS1 - Percentage of participants using the available gaps at the 6m and 3m BA line for the BA and NoBA trials.

Also, the greater the distance from the exit, the more people tended to spread out (comparing extremity usage at 6m compared to 3m both with BA and with NoBA) resulting in greater usage of the extremities.

Key Finding - 4_BA_3m_TS1: At a distance of 3m from the exit, the central gaps were used by a disproportionate number of participants whether or not the BA was present. However, slightly more people tend to use the gaps in the extremity if the BA is present at 3m compared to if the BA was not present.

4.2.2.4 DENSITY ANALYSIS

The densities recorded at the BA location during the 3m BA and NoBA trials are shown in Table 43-Table 46. These show the densities over time (Table 43 and Table 44) or according to the area examined (Table 45 and Table 46). As with the 6m bollard line (see Section 4.2.1.7) the densities presented in Tables Table 43 and Table 44 underestimate the actual density that the participants were exposed to as it assumes that the entire area was used.

The average densities produced were 0.39 p/m^2 for the NoBA trials (with the density still taken at the 3m line) and 0.45 p/m^2 for the 3m BA trials, representing a **15.4% increase in density when the BA was introduced**. This should be compared to the differences produced during the equivalent 6m trials (see Table 31 and Table 32), where densities of 0.46 p/m^2 (NoBA trials, measurement made at 6m line) and 0.49 p/m^2 (trials where the BA was present at 6m line) were produced, representing a smaller **6.5% increase in the densities recorded once the BA was introduced**. Comparing the NoBA condition during the 3m and 6m trials (i.e., taking the measurement where the BA would be), produces densities of 0.39p/m^2 and 0.46p/m^2 respectively, representing a **17.9% increase in the densities produced during the NoBA trials when the measurement is made further from the exit point**. Comparing the BA condition during the 3m and 6m trials (i.e., comparing the measurements made during trials when the BA was located at 3m and 6m), we see densities of 0.45p/m^2 and 0.49p/m^2, representing an **8.8% increase in the densities as the BA was moved further from the exit point**. This result may reflect a real underlying factor (i.e. that effectively the densities are broadly the same at the two stand-off distances), or may have been influenced by the methodology adopted (i.e. that the discretisation of the conditions produced through taking snapshots observations did not adequately reflect the underlying conditions). Additional trials and analysis may assist in resolving this issue.

These levels are also similar to the densities produced during the 6m trials (see Table 31 and Table 32). Both demonstrated a significant reduction in comparison with the initial 4p/m^2 density conditions within the holding area. The density analysis also reflects the use of the central routes identified in the gap analysis (see Table 42).

Table 43: TS1– Density at the 3m BA line (NoBA present) for the 4p/m^2 initial density

4_NoBA_3m_TS1	**Time interval (sec)**							**Average (p/m^2)**
	10	**15**	**20**	**25**	**30**	**35**	**40**	
Trial B7 (p/m^2)	**0.44**	**0.36**	**0.36**	**0.44**	**0.27**	**0.44**	**0.44**	**0.39**

Only one of the core trials is shown in Table 43 as the other core trials came from the narrower setup that was used on Day 1 (see Section 3.3). This meant that the densities could not be measured in the same way for these trials as the regions A and C lay mostly outside the barriers and hence could not be occupied by the participants.

Table 44: TS1 - Density at the 3m BA for the 4p/m^2 initial density

4_BA_3m_TS1	Time (sec)							Average (p/m^2)
	10	15	20	25	30	35	40	
Trial 13 (p/m^2)	0.63	0.54	0.36	0.45	0.54	0.45	0.18	0.45
Trial 15 (p/m^2)	0.54	0.36	0.36	0.45	0.54	0.45	0.54	0.46
Trial 17 (p/m^2)	0.54	0.36	0.45	0.45	0.18	0.36	0.63	0.43
Average (p/m^2)	0.57	0.42	0.39	0.45	0.42	0.42	0.45	**0.45**

From Table 45 and Table 46 we note, as expected, the average density in the central region (B) is considerably higher than that for the outer regions. While this goes up to a maximum of 1.0 p/m^2 in the case of the 3m BA and 0.9 p/m^2 in the NoBA case it is still considerably less than the 4 p/m^2 of the initial holding area.

Table 45: TS1 – Average density at the 3m BA line (NoBA) for the 4p/m^2 initial density measured in the three regions during the peak period.

4_NoBA_3m_TS1	p/m^2
A	0.13
B	0.57
C	0.13

Table 46: TS1– Average density at the 3m BA for the 4p/m^2 initial density measured in the three regions during the peak period.

4_BA_3m_TS1	p/m^2
A	0.09
B	0.69
C	0.06

The higher usage of the A and C gaps noted in the gate usage for the 6m BA (see Figure 58) is reflected in the lower A/C densities noted for the 3m BA (compare Table 46 with Table 34).

Key Finding - 4_BA_3m_TS1: The densities produced at the bollard array during the 4_BA_3m_TS1 trials were 15.4% greater than during the 4_NoBA_TS1. However, both are lower than the initial population density of 4p/m^2 in the holding area.

It is perhaps more instructive to examine the densities produced in the central area only, given the earlier discussion. From Table 47 it is apparent that the use of the central area (B) is reasonably consistent between the 3m BA and NoBA trials demonstrating the general tendency for this route to be adopted throughout the trials.

Table 47: TS1 – Density Region B at the 3m BA line (NoBA) for the 4p/m^2 initial density

4_NoBA_TS1	Time interval (sec)							Average (p/m^2)
	10	15	20	25	30	35	40	
Trial B7	0.74	0.59	0.59	0.44	0.30	0.74	0.59	0.57

(p/m^2)								
Trial 7 (p/m^2)	0.89	0.89	1.03	0.74	0.44	0.74	-	0.79
Trial 9 (p/m^2)	0.74	0.89	0.59	0.89	0.89	0.74	-	0.79
Average (p/m^2)	0.79	0.79	0.74	0.69	0.54	0.74	0.59	**0.72**

Table 48: TS1 – Density Region B at the 3m BA for the 4p/m^2 initial density

4_BA_3m_TS1	**Time interval (sec)**							**Average (p/m^2)**
	10	**15**	**20**	**25**	**30**	**35**	**40**	
Trial 13 (p/m^2)	1.05	0.90	0.60	0.75	0.90	0.75	0.30	0.75
Trial 15 (p/m^2)	0.90	0.60	0.60	0.60	0.90	0.75	0.75	0.73
Trial 17 (p/m^2)	0.75	0.45	0.45	0.75	0.30	0.45	1.05	0.60
Average (p/m^2)	0.90	0.65	0.55	0.70	0.70	0.65	0.70	**0.69**

4.2.3 INITIAL POPULATION 4P/M^2 – 0M BOLLARD ARRAY LOCATION

The results produced in the 4_BA_0m_TS1 trials are discussed in this section and compared with the 4_NoBA_TS1 trials (see Figure 60).

Figure 60: Overview of TS1 trials with BA set at 0m (location highlighted).

This section compares the exit flow conditions of the 0m BA trials and the NoBA trials conducted at 4p/m^2 (see Table 49). In this case the fastest and slowest NoBA trials have been removed before analysis is performed. It is apparent that the NoBA trials produce a slightly higher (1.0%) average flow rate than the 0m BA trials (247.1ppm as compared to 244.6ppm).

Table 49: TS1: Exit Flow for peak period at initial density of 4p/m^2.

	Flow (ppm) at Exit
4_NoBA_TS1	247.1 [242.0 – 252.0]

4_BA_0m_TS1	244.6 [243.4 – 245.1]

The manner in which the exit flow rates vary with the BA placed at 0m from the exit can be seen in Figure 61. As can be seen from Figure 61 the flow conditions in each of the trials during the peak flow were broadly similar, producing broadly similar trends in exit flows.

The results in Table 49 show that the 0m BA trials produced exit flow rates that were on average 2.5 ppm or 1.0% lower (with a range of -3.0% to +1.1%) than the equivalent NoBA trials. The NoBA trials produced an average flow rate of 247.1ppm (with a standard deviation of 5.00 and a range of -2.1% to +2.0%) while the 0m BA trials produced an average flow rate of 244.6ppm (with a standard deviation of 0.99 and a range of -0.5% to +0.2%).

This difference in average exit flow rates is small and as shown in Figure 62, during the peak flow period, the NoBA and 0m BA trials alternate in producing marginally greater flow rates. It is noted that the difference in average exit flow rates between the two sets of conditions is greater than the trial by trial variability within the series of 0 m BA trials, but less than the variability in the NoBA trials. The 0m BA average flow rate was higher than one of the three individual NoBA results and lower than two.

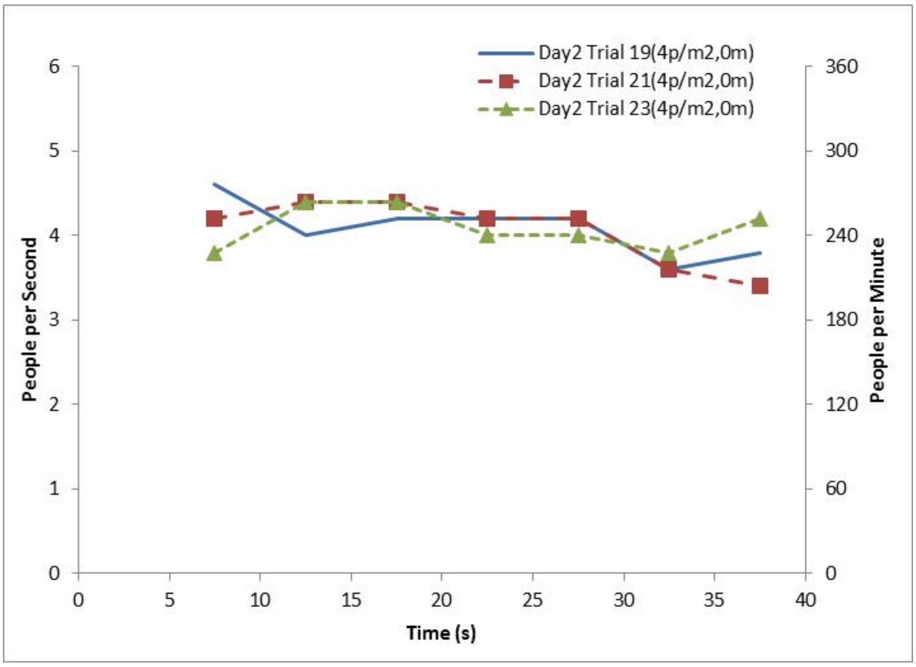


Figure 61:TS1- Exit flow rate over peak period measured in 5 second intervals for the three 0m BA trials at $4p/m^2$

Table 50 shows the ranking of the trials according to the exit flow rates produced. From Table 50 it can be seen that in 33% of the comparisons the trials with the bollards present (0m BA) produced higher flow rates; in 67% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates. **This suggests that overall the presence of a bollard at 0m is more likely to result in a decrease in flow rate at the exit.**

Table 50: TS1: Ranking of trials.

4_BA_0m_TS1	Higher than 4_NoBA_TS1 Trials	Lower than 4_NoBA_TS1 Trials	Equal to 4_NoBA_TS1

			Trials
Trial 19	1	2	0
Trial 21	1	2	0
Trial 23	1	2	0
Total	3	6	0

Table 51 shows the average flow rate produced at the exit within each 5 second interval of the peak flow period for each of the 0m BA trials. The data in Table 51 has then been used to calculate the overall average flow in persons per minute.

Table 51: TS1: Peak flow per time interval for core trials with 0m BA.

4_BA_0m_TS1	Peak period flow (ppm)							Average (ppm)
	Time interval (sec)							
	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Trial 19	276	240	252	252	252	216	228	245.1
Trial 21	252	264	264	252	252	216	204	243.4
Trial 23	228	264	264	240	240	228	252	245.1
Average (ppm)	252.0	256.0	260.0	248.0	248.0	220.0	228.0	244.6

The quantitative and qualitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 62. The flow rates shown in Table 51 should be compared with those in Table 25.

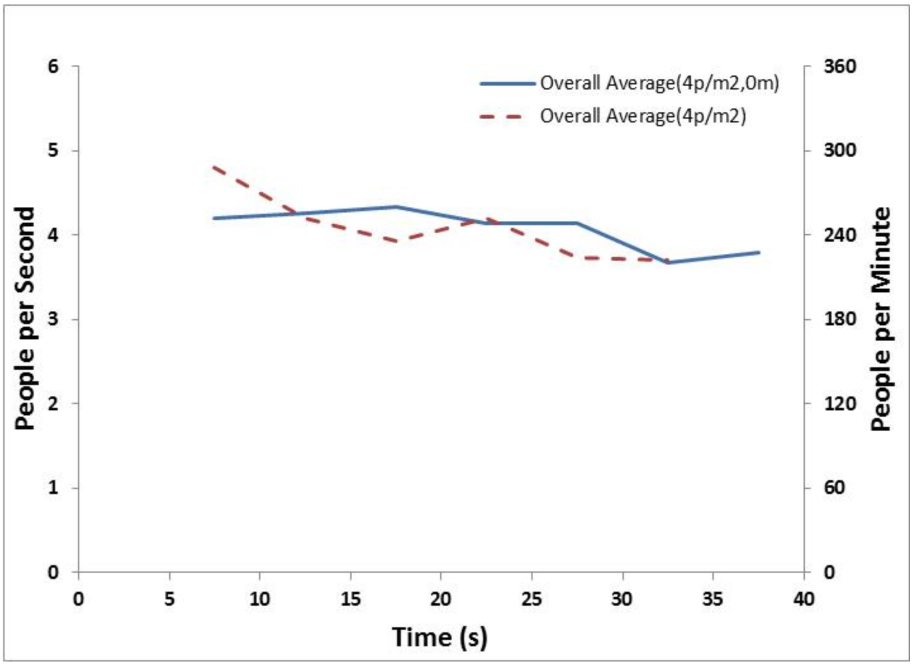


Figure 62: TS1 - Average exit peak flow rate of the core NoBA and 0m BA trials.

Figure 63 shows the results of the average and range of the peak flow rates produced over the core NoBA trials and the three 0m Bollards trials.

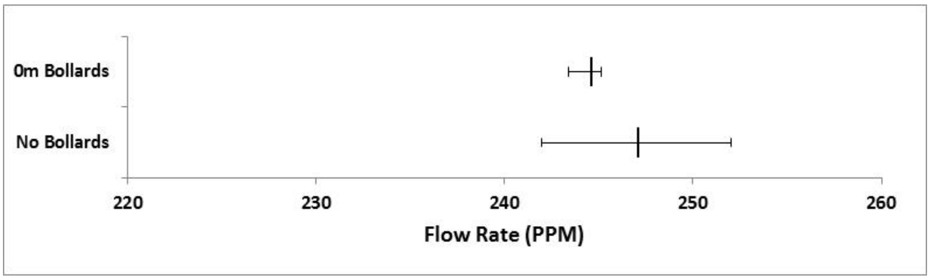


Figure 63: TS1 - Average and range of peak exit flow rates for the 0m BA and NoBA 4 p/m^2 trials

This shows that the NoBA case produces higher flow rates (247.1 ppm as compared to 244.6 ppm) and a wider range of results (242-252 ppm compared to 243.4-245.1 ppm). The narrow range of the 0m BA suggests that the presence of the bollard at 0m dominated the other variability inherent in this trial. The difference in the averages is considerably larger than the spread in results for the 0m BA case, but less than the spread in results for the NoBA case.

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 rate to be 9.4% lower with the bollard present. However, it is measured to be only 1.0% lower. This difference can be explained by considering the unit flow rate for the exit.

A fundamental measure of the flow capacity of an exit is the unit flow rate. This measures the flow rate per unit exit width. While the flow rate of an exit is dependent on the width of the exit, the unit flow rate for an exit is a fundamental property of the exit. According to UK Building Regulations [3], the unit flow rate for a standard exit (no door leaf) is 1.33 people/m/sec. For safety reasons, this number is conservative, with unit flow rate values as high as 2.00 people/m/sec reported in the literature [4].

Using the available free exit width, the average unit flow rate for the exit without bollard is 1.72 p/m/sec while that for the exit with the bollard is 1.87 p/m/sec. Thus we note that with the bollard present, the unit flow rate for the exit is 9.2% higher than without the BA present (see Table 52). The improvement in unit flow rate 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 resulted in a more ordered flow through the exit which in turn produces a higher than expected flow rate. Thus, the 9.4% reduction in flow rate produced by the reduction in effective width of the exit due to the presence of the bollard is partially compensated by the 9.2% improvement in unit flow rate achieved by the ordered exit flow generated by the presence of the bollard.

Table 52: TS1 – Flow and Unit flow at exit for core NoBA trials 0m BA trials at peak flow for 4p/m^2.

Scenario	Flow (ppm)	Unit Flow (p/m/min)	Unit Flow (p/m/sec)
No Bollards (4_NoBA)	247.1 [242.0 – 252.0]	102.94 [100.8 – 105.0]	1.72 [1.68 – 1.75]
0m Bollards	244.6	112.45	1.87

(4_BA_0m)	[243.4 – 245.1]	[111.9 – 112.7]	[1.86 – 1.88]

It must be noted that the improvement in unit flow rate was achieved with pedestrians largely without luggage. It is unclear if this mechanism will be as effective in situations involving passengers with luggage. In this case the bollard may exert a greater negative impact on the exit flow rate. As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

Key Finding – 4_BA_0m_TS1: On average the flow rate at the exit with a 0m bollard present was some 1% lower than the case without bollards. This reduction in flow rate is less than the natural variation in the no bollard case but greater than the variation in the 0m bollard case. Therefore it is difficult to determine whether or not the presence of the bollard resulted in an appreciable reduction in flow rate. **However, the reduction in flow rate due to the presence of the bollard was not as great as would be expected due to the reduction in exit width**. The better than expected flow rate with the 0m bollard present is due to a 9% improvement in the unit flow rate for the exit with the bollard present. The reduction in flow rate due to the reduction in exit width was partially compensated by the improvement in unit flow rate. In is not known whether this improvement in exit unit flow rate will also be evident in situations with passengers carrying luggage.

4.2.4 TS1 4 P/M^2 RESULT SUMMARY

A summary of the key results for the TS1 4p/m^2 trials are presented in Table 53. The average peak exit flow rates are broadly comparable irrespective of whether there is no bollard array or if the stand-off is 0m, 3m or 6m. The difference in the average peak flow rate values for the various bollard locations is smaller than the variation in the trial results for each case. The only exception is for the 0m bollard location, where the difference between the average flow rate for the 0m bollard case and the no bollard case is greater than the variation in the 0m bollard cases.

Table 53: Summary average peak flow rates produced during the core TS1 4p/m^2 trials.

BA Conditions	Flow (ppm) at Exit	Comparison BA Vs NoBA	Flow (ppm) at BA	Comparison BA Vs NoBA
4_NoBA_TS1 (at 0m)	247.1 [242.0-252.0]	-	247.1 [242.0-252.0]	-
4_NoBA_TS1 (at 3m)	247.1 [242.0-252.0]	-	248.7 [246.0-250.0]	-
4_NoBA_TS1 (at 6m)	247.1 [242.0-252.0]	-	246.2 [238.3-250.3]	-
4_BA_0m_TS1	244.6 [243.4-245.1]	-1.0%	244.6 [243.4-245.1]	-1.0%
4_BA_3m_TS1	245.5 [236.6-260.0]	-0.6%	243.4 [234.9-255.4]	-2.1%
4_BA_6m _TS1	248.7 [242.0-252.0]	+0.6%	246.4 [241.7-254.0]	+0.1%

As the bollard array is brought closer to the exit (i.e. from 6m to 3m), the average exit flow rate decreases and becomes less than that for the no bollard case. However, the difference in average flow rates is less than the natural variation within each of the cases. It is unclear what may occur if the bollard array was brought closer to the exit (e.g. between 0m and 3.0m), but it is likely that the average exit peak flow rate would decrease further. As this aspect was not was not tested in these trials it may warrant further analysis in future trials. At 0m, the decrease in exit flow rate due to the presence of the bollard is partially compensated by the increase in exit unit flow rate due to the presence of the bollard and so the reduction in exit flow rate is not as large as would be expected.

These results suggest that a BA placed at 3m, or 6m from an exit or a single bollard placed in the centre of the exit DOES NOT have a pronounced numerical impact on the exit flow rate.

4.2.5 INITIAL POPULATION 3P/M^2– 6M BOLLARD ARRAY LOCATION

The results produced in the 3_NoBA_TS1 trials are now presented and briefly discussed.

4.2.5.1 BASIC NoBA RESULTS – 3p/m^2

The NoBA trials are referred to throughout the section describing the results produced in trials of an initial density of 3p/m^2. An overview of these results is presented in Table 54 and Table 55. These are the results with the fastest and slowest cases removed and so represent the core cases.

Table 54: TS1: Exit flow rate for core NoBA trials at 3p/m^2.

Scenario	Flow (ppm) at Exit
3_NoBA_TS1	233.33 [224.0 – 252.0]

Presented in Table 55 are the exit flows for each of the TS1 NoBA trials for the 3 p/m^2 initial density presented in 5 second time periods during the peak period. Also presented is the average peak period flow.

Table 55: TS1 – Exit flow during peak period measured in 5 sec time intervals for the 3p/m^2 NoBA trials.

3_NoBA_TS1	Peak period flow (ppm)						Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 10	252	228	216	240	192	216	224.0
Trial 12	288	240	204	168	264	180	224.0
Trial B6	240	240	264	252	264	--	252.0
Average (ppm)	260.0	236.0	228.0	220.0	240.0	198.0	233.3

4.2.5.2 EXIT FLOW

Table 56 shows the exit flow results with an initial density of 3p/m^2 for the NoBA and the 6m BA cases (see Figure 31). In this case the fastest and slowest of each of the trial sets have been removed before analysis is performed.

Table 56: TS1: Exit Flow for peak period at initial density of 3p/m^2.

Trial Type	Flow (ppm) at Exit

No BA (3_NoBA)	233.3 [224.0 – 252.0]
6m BA (3_BA_6m)	230.7 [224.0 – 235.2]

The results in Table 56 show that the 6m BA trials produced exit flow rates that were on average 2.6 ppm or 1.1% lower (with a range of -9.2% to +2.9%) than the equivalent NoBA trials. The NoBA trials produced an average flow rate of 233.3ppm (with a standard deviation of 16.17 and a range of -4.0% to +8.0%) while the 6m BA trials produced an average flow rate of 230.7ppm (with a standard deviation of 5.90 and a range of -2.9% to +2.0%).

The manner in which the exit flow rates vary for the NoBA case and when the BA is placed at 6m from the exit can be seen in Figure 64 and Figure 65 respectively. As can be seen the flow conditions in each of the trials were broadly similar. Although there is some variability within each of set of trials, the two sets are broadly similar.

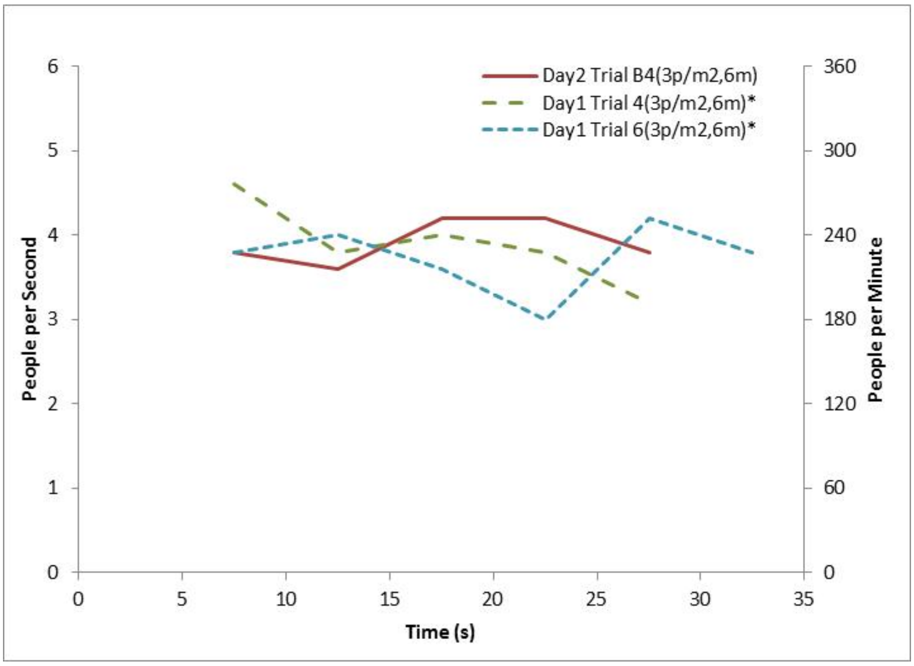


Figure 64: TS1 – Peak exit flow rate measured in 5 second intervals for the three 6m BA trials at 3 p/m^2.

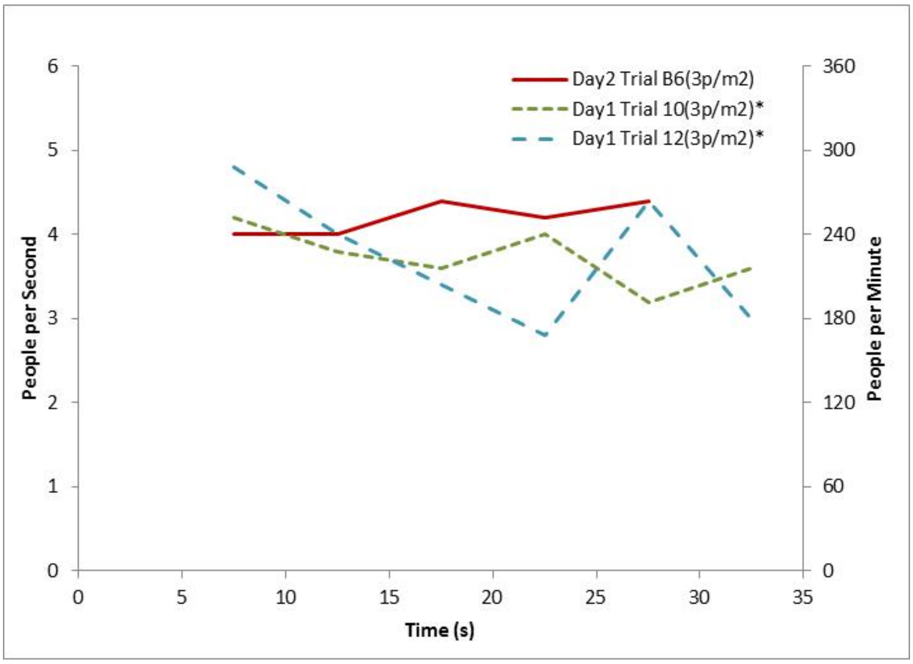


Figure 65: TS1 – Peak exit flow rate measured in 5 second intervals for the three NoBA trials at 3 p/m^2.

The difference in average peak exit flows between the 6m BA and NoBA cases is -2.6 ppm or -1.1%. This difference in exit flow rates is relatively small and, as shown in Figure 66, during the peak flow period the highest flow rate alternates between the two scenarios.

Table 57 shows the ranking of the individual runs for the 6m BA and the NoBA trials. From Table 57 it can be seen that in 44% of the comparisons, BA produced higher flow rates; in 33% of the comparisons they produced lower flow rates and in 22% of the comparisons they produced equal flow rates. **This indicates that, more often than not, the presence of bollards at 6m produced a lower or equal flow rate at the exit.**

Table 57:TS1: Ranking of the trials.

3_BA_6m_TS1	Higher than No BA Trials	Lower than No BA Trials	Equal to No BA Trials
Trial 4	2	1	0
Trial 6	0	1	2
Trial B4	2	1	0
Total	4	3	2

Table 58 and Table 55 include, for each of the core 6m BA and NoBA trials respectively, the average exit flow rate within 5 second intervals during the peak flow period. The data has been used to calculate the overall average flow in persons per minute. It is apparent that the average flow rates produced in the 6m BA trials (230.7 ppm) are similar to those produced during the NoBA trials (233.3ppm).

Table 58: TS1 - Exit flow during peak period measured in 5 sec time intervals for the 3p/m^2 trials with 6m BA.

3_BA_6m_TS1	Peak period flow (ppm)						Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	

Trial 4	276	228	240	228	192	--	232.8
Trial 6	228	240	216	180	252	228	224.0
Trial B4	228	216	252	252	228	--	235.2
Average (ppm)	244.0	228.0	236.0	220.0	224.0	228.0	**230.7**

The quantitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 66, Table 58 and Table 55.

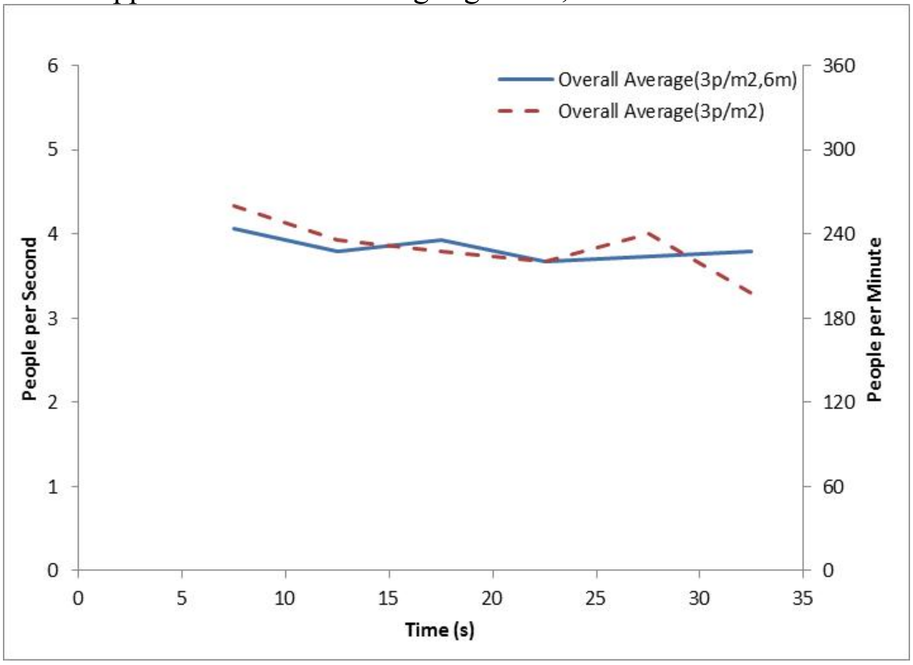


Figure 66: TS1 - Average exit peak flow rate measured in 5 second intervals for both the 6m BA and NoBA trials at 3p/m^2.

It is noted that the difference in the average exit flow rates between the two sets of conditions is lower than the trial by trial variability within the series of NoBA trials and the 6m BA trials.

Figure 67 shows the results of the average and range of the average peak flow rates produced during the core NoBA and 6m BA trials at 3p/m^2. This shows that the 6m BA trials produced a slightly lower flow rate (230.7 ppm compared to 233.3ppm) with an appreciably narrower range of flow rates produced (224.0-235.2 ppm compared to 224.0-252.0 ppm). However, the difference between the averages is considerably less than the spread in the trial results for each case.

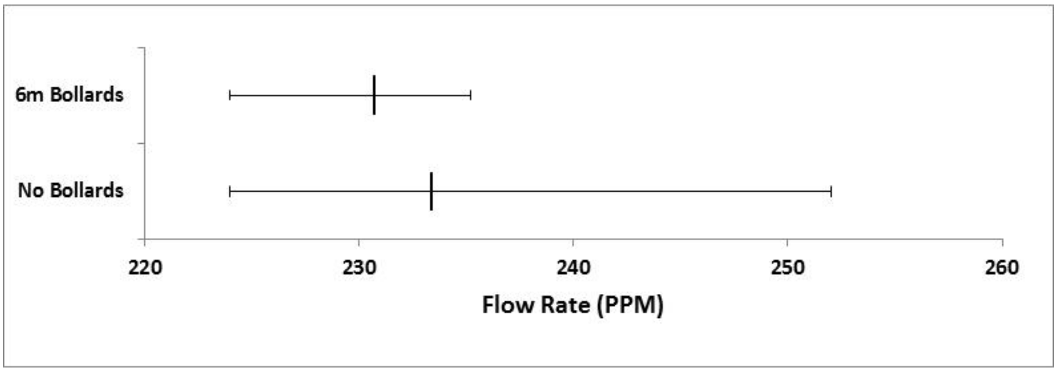


Figure 67: TS1 - Average and range of peak exit flow rates for the 6m BA and NoBA 3 p/m^2 trials.

Key Findings - 3_BA_6m_TS1: The core 6m BA trials with an initial population density of $3p/m^2$ produced average exit point flow rates 1.1% lower than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 6m from the exit compared to the case in which there was no bollard array present.**

4.2.5.3 BOLLARD FLOW

Table 59 compares the peak BA flow results produced during the core trials with an initial density of $3p/m^2$for the NoBA trials and the 6m BA trials.

The results in Table 59 show that the 6m BA trials produced flow rates that were on average 0.1% greater (with a range of -7.4% to +4.2%) than the equivalent NoBA case. The NoBA trials produced an average flow rate of 230.7 ppm (with a standard deviation of 15.04 and a range of -4.1% to +7.5%) while the 6m BA trials produced an average flow rate of 230.9 ppm (with a standard deviation of 13.25 and a range of -4.2% to +6.5%). The quantitative and qualitative similarity between the flow rates at the 6m BA line is more apparent when examining Figure 68.

Table 59: TS1 – Peak flow rates at the position of the Bollard Array for the core NoBA and 6m BA trials at $3p/m^2$.

	Flow (ppm) at BA
3_NoBA_TS1	230.7 [221.1 – 248.0]
3_BA_6m_TS1	230.9 [221.1 – 246.0]

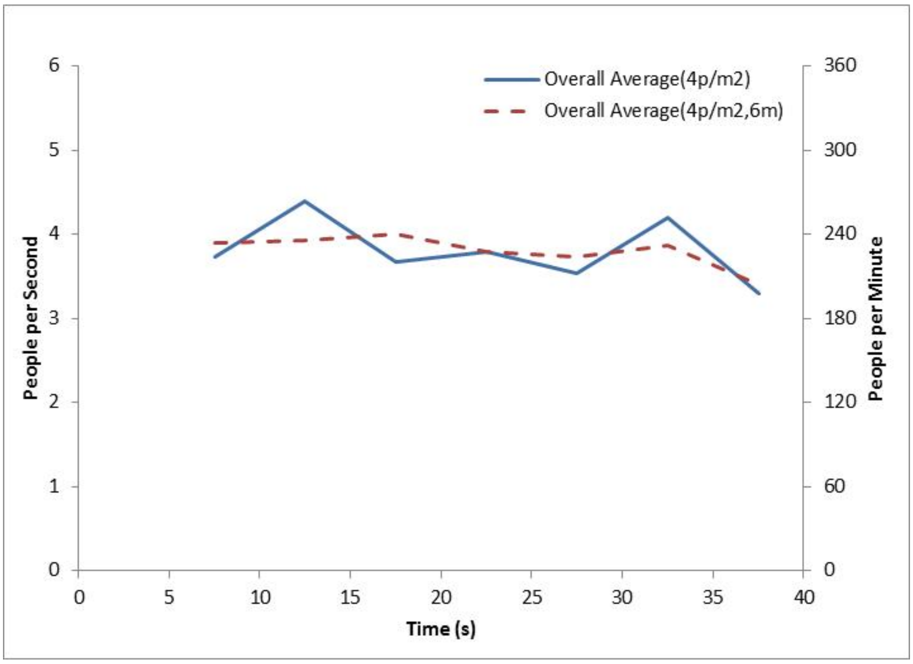


Figure 68: TS1 - Average BA peak flow rate measured in 5 second intervals for the core 6m BA and NoBA $3p/m^2$ trials.

Figure 69 shows the results of the average and range of the peak flow rates produced during the core NoBA and 6m BA trials at the BA line for an initial density of $3p/m^2$. The 6m BA trials produced a marginally higher flow rate (230.9 ppm compared to 230.7 ppm), but a slightly narrower range (221.1-246.0 compared with 221.1-248.0). However, the difference between the averages is considerably less than the spread in the trial results for each case.

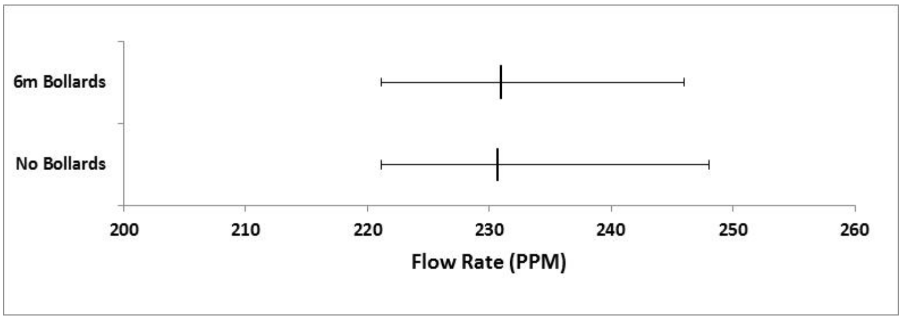


Figure 69: TS1 - Average and range of peak flow rates at the BA line produced for the core 6m BA and NoBA $3p/m^2$ trials.

Key Findings - 3_BA_6m_TS1: There is little difference between the average flow rates produced at the bollard array for the NoBA and 6m BA trials, with the 6m BA trials producing 0.1% higher flow rates. **The results suggest that there is no appreciable difference in the average flow rate at the line of the 6m BA that would be produced if a bollard array was located 6m from the exit compared to the case in which there was no bollard array present.**

4.2.5.4 GAP ANALYSIS

The manner in which the participants made use of the various gaps between the BA was examined. The gaps in the BA were numbered 1-5 (from left to right within the BA, see Figure 26). The results for the 6m BA trials at $3p/m^2$ are shown in Table 60. As in the previous cases (i.e., with $4p/m^2$), the central gap is disproportionately utilised (see Figure 70).

Table 60: TS1 - Percentage of participants using the available gaps between bollards in the 6m BA trials at $3p/m^2$.

3_BA_6m_TS1: % Gap Usage				
1	**2**	**3**	**4**	**5**
9.4	27.3	31.9	24.7	6.6

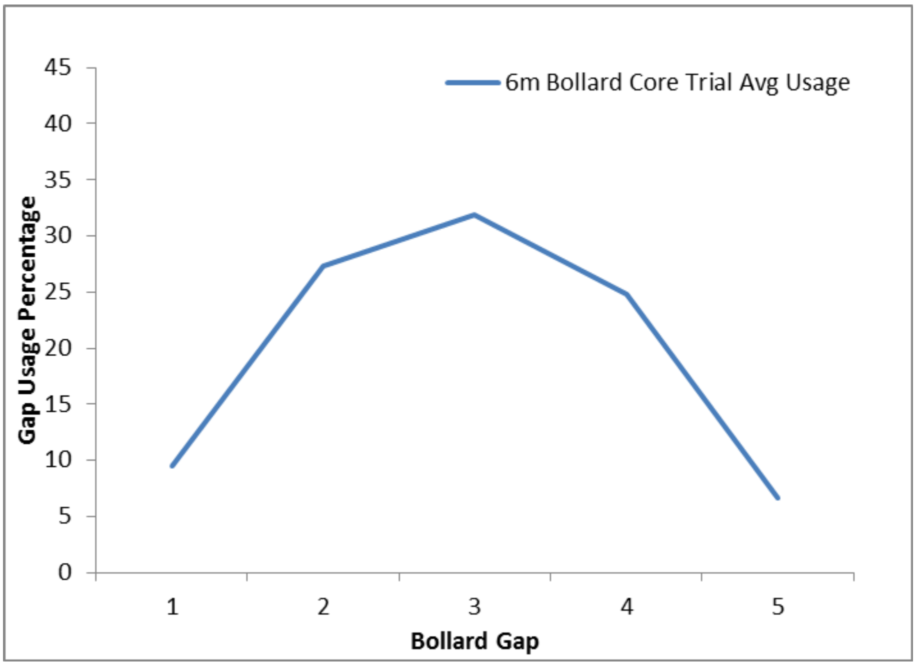


Figure 70: TS1 – Percentage of participants using the available gaps between bollards for the 6m BA trials at $3p/m^2$.

If the BA and NoBA trials are compared, we note that the "gap" usage at the 6m BA line is slightly different (see Figure 71). In particular, in the BA case, the gaps in the extremities (gaps 1 and 5) were used slightly more than in the NoBA case and the central gap (gap 3) was used slightly less. In this case, the BA encourages the participants to spread out a little more than in the NoBA case. This is different to the 4 p/m^2 case where the extreme gap usage was essentially the same in the BA and NoBA case (see Figure 50).

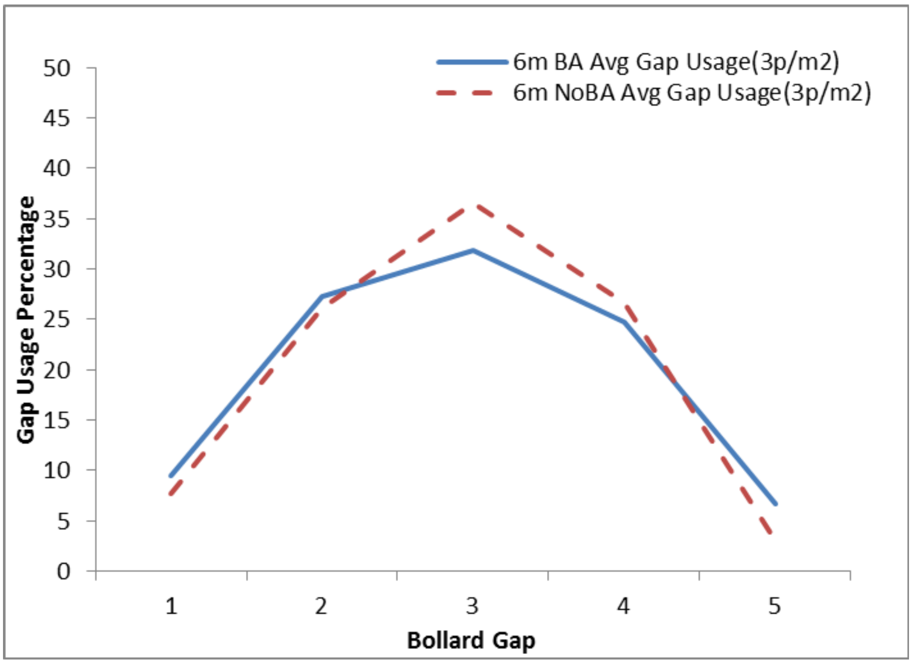


Figure 71: TS1 – Percentage of participants using the available gaps between bollards for the 6m BA and NoBA trials at 3p/m^2.

If we compare the 4p/m^2 gap usage at the 6m line with BA present with that for the 3p/m^2 case we note that in the lower density case there is slightly greater use of the outer gaps and slightly less usage of the central gap (see Figure 72). This suggests that in the lower density case, the participants were more able to spread out and make greater use of more of the BA.

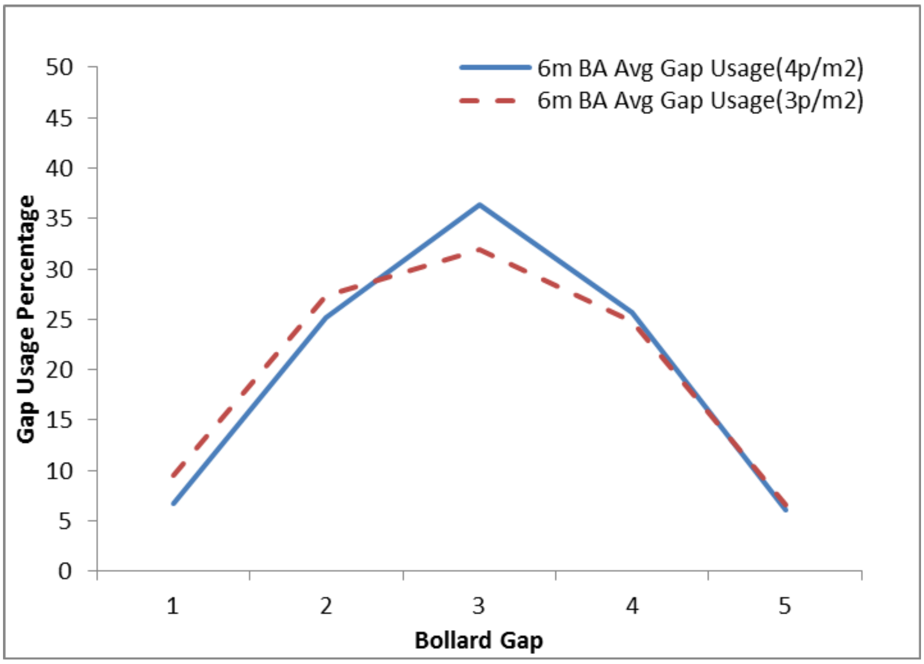


Figure 72: TS1 – Percentage of participants using the available gaps between bollards for the 6m BA trials at 3p/m^2 and 4p/m^2.

Key Findings - 3_BA_6m_TS1: The central gap was disproportionately used in the 6m 3p/m^2 trial, as in the 4 p/m^2 trial (see Section 4.2.1.6). The gaps in the extremities were used by more people with the BA present then without the BA. This is different to the 4 p/m^2 trial and suggests that in the lower density case, the participants are more able to spread out and make greater use of the BA.

4.2.5.5 DENSITY ANALYSIS

The densities recorded at the BA location during the 3m BA and NoBA trials are shown in Table 61 to Table 64. These show the densities over time (Table 61 and Table 62) or according to the area examined (Table 63 and Table 64). As with the 4 p/m^2 cases (see Section 4.2.1.7) the densities presented in Table 61 and Table 62 underestimate the actual density that the participants were exposed to as it assumes that the entire area was used.

Table 61: TS1 – Density at the 6m line for the 3p/m^2 initial density, NoBA trial.

3_NoBA_6m_TS1	Time interval (sec)							Average (p/m^2)
	10	15	20	25	30	35	40	
Trial B6 (p/m^2)	0.53	0.62	0.27	0.44	0.62	0.53	--	0.50
Trial 10 (p/m^2)	0.36	0.36	0.36	0.36	0.18	0.53	0.27	0.34
Trial 12 p/m^2	0.36	0.36	0.53	0.09	0.89	0.27	0.53	0.43
Average (p/m^2)	0.41	0.44	0.38	0.30	0.56	0.44	0.40	**0.42**

Table 62: TS1- Density at the 6m BA for the 3p/m^2 initial density trial.

3_BA_6m_TS1	Time interval (sec)							Average (p/m^2)
	10	15	20	25	30	35	40	
Trial B4 (p/m^2)	0.27	0.36	0.45	0.36	0.72	0.36	--	0.42
Trial 4 (p/m^2)	0.81	0.45	0.45	0.54	0.54	0.45	--	0.54
Trial 6 (p/m^2)	0.45	0.36	0.27	0.27	0.45	0.36	0.09	0.32
Average (p/m^2)	0.36	0.39	0.39	0.39	0.57	0.39	0.09	**0.44**

From Table 61 and Table 62, it is apparent that the average densities produced (0.42 and 0.44 p/m^2) were reasonably consistent, but lower than the initial density of 3p/m^2 within the holding area. This finding is consistent with those found during the trials when the initial density was 4p/m^2; i.e., the BA had little impact, but the densities dropped in comparison with the holding area. These results are expected given the distance between the BA and the holding area and the ability of the population to spread out (diffuse) on traversing the distance to the BA and spreading out across the BA.

From Table 63 and Table 64 we note, as expected, the average density in the central region (B) is considerably higher than that for the outer regions. While this goes up to a maximum of 1.2 p/m^2 in the case of the 6m BA and 1.3 p/m^2 in the NoBA case it is still considerably less than the 3 p/m^2 of the initial holding area.

Table 63: TS1: Average density at the 6m BA line (NoBA) for the $3p/m^2$ initial density measured in the three regions during the peak period

3_NoBA_6m_TS1	p/m^2
A	0.23
B	0.62
C	0.05

Table 64: TS1: Average density at the 6m BA for the $3p/m^2$ initial density measured in the three regions during the peak period

3_BA_6m_TS1	p/m^2
A	0.32
B	0.53
C	0.13

It is also apparent that the peripheral areas (A and C) were used more heavily during the BA trials (0.32/0.13 p/m^2 during the BA trials compared with 0.23/0.05 p/m^2 during the NoBA trials). This may have been due to the lane formation effect identified during the 0m BA trials. Then, the presence of the barrier reduced lateral conflict between participants through the general of lanes. Here, an equivalent effect may have syphoned participants into the peripheral areas. As noted previously, this result may reflect a real underlying factor, or may have been influenced by the methodology adopted (i.e. that the discretisation of the conditions produced through taking snapshot observations did not adequately reflect the underlying conditions). In conditions where there were only occasionally participants present producing elevated density values, the method adopted may have been vulnerable to selecting snapshots where people were present, thereby artificially overestimating the densities present.

Key Findings - 3_BA_6m_TS1: The presence of the bollard array did not unduly influence the average densities produced across the 6m bollard line, there seems to be a difference in the manner in which these densities were distributed across the BA line. It is not clear whether this difference is due to methodological factors or flow dynamics.

4.2.6 INITIAL POPULATION 3P/M^2 – 3M BOLLARD ARRAY LOCATION

The results produced in the 3_BA_3m_TS1 trials are discussed in this section and compared with the results produced in the 3_NoBA_TS1 trials (see Figure 51).

4.2.6.1 EXIT FLOW

Table 65 shows the exit flow results with an initial density of $3p/m^2$ for the NoBA trials and the 3m BA cases. In this case the NoBA trials with the highest and lowest flow rates have been removed before any analysis is performed.

Table 65: TS1 - Exit Flow for peak period for 3m BA and NoBA trials at initial density of $3p/m^2$.

Scenario	Flow (ppm) at Exit
3_NoBA_TS1	233.3 [224.0 – 252.0]
3_BA_3m_TS1	235.2 [228.0 – 244.8]

The results in Table 65 show that the 3m BA trials produced exit flow rates that were on average 1.9 ppm or 0.8% higher (with a range of -7.1% to +4.8%) than the equivalent NoBA trials. The NoBA trials produced an average flow rate of 233.3ppm (with a standard deviation of 16.17 and a range of -4.0% to +8.0%)while the 3m BA trials produced an average flow rate of 235.2ppm (with a standard deviation of 8.65 and a range of -3.1% to +4.1%).

The manner in which the exit flow rates vary for the NoBA case and when the BA is placed at 3m from the exit can be seen in Figure 73. It can be seen that the flow conditions and the resultant exit flow produced broadly similar trends.

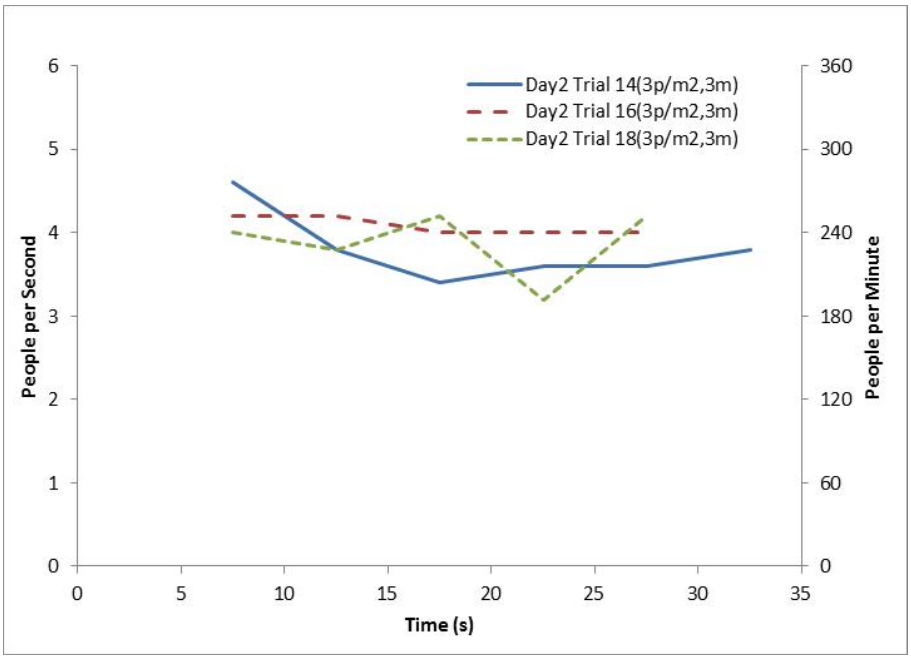


Figure 73: TS1 – Peak exit flow rate measured in 5 second intervals for the three 3m BA trials at 3p/m^2.

Table 66 shows the ranking of the individual runs for the 3m BA and the NoBA trials. From Table 66 it can be seen that in 67% of the comparisons, BA trials produced higher flow rates; in 33% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates. This indicates that, overall, the presence of bollards at 3m more likely results in a slight increase in flow rate at the exit.

Table 66:TS1 - Ranking of NoBA and 3m BA trials at 3 p/m^2.

3_BA_3m_TS1	Higher than No BA Trials	Lower than No BA Trials	Equal to No BA Trials

Trial 14	2	1	0
Trial 16	2	1	0
Trial 18	2	1	0
Total	6	3	0

Table 67 and Table 55 include, for each of the core 3m BA and NoBA trials respectively, the average exit flow rate within 5 second intervals during the peak flow period. The data has been used to calculate the overall average ppm. It is apparent that the average flow rates produced in the 3m BA trials (235.2 ppm) are similar to those produced during the NoBA trials (233.3ppm). The quantitative and qualitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 74.

Table 67: TS1 – Exit flow during peak period measured in 5 sec time intervals for the 3p/m^2 trials with 3m BA

3_BA_3m_TS1	Peak period flow (ppm)						Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 14	276	228	204	216	216	228	228.0
Trial 16	252	252	240	240	240	--	244.8
Trial 18	240	228	252	192	252	--	232.8
Average (ppm)	256.0	236.0	232.0	216.0	236.0	228.0	**235.2**

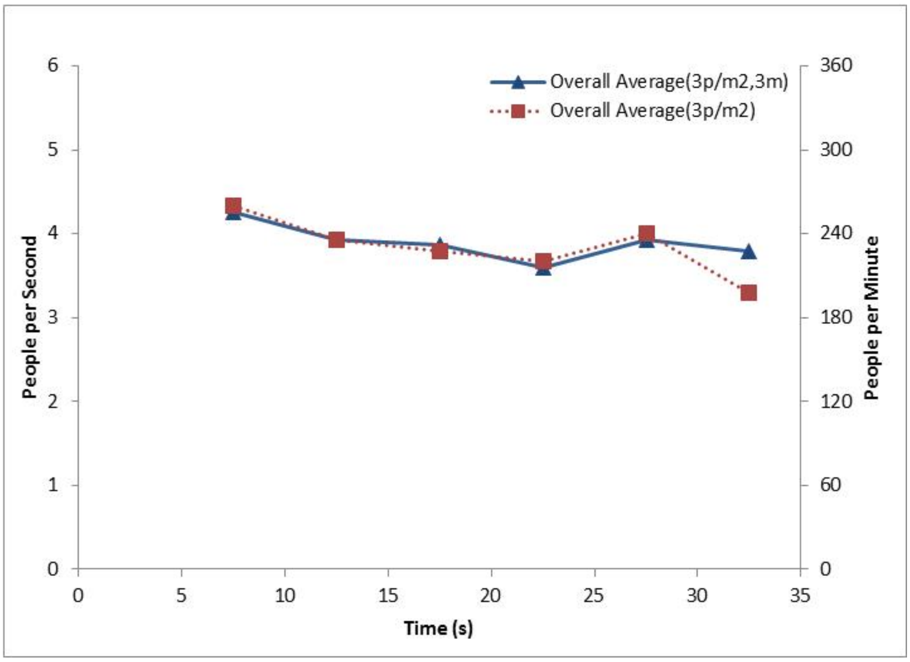


Figure 74: TS1 - Average exit peak flow rate measured in 5 second intervals for both the 3m BA and NoBA trials at 3p/m^2.

Figure 75 shows the results of the average and range of the average peak flow rates produced during the core NoBA and 3m BA trials at 3p/m^2. This shows that the 3m BA trials produced a slightly higher flow rate (235.2 ppm compared to 233.3 ppm) with a narrower range of flow rates produced (228.0-244.8 ppm compared to 224.0-252.0 ppm). It is noted that the difference in average exit flow rates between the two sets of conditions is lower than the trial by trial variability within the series of no BA trials and the 3m BA trials. The standard deviations produced indicate more variability in the results for the NoBA case than the 3m bollard case. The 3m BA average flow rate was higher than two of the three individual NoBA results and lower than one.

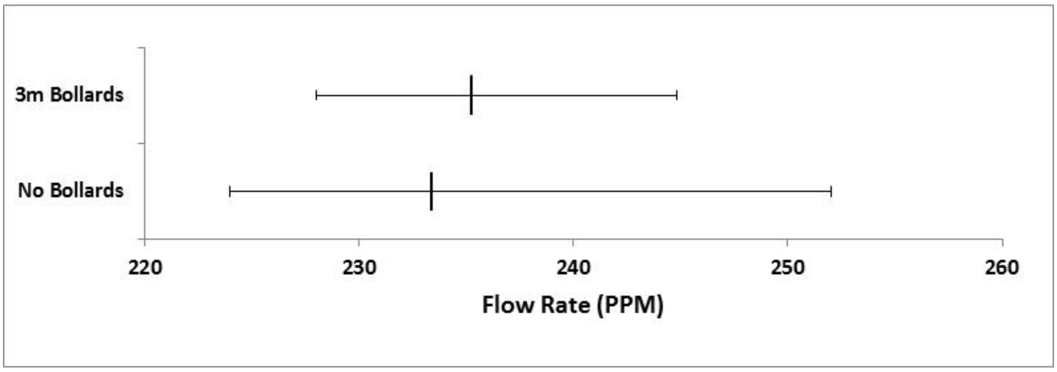


Figure 75: TS1 - Average and range of peak exit flow rates for the 3m BA and NoBA 3 p/m^2 trials

Key Findings - 3_BA_3m_TS1: The core 3m BA trials with an initial population density of 3p/m^2 produced average exit point flow rates 0.8% higher than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 3m from the exit compared to the case in which there was no bollard array present.**

4.2.6.2 BOLLARD FLOW

Table 68 compares the peak BA flow results produced during the core NoBA trials and the 3m BA trials with an initial density of 3p/m^2.

The results in Table 68 show that the 3m BA trials produced flow rates that were on average 3.5 ppm or 1.5% greater (with a range of -4.6% to +6.2%) than the equivalent NoBA trials. The NoBA trials produced an average flow rate of 235.2ppm (with a standard deviation of 13.1 and a range of -4.8% to +6.1%) while the 3m BA trials produced an average flow rate of 238.7 ppm (with a standard deviation of 8.1 and a range of -2.0% to +3.9%).

Table 68: TS1 – Peak flow rates at the position of the Bollard Array for the core NoBA and 3m BA trials at 3p/m^2.*

	Flow (ppm) at BA
3_NoBA_TS1	235.2 [224.0 – 249.6]
3_BA_3m_TS1	238.7 [234.0 – 248.0]

*It should be noted here that the final flow rate of 144.0ppm within the NoBA Trial 2 trial had a large impact on the overall results. The value indicated a considerable drop-off of the flow conditions. It was decided that the data would be truncated to exclude this value from the data-set.

The qualitative and quantitative similarity between the flow rates at the 3m BA line is more apparent when examining Figure 76.

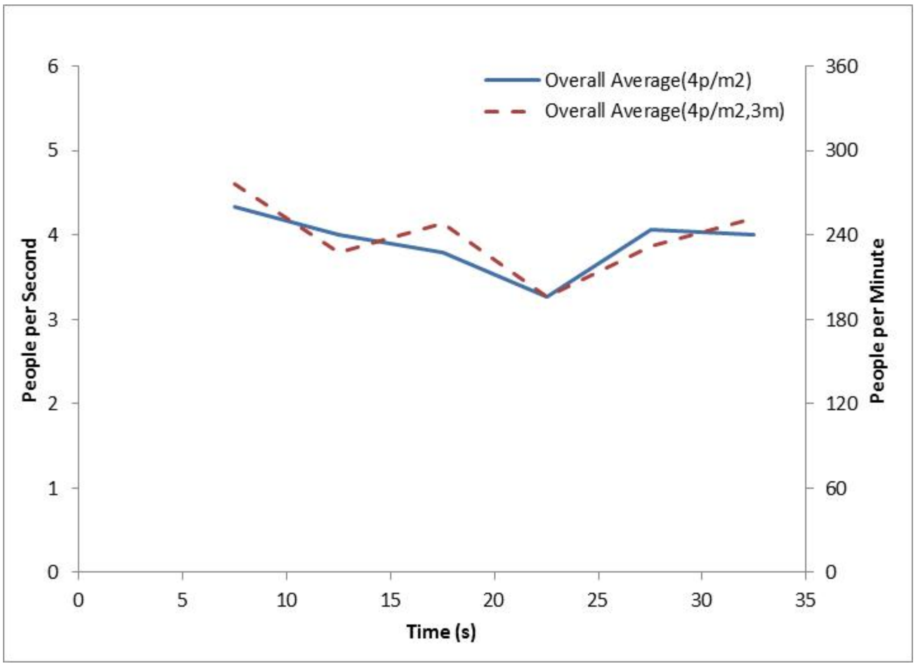


Figure 76: TS1 - Average BA peak flow rate measured in 5 second intervals for the core 3m BA and NoBA trials at $3p/m^2$.

Figure 77 shows the results of the average and range of the peak flow rates produced during the core NoBA and 3m BA trials at the BA line for an initial density of $3p/m^2$. The 3m BA trials produced a slightly higher (238.7 ppm compared with 235.2 ppm), but produced a narrower range of values (234.0-248.0 ppm compared with 224.0-249.6 ppm). The difference between the averages is less than the spread in both cases.

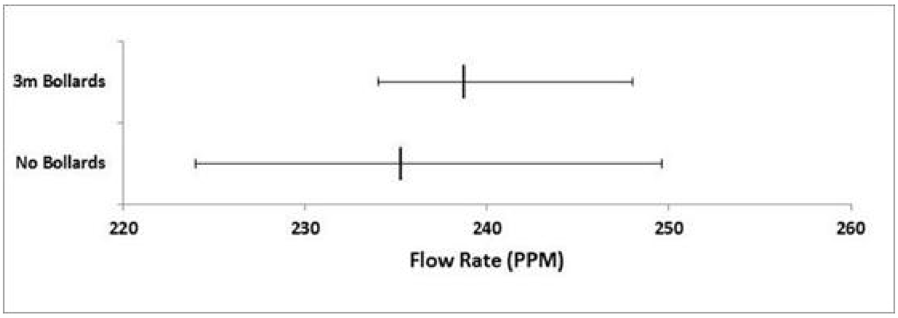


Figure 77: TS1 - Average and range of the peak flow rates at the BA line produced for the core 3m BA and NoBA $3p/m^2$ trials.

Key Findings - 3_BA_3m_TS1: There is little difference between the average flow rates produced at the bollard array for the NoBA and 3m BA trials, with the 3m BA trials producing 1.5% higher flow rates. The results suggest that there is not a pronounced difference in the average flow rate at the line of the 3m BA that would be produced if a bollard array was located 3m from the exit compared to the case in which there was no bollard array present.

4.2.6.3 GAP ANALYSIS

The manner in which the participants made use of the various gaps between the BA has been examined. The gaps available were numbered 1-5 (from left to right within the BA, see Figure 26). The results produced during the 3m BA trials at $3p/m^2$ are shown in Table 69. As in the previous cases (i.e., with $4p/m^2$), the central gap is disproportionately used with 37% of the participants using the central route (see Figure 78).

Table 69: Percentage of participants using the available gaps between bollards in the 3m BA trials at $3p/m^2$.

3_BA_3m_TS1: % Gap Usage				
1	**2**	**3**	**4**	**5**
3.2	28.3	37.4	27.1	3.9

The gap usage was reasonably consistent between the trials where the BA was placed at 3m and 6m. There is a slight increase in the proportion of those using the central gap during the 3m trials (5.5%). Furthermore, there is a slight increase in the number of participants using the extreme gaps (gaps 1 and 5) when the BA is at 6m compared to 3m (see Figure 79). This might be expected given the reduced opportunity for the participants to diffuse between the exit point and the BA when the BA is at 3m compared to 6m.

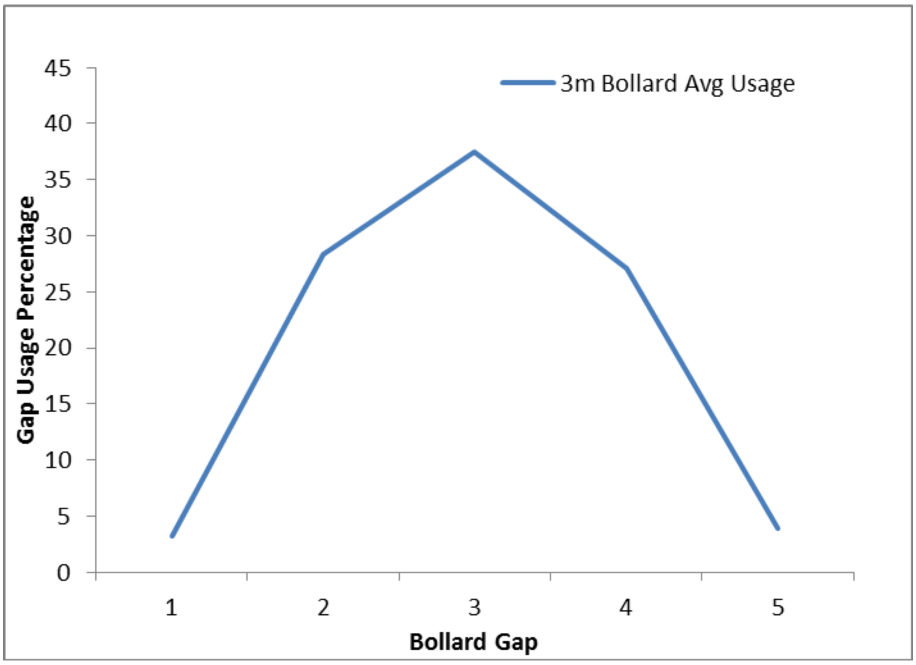


Figure 78: TS1 - Percentage of participants using the available gaps between bollards for the 3m BA trials at $3p/m^2$.

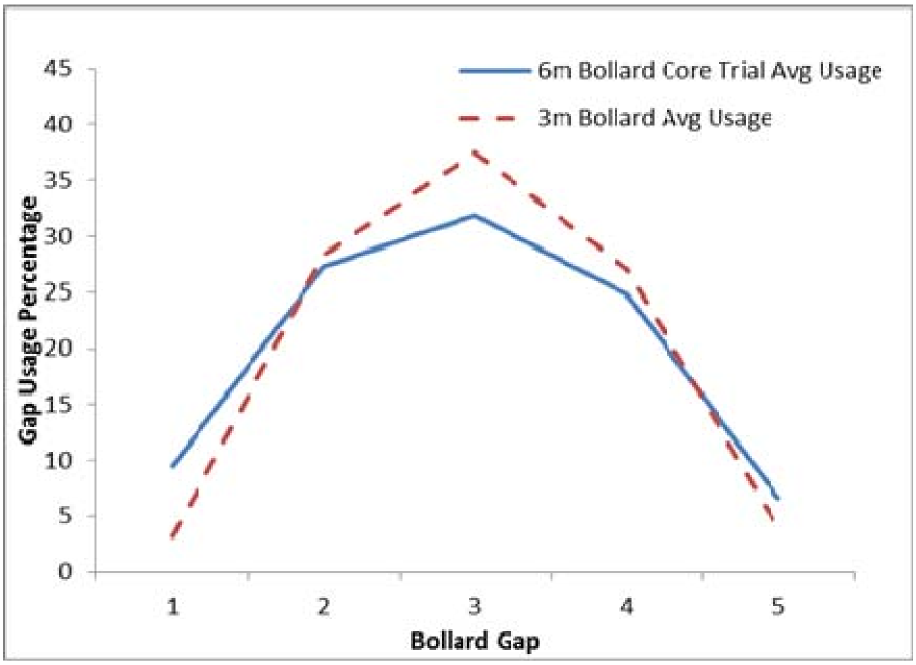


Figure 79: TS1- Percentage of participants using the available gaps between bollards given the sets of 6m BA and the 3m BA trials at 3p/m^2.

Key Findings - 3_BA_3m_TS1: At a distance of 3m from the exit, the central gap was disproportionately used by the participants in the 3p/m^2 case, similar to that observed in the 4p/m^2 case. More participants made use of the extreme gaps when the BA was at 6m compared to 3m, again similar to the behaviour observed in the 4 p/m^2 case.

4.2.6.4 DENSITY ANALYSIS

The densities produced at the BA location during the NoBA and the 3m BA trials are shown in Table 70 to Table 73. These show the densities over time (Table 70 and Table 71) or according to the area examined (Table 72 and Table 73). As with the 4 p/m^2 cases (see Section 4.2.2.4) the densities presented in Table 70 and Table 71 underestimate the actual density that the participants were exposed to as it assumes that the entire area was used.

From Table 70 and Table 71, it is apparent that the average densities produced (0.46 and 0.42 p/m^2) were reasonably consistent with each other, but lower than the initial density of 3p/m^2 within the holding area. This finding is consistent with those found during the trials when the initial density was 4p/m^2; i.e., the BA had little impact, but that the densities dropped in comparison with the holding area. These results are expected given the distance between the BA and the holding area and the ability of the population to spread out (diffuse) – on traversing the distance to the BA and spreading out across the BA. Even though the stand-off distance is reduced from the 6m BA trials, the drop-off from the initial densities in the holding area is consistent (e.g., 0.46 / 0.42 p/m^2 here, as opposed to 0.42 / 0.44p/m^2 for the comparable 6m BA trials, compare Table 70-Table 71 with Table 61-Table 62).

Table 70: TS1 – Density at the 3m line for the 3p/m^2 initial density, NoBA trial

3_NoBA_3m_TS1	Time interval (sec)					Average (p/m^2)
	10	15	20	25	30	
Trial B6 (p/m^2)	0.44	0.36	0.53	0.44	0.53	**0.46**

Only one of the core trials is shown in Table 43 as the other core trials came from the narrower setup that was used on Day 1 (see Section 3.3). This meant that the densities could not be measured for these trials as the regions A and C lie mostly outside the barriers and hence could not be occupied by the participants.

Table 71: TS1 - Density at the 3m BA for the 3p/m^2 initial density trial.

3_BA_3m_TS1	Time interval (sec)						Average (p/m^2)
	10	15	20	25	30	35	
Trial 14 (p/m^2)	0.451	0.451	0.451	0.271	0.451	-	0.42
Trial 16 (p/m^2)	0.451	0.451	0.451	0.541	0.271	0.361	0.42
Trial 18 (p/m^2)	0.361	0.451	0.451	0.451	0.541	0.271	0.42
Average (p/m^2)	0.42	0.45	0.45	0.42	0.42	0.21	**0.42**

From Table 72 and Table 73 we note, as expected, the density in the central region (B) is considerably higher than that for the outer regions. While this goes up to a maximum of 0.75 p/m^2 in the case of the 3m BA and 1.18 p/m^2 in the NoBA case it is still considerably less than the 3 p/m^2 of the initial holding area.

Table 72: TS1 – Average density at the 3m BA line (NoBA) for the 3p/m^2 initial density measured in the three regions during the peak period

3_NoBA_3m_TS1	p/m^2
A	0.00
B	0.74
C	0.09

Table 73: TS1 – Average density at the 3m BA for the 3p/m^2 initial density measured in the three regions during the peak period

3_BA_3m_TS1	p/m^2
A	0.00
B	0.63
C	0.10

It is perhaps more instructive to examine the densities produced in the central area only, given the earlier discussion. From Table 74 and Table 75 it is apparent that the use of the central area (B) is reasonably consistent demonstrating the general tendency for this route to be adopted throughout the trials.

Table 74: TS1 – Density Region B at the 3m BA line (NoBA present) for the $3p/m^2$ initial density

3_NoBA_3m_TS1	Time (sec)						Average (p/m^2)
	10	15	20	25	30	35	
Trial B6 (p/m^2)	0.74	0.44	0.89	0.74	0.89	0.44	0.69
Trial 10 (p/m^2)	0.59	0.74	0.89	1.18	0.74	0.74	0.81
Trial 12 (p/m^2)	1.03	0.59	0.89	0.44	0.59	0.74	0.71
Average (p/m^2)	0.79	0.59	0.89	0.79	0.74	0.64	**0.74**

Table 75: TS1 – Density Region B at the 3m BA for the $3p/m^2$ initial density

3_BA_3m_TS1	Time (sec)						Average (p/m^2)
	10	15	20	25	30	35	
Trial 14 (p/m^2)	0.60	0.75	0.75	0.45	0.75	-	0.66
Trial 16 (p/m^2)	0.75	0.75	0.75	0.75	0.45	0.45	0.65
Trial 18 (p/m^2)	0.60	0.75	0.75	0.75	0.75	0.45	0.68
Average (p/m^2)	0.65	0.75	0.75	0.65	0.65	0.45	**0.66**

Key Findings - 3_BA_3m_TS1: The presence of the bollard array did not unduly influence the densities produced at the 3m bollard line; however, as is to be expected, the densities are considerable smaller than the initial $3p/m^2$ in the holding area.

4.2.7 INITIAL POPULATION 3P/M^2 – 0M BOLLARD ARRAY LOCATION

The results produced in the 3_BA_0M_TS1 trials are discussed in this section and compared with the 3_NoBA_TS1 trials (see Figure 60). This section compares the exit flow conditions of the 0m BA trials and the NoBA trials conducted at $3p/m^2$ (see Table 76). In this case the fastest and slowest NoBA trials have been removed before analysis is performed. It is apparent that the NoBA trials produce a slightly higher (0.2%) average flow rate than the 0m BA trials (233.3ppm as compared to 232.9ppm).

Table 76: TS1 - Exit Flow for peak period at initial density of $3p/m^2$.

Scenario	Flow (ppm) at Exit
3_NoBA_TS1	233.3 [224.0 – 252.0]
3_BA_0m_TS1	232.9 [226.0 – 242.4]

The manner in which the exit flow rates vary with the BA placed at 0m from the exit can be seen in Figure 80. As can be seen from Figure 80 the flow conditions in each of the trials were broadly similar, producing broadly similar trends in exit flows.

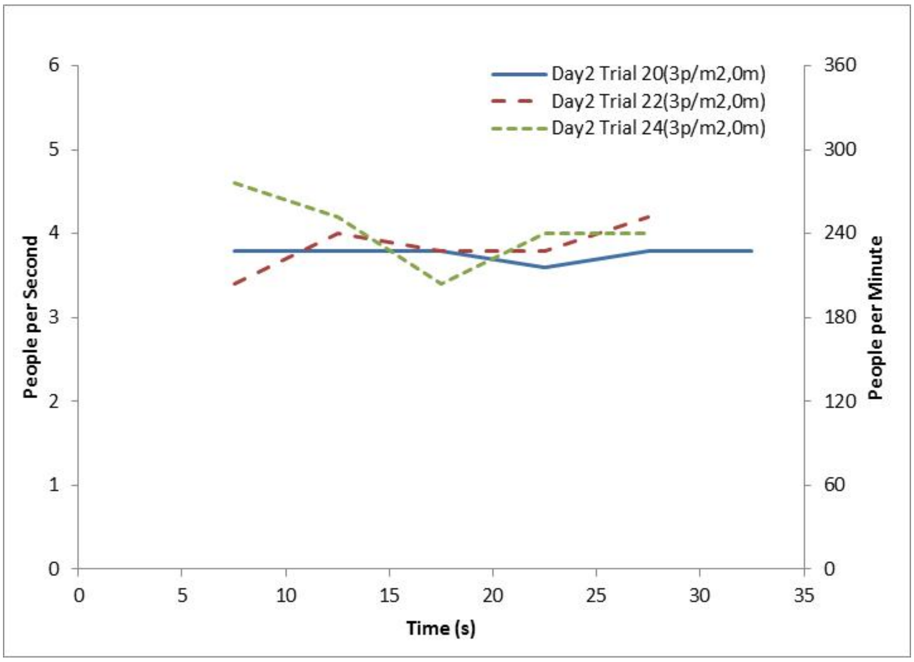


Figure 80: TS1 - Exit flow rate over peak period measured in 5 second intervals for the three 0m BA trials at 3p/m^2.

The results in Table 76 show that the 0m BA trials produced flow rates that were on average 0.4 ppm or 0.2% lower (with a range of -8.2% to +3.8%) than the equivalent NoBA trials. The NoBA trials produced an average flow rate of 233.3 ppm (with a standard deviation of 16.17 and a range of -4.0% to +8.0%) while the 0m BA trials produced an average flow rate of 232.9 ppm (with a standard deviation of 8.49 and a range of -3.0% to +4.1%).

The difference in average peak exit flows between the 0m BA and NoBA cases is relatively small (0.2%) and, as shown in Figure 81, during the peak flow period the NoBA and 0m BA trials alternate in producing marginally greater flow rates.

Table 77 shows the ranked trials according to the exit flow rates produced. From Table 77 it can be seen that in 67% of the comparisons the trials with the bollard present produced higher flow rates; in 33% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates. This suggests that, overall, the presence of bollards at 0m originally resulted in an increase in flow rate at the exit (although overall the flow rates produced were 0.2% lower). Table 78 and Table 55 show the average flow rate produced at the exit within each 5 second interval of the peak flow period for each of the 0m BA and NoBA trials respectively. The data in these tables has then been used to calculate the overall average flow in persons per minute.

Table 77:TS1: Ranking of trials.

3_BA_0m_TS1	Higher than	Lower than	Equal to

	3_NoBA_TS1 Trials	3_NoBA_TS1 Trials	3_NoBA_TS1 Trials
Trial 20	2	1	0
Trial 22	2	1	0
Trial 24	2	1	0
Total	6	3	0

Table 78: TS1:Peak flow per time interval for core trials with 0m BA, 3p/m^2.

3_BA_0m_TS1	Peak period flow (ppm)						Average (ppm)
	Time interval (sec)						
	5-10	10-15	15-20	20-25	25-30	30-35	
Trial 20	228	228	228	216	228	228	226.0
Trial 22	204	240	228	228	252	--	230.4
Trial 24	276	252	204	240	240	--	242.4
Average (ppm)	236.0	240.0	220	228	240	228	**232.9**

The quantitative and qualitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 81.

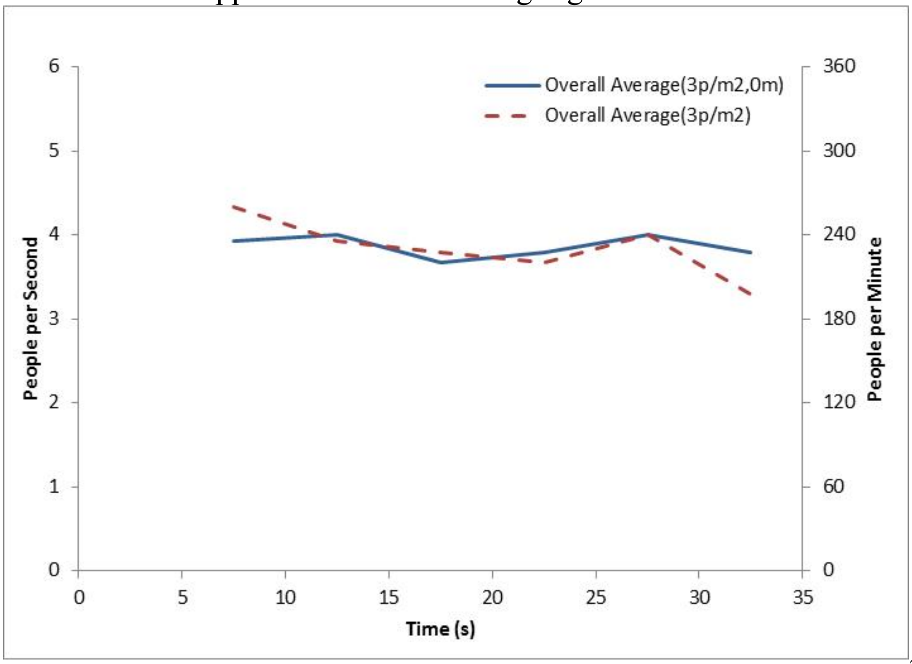


Figure 81: TS1 - Average exit peak flow rate for the NoBA and 0m BA 3p/m^2 trials

Figure 82 shows the results of the average and range of the peak flow rates produced over the core NoBA and the three 0m BA trials at 3p/m^2. This shows that the 0m BA trials produced a slightly lower flow rate (232.9 ppm compared to 233.3 ppm) with a narrower range of results (226.0-242.4 ppm compared to 224.0-252.0 ppm). It is noted that the difference in average exit flow rates between the two sets of trials is less than the trial by trial variability within both the series of 0 m BA trials and the NoBA trials. The 0m BA average flow rate was higher than two of the three individual NoBA results and lower than one.

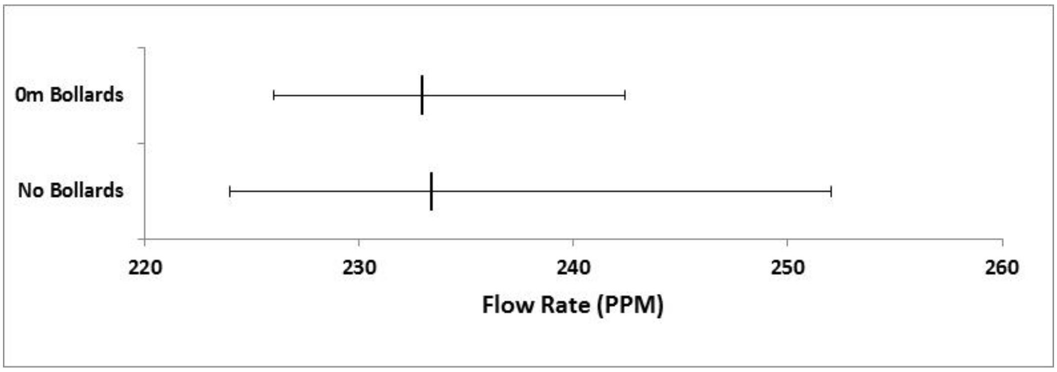


Figure 82:TS1 - Average and range of peak exit flow rates for the core 0m BA and NoBA 3 p/m^2 trials.

As with the 4p/m^2 0m BA case, the 0m BA case with 3p/m^2 produced greater flows than expected given the reduction in exit width associated with of the bollard. As with the previous case, this is due to the improvement in the **unit flow rate** in the presence of the 0m BA. The presence of the bollard in the exit results in a 9.4% reduction in the available exit width and as result we would again expect the flow rate to be 9.4% lower with bollard present. However, it is measured to be 0.2% lower – a noticeably greater flow rate than expected.

Using the available free exit width, the average unit flow rate for the exit without the bollard in place is 1.62 p/m/sec while that for the exit with the bollard in place is 1.78 p/m/sec. Therefore, we note that with the bollard present, the unit flow rate for the exit is 10.1% higher than without the BA present (see Table 79). Thus, the 9.4% reduction in flow rate produced by the reduction in effective width of the exit due to the presence of the bollard is partially compensated for by the 10.1% improvement in unit flow rate achieved by the more ordered exit flow generated by the presence of the bollard. It is also noted that the flow rates achieved in the 3p/m^2 case (see Table 79) are smaller than those produced in the 4p/m^2 case (see Table 52) due to the smaller initial density.

As with the 4 p/m^2 0m bollard case, it is noted the improvement in unit flow rate observed in these trials may not necessarily be achieved in cases where the pedestrians are carrying luggage. As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

Table 79:TS1 – Flow and Unit flow at exit for core NoBA trials 0m BA trials at peak flow for 3p/m^2.

Scenario	Flow (ppm)	Unit Flow (p/m/min)	Unit Flow (p/m/sec)
No Bollards (4_NoBA)	233.3 [224.0 – 252.0]	97.21 [93.3 – 105.0]	1.62 [1.55 – 1.75]
0m Bollards (4_BA_0m)	232.9 [226.0 – 242.4]	107.08 [103.9 – 111.4]	1.78 [1.73 – 1.86]

Key Finding – 3_BA_0m_TS1: On average the flow rate at the exit with a 0m bollard present was some 0.2% lower than the case without bollards. This reduction in flow rate is smaller than the variation in the 0m bollard and the NoBA cases. **Therefore, it is unlikely**

that the presence of the bollard resulted in an appreciable reduction in flow rate. However, the reduction in flow rate due to the presence of the bollard was not as great as would be expected given the reduction in exit width. The better than expected flow rate produced with the 0m bollard present is due to a 10.2% improvement in the unit flow rate for the exit with the bollard present. The reduction in flow rate due to the reduction in exit width was partially compensated by the improvement in unit flow rate. It is unknown whether this improvement in exit unit flow rate will also occur in situations with more passengers carrying luggage.

4.2.8 SUMMARY RESULTS

A summary of the key results for the TS1 3p/m^2 trials are presented in Table 80. **The average peak exit flow rates are broadly comparable irrespective of whether there is no bollard array or if the stand-off is 0m, 3m or 6m.** The difference in the average values for the various bollard locations is smaller than the variation in the trial results for each case. This is similar to the findings for the 4 p/m^2 case. However, unlike the 4 p/m^2 case which suggested a possible weak relationship between stand-off distance and exit flow rate (i.e., the greater the stand-off distance the greater the exit flow rate) no such relationship can be seen in the 3 p/m^2 case.

Table 80: Summary average peak flow rates produced during the core TS1 3p/m^2 trials.

BA Conditions	Flow (ppm) at Exit	Comparison BA & NoBA	Flow (ppm) at BA	Comparison BA & NoBA
3_NoBA_TS1 (at 0m)	233.3 [224.0-252.0]	-	233.3 [224.0-252.0]	-
3_NoBA_TS1 (at 3m)	233.3 [224.0-252.0]	-	235.2 [224.0-249.6]	-
3_NoBA_TS1 (at 6m)	233.3 [224.0-252.0]	-	230.7 [221.0-248.0]	-
3_BA_0m_TS1	232.9 [226.0-242.4]	-0.2%	232.9 [226.0-242.4]	-0.2%
3_BA_3m_TS1	235.2 [228.0-244.8]	+0.8%	238.7 [234.0-248.0]	+1.5%
3_BA_6m_TS1	230.7 [224.0-235.2]	-1.1%	230.9 [221.1-246.0]	-0.1%

At 0m, the decrease in exit flow rate due to the presence of the bollard is partially compensated for by the increase in exit unit flow rate produced due to the presence of the bollard. As a consequence, the reduction in exit flow rate is not as large as would be expected. For the lower initial population density these results do not demonstrate that the BA has an impact on the exit flow rate. However, it is unclear what may occur if the bollard array was brought closer to the exit (e.g. between 0m and 3.0m). As this aspect was not was not tested in these trials it may warrant further analysis in future trials. **These results suggest that a BA placed at 0m, 3m, or 6m from an exit DOES NOT have a pronounced numerical impact on the exit flow rate.**

4.3 TS2: BOLLARD FLOW TRIALS

The TS2 trials examined the impact of a bollard array on pedestrian flows of a given initial density. In these trials, the population does not have the opportunity to diffuse in the same manner as they did in TS1 (see Figure 83); their lateral movement is constrained by the narrower experimental space and the presence of others, the longitudinal movement is constrained by their proximity to the BA and the surrounding population. In these trials, the pedestrian population is assumed to have exited the station and arrived at the BA location at the given initial density.

Figure 83: TS2 configuration with NoBA (left) and with BA in place (right).

4.3.1 POPULATION DENSITY: 4 p/m^2

In this section the results for 4_BA_TS2 trials are discussed and compared with the 4_NoBA_TS2 trials. The flow rates described in this section are peak flows during the steady-state period. This excludes the start-up period of the flow, where flow is low due to the crowd just starting to move, and the slow-down period of the flow where the flow is low due to the reduced number of people available at the very end of the trial. Presented in Figure 84 is a typical set of flow curves showing the start-up, peak flow and slow-down periods. In these example trials, the peak period typically runs from 4.5 sec to 13.5 sec and the flow rate was measured in intervals of 3 seconds.

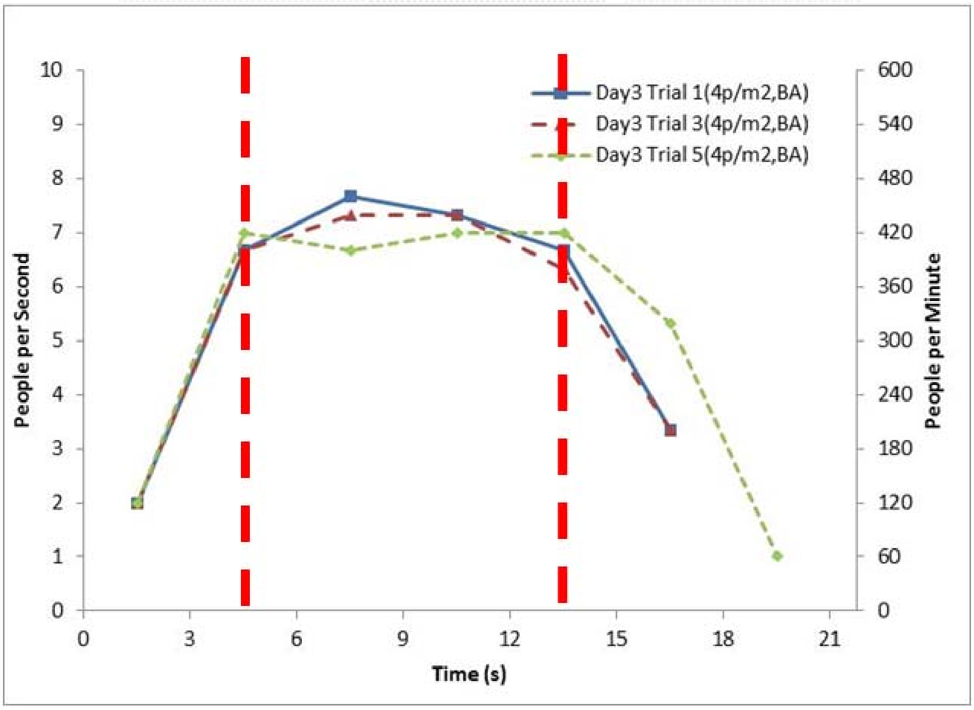


Figure 84: Example curves for entire duration of trial highlighting the start-up, peak and slow-down periods.

4.3.1.1 BOLLARD ARRAY FLOW

Presented in Table 81 are the flow rates produced at the BA line for the NoBA and BA trials with an initial density of 4p/m^2.

Table 81: TS2 - BA flow for trials at 4p/m^2.

Scenario	Flow (ppm) at BA
4_NoBA_TS2	448.3 [440.0 – 465.0]
4_BA_TS2	412.0 [396.0 – 425.0]

The results in Table 81 show that the trials where bollards were present (BA) produced flow rates that were on average 36.3 ppm or 8.1% lower than the equivalent trials where the bollards were absent (NoBA). The NoBA trials produced an average flow rate of 448.3 ppm (with a standard deviation of 14.43 and a range of -1.9% to +3.7%) while the BA trials produced an average flow rate of 412.0 ppm (with a standard deviation of 14.73 and a range of -3.9% to +3.2%).

The manner in which the flow rates changed over time is shown in Figure 85 to Figure 87. From Figure 85 and Figure 86 it is clear that the three trials produced reasonably consistent results. The results from the three repeat trials have been averaged producing the peak curves shown in Figure 87. It is apparent from Figure 87 that although the curves track each other quite closely, the BA curve is consistently below the NoBA curve, indicating that the flow rates produced were lower throughout the peak period.

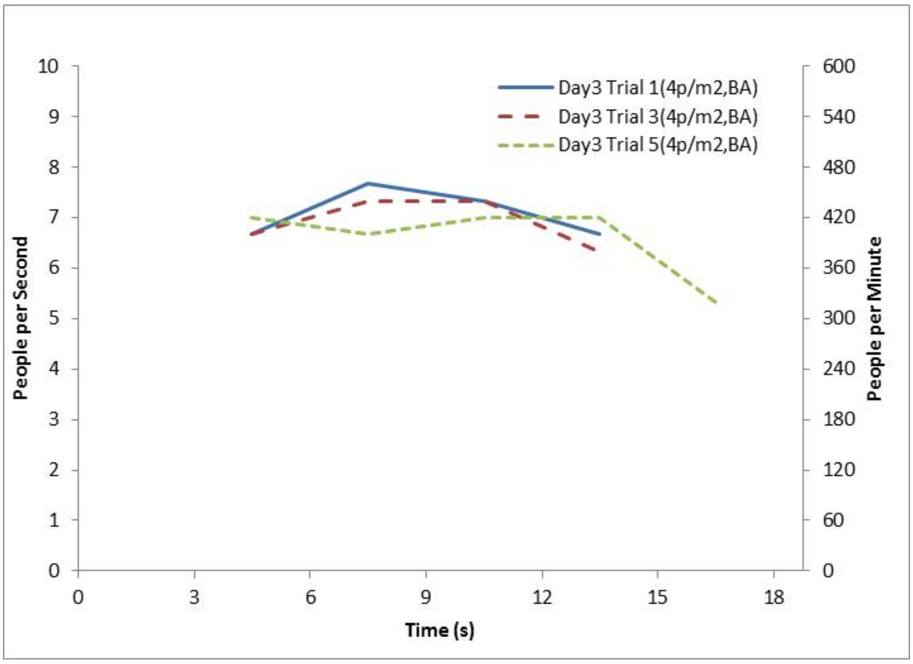


Figure 85: TS2 – Peak flow rate measured in 3 sec intervals at the BA line for the three BA, 4 p/m^2 trials

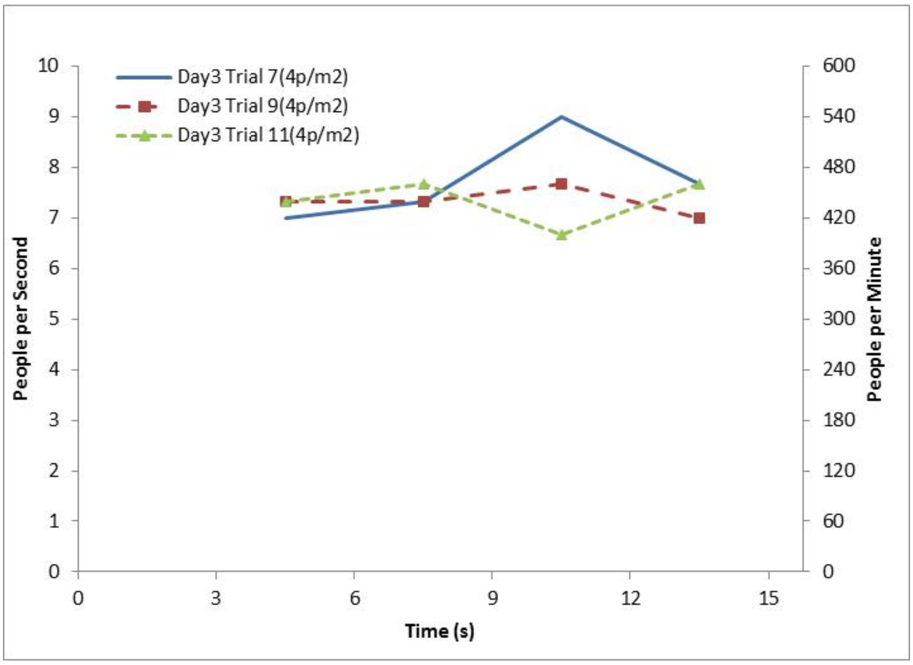


Figure 86: TS2 – Peak flow rate measured in 3 sec intervals at the BA line for three NoBA, 4 p/m^2 trials.

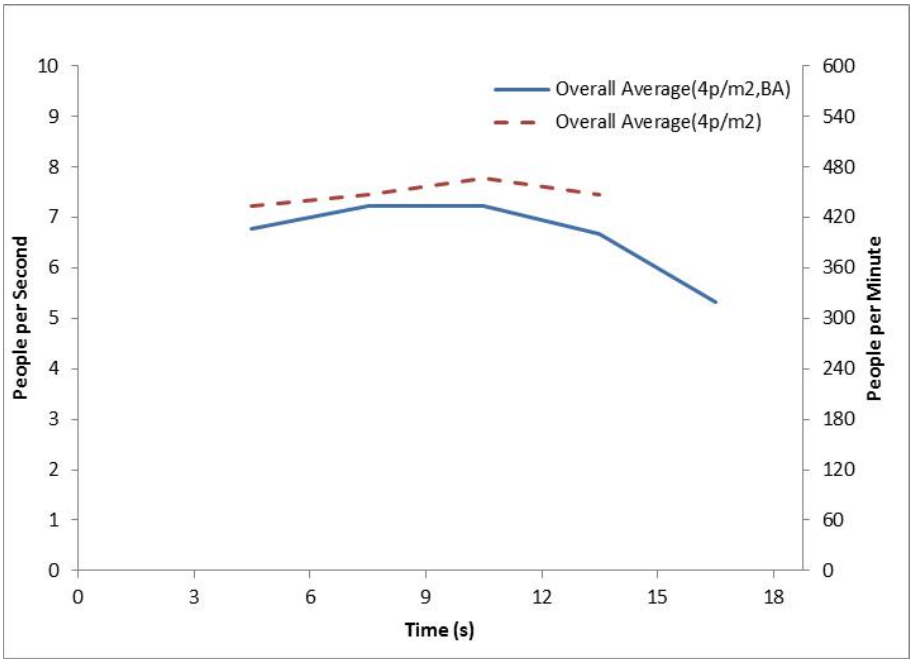


Figure 87: TS2 - Average peak flow rate at the BA line for NoBA and BA 4 p/m^2 trials.

From Table 82 it can be seen that in 0% of the comparisons the BA trials produced higher flow rates, in 100% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates.

Table 82:TS2 - Ranking of 4 p/m^2 trials.

4_BA_TS2	Higher than 4_NoBA_TS2 Trials	Lower than 4_NoBA_TS2Trials	Equal to 4_NoBA_TS2Trials

Trial 1	0	3	0
Trial 3	0	3	0
Trial 5	0	3	0
Total	0	9	0

Presented in Figure 88 are the average and range of the peak flow rates at the BA line produced during the NoBA and BA trials with an initial density of 4p/m^2.

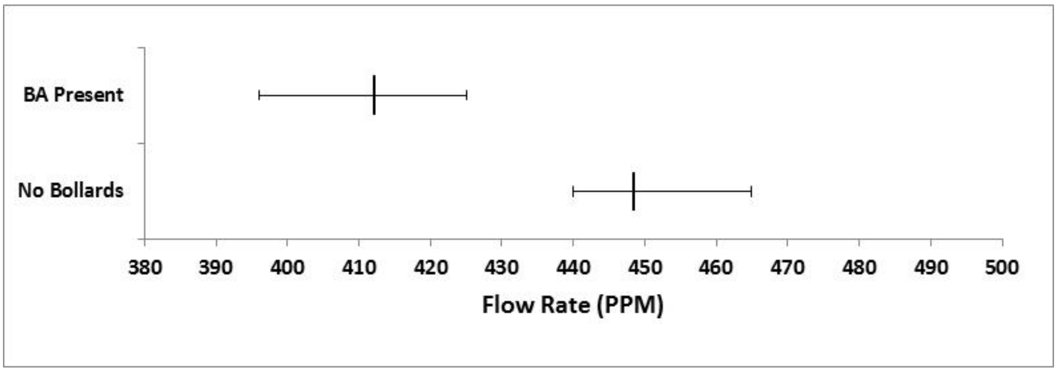


Figure 88: TS2 - Average and range of peak flow rates at the BA line for the BA and NoBA trials at 4p/m^2.

This demonstrates that the trials with BA present produced a lower average flow rate (412.0 ppm compared with 448.3 ppm) with a slightly wider range of flow rates produced (396.0-425.0 ppm compared with 440.0-465.0 ppm) than the case with no bollard array present. Furthermore, the difference in the average flow rates is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate.

While the BA case produced a flow rate which was 8.1% less than the equivalent case without the BA, the flow rate achieved in the BA case was greater than expected given the reduction in available width associated with positioning of the BA. The presence of the BA across the pedestrian movement path resulted in a 20% reduction in the available exit width; i.e. a 3.6m width with the BA compared with a 4.5m without the BA. As a result, we would expect the flow rate to be 20% lower with the BA present. However, it is measured to be only 8% lower – a much smaller reduction than expected. This difference can be explained by considering the unit flow rate for the exit path.

Using the available free exit width, the average unit flow rate for the exit path with NoBA is 1.66 p/m/sec while for the exit path with the BA the unit flow is 1.91 p/m/sec. Therefore, with the BA present the unit flow rate is 15.1% higher than without the BA present (see Table 83). The improvement in unit flow rate is likely due to the reduction of conflicts between pedestrians at the BA line resulting from the presence of the BA. The bollards act as a barrier, preventing lateral conflicts from occurring between pedestrians at the BA line. This effect leads to a more ordered flow through the BA line which, in turn, produces a higher than expected flow rate. Thus, the 20% reduction in flow rate produced by the reduction in effective width of the exit path due to the presence of the BA is partially compensated by the 15.1% improvement in unit flow rate achieved by the ordered flow generated by the presence of the BA.

Table 83: Flow and Unit flow at the BA line for the NoBA and BA trials at peak flow for $4p/m^2$.

Scenario	Flow (ppm)	Unit Flow (p/m/min)	Unit Flow (p/m/sec)
No Bollards (4_NoBA)	448.3 [440.0 – 465.0]	99.62 [97. 8 – 103.3]	1.66 [1.63 – 1.72]
Bollard Array (4_BA)	412.0 [396.0 – 425.0]	114.44 [110.0 – 118.1]	1.91 [1.83 – 1.97]

As with the 0m bollard case (TS1), it must be noted that the improvement in unit flow rate was achieved with pedestrians without luggage. It is unclear if this mechanism will be as effective in situations involving passengers with luggage. In this case the BA may exert a greater negative impact on the BA flow rate. As this aspect was not tested in these trials it may warrant further analysis in future trials.

Key Findings - 4_BA_TS2: The presence of the BA produced a flow rate at the BA location that was on average 8.1% lower than the NoBA trials. This reduction in flow rate is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate. However, the reduction in flow rate due to the presence of the BA was not as great as would be expected due to the reduction in effective width of the path. The better than expected flow rate produced with the BA present is due to a 15% improvement in the unit flow rate for the exit path with the BA present. The reduction in flow rate due to the reduction in path width was partially compensated by the improvement in unit flow rate. It is unknown whether this improvement in unit flow rate will occur in situations with more passengers carrying luggage.

4.3.1.2 BOLLARD ARRAY DENSITY ANALYSIS

The population density was measured at the BA line during the TS2 trials where the initial population density was set to $4p/m^2$. The time interval for the $4p/m^2$ measurements was set to 3 seconds to ensure a sufficiently representative sample. These measurements were made across the entire width of the BA taking into account an area 1m before and 1m after the BA.

The manner in which the density at the BA line changed over time is shown in Figure 89 to Figure 91. From Figure 89 and Figure 90 it is clear that the three trials produced reasonably consistent results in both cases.

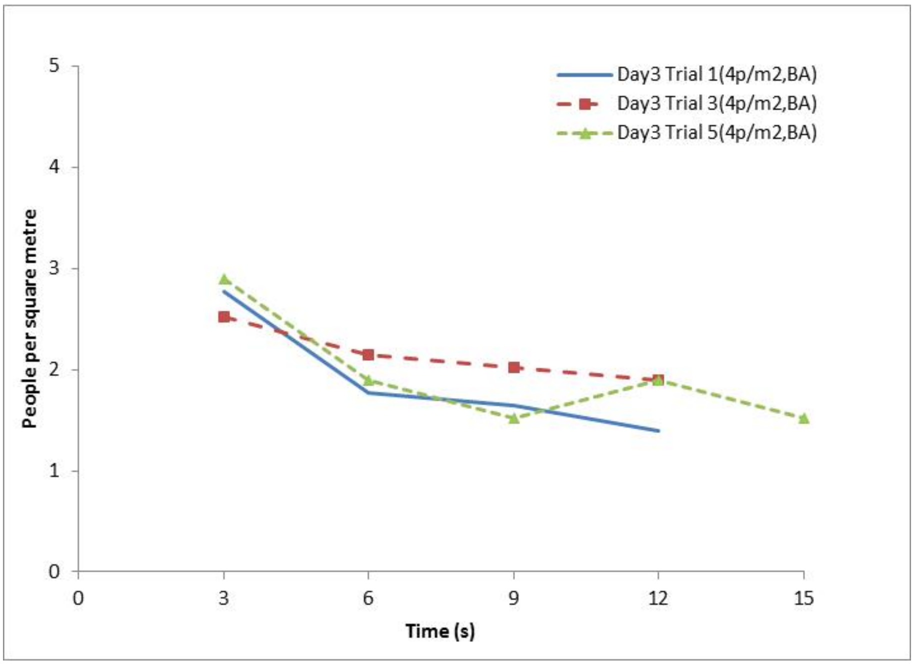


Figure 89: TS2 – Population density measured in 3 sec intervals at the BA line for the three BA, 4p/m^2 initial density trials

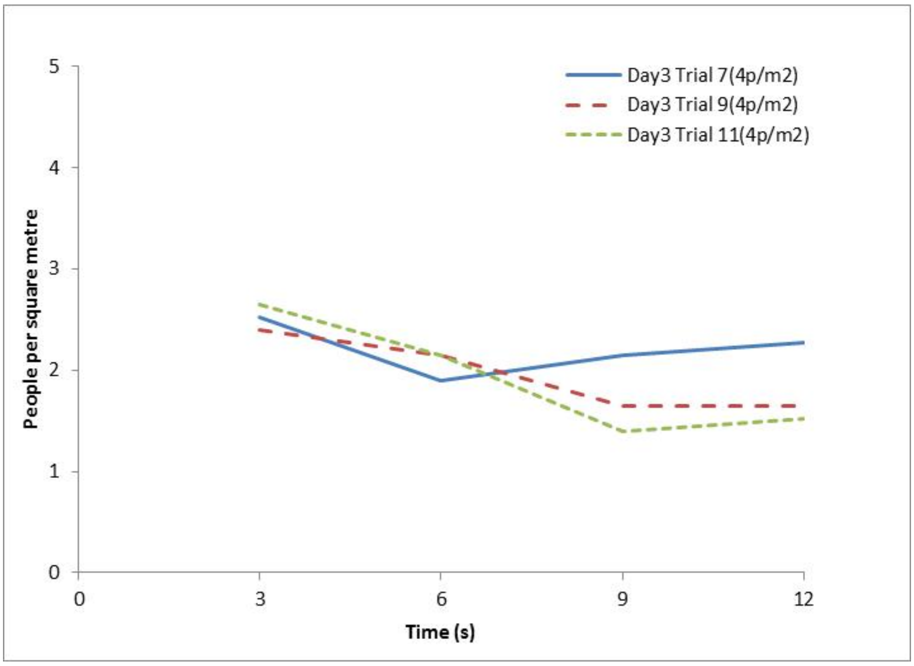


Figure 90: TS2 – Population density measured in 3 sec intervals at the BA line for the three NoBA, 4p/m^2 initial density trials.

The results from the three repeat trials were then averaged producing the average curves shown in Figure 91. It is apparent from Figure 91 that the average density across the BA line in both the BA and NoBA are similar.

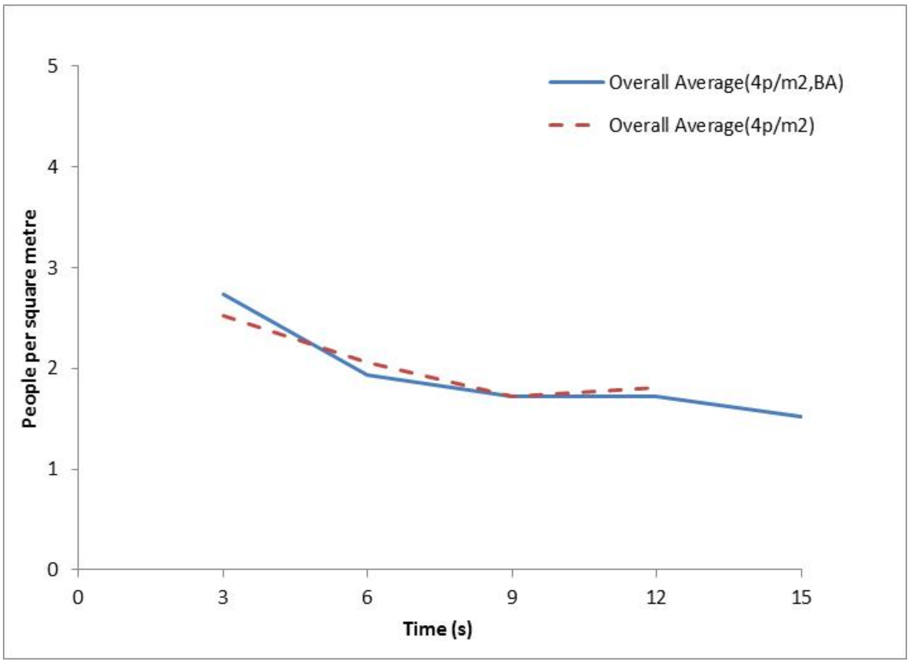


Figure 91: TS2 – Average population density in 3 sec intervals at the BA line for the NoBA and BA $4p/m^2$ initial density trials.

Presented in Table 84 and Table 85 are the detailed density measurements over each 3 second time interval from the start of the trial to near the end of the trial. In both cases the density drops off from the initial 4 p/m^2, with the highest densities being recorded at the start of the trial. The drop off in densities is to be expected as the front of the pedestrian queue can rapidly move away from the BA line into unencumbered space. This result is considered representative of what may happen in a real situation where the crowd can rapidly disperse after they cross the BA line.

Table 84: TS2 – Population density in 3 sec intervals at the BA line for the NoBA $4p/m^2$ trials.

4_NoBA_TS2	**Time (sec)**				**Average (p/m^2)**
	3	**6**	**9**	**12**	
Trial 7 (p/m^2)	2.49	1.87	2.12	2.24	2.18
Trial 9 (p/m^2)	2.36	2.12	1.62	1.62	1.93
Trial 11 (p/m^2)	2.61	2.12	1.37	1.49	1.90
Average (p/m^2)	2.49	2.03	1.70	1.78	**2.00**

Table 85: TS2 – Population density in 3 sec intervals at the BA line for the BA $4p/m^2$ trials.

4_BA_TS2	**Time (sec)**					**Average (p/m^2)**
	3	**6**	**9**	**12**	**15**	
Trial 1 (p/m^2)	2.78	1.77	1.64	1.39	--	1.89
Trial 3 (p/m^2)	2.53	2.15	2.02	1.89	--	2.15

Trial 5 (p/m^2)	2.91	1.89	1.52	1.89	1.52	1.95
Average (p/m^2)	2.74	1.94	1.73	1.73	1.52	**2.00**

Key Findings - 4_BA_TS2: In both the BA and NoBA trials, the average density at the BA line was approximately half the initial packing density; i.e. 2.0 p/m^2 rather than the 4.0 p/m^2.

4.3.1.3 ENDLINE FLOW

Presented in Table 86 are the average peak flow rates at the Endline during the 4p/m^2 trials, a distance of 3.76 m beyond the BA line (see also Figure 92). The location of the Endline is shown in Figure 92. The results in Table 86 show that the BA trials produced flow rates that were on average 7.5% lower than the equivalent NoBA trials. This is comparable to the 8.1% drop off evident at the BA line (see Table 81). The NoBA trials produced an average flow rate of 470.7 ppm (with a standard deviation of 10.07 and a range of -2.3% to +2.0%) while the BA trials produced an average flow rate of 435.6 ppm (with a standard deviation of 25.10 and a range of -6.6% to +3.8%).

Table 86: TS2 – Endline flow for trials at $4p/m^2$.

Scenario	Flow (ppm)
4_NoBA_TS2	470.7 [460.0 – 480.0]
4_BA_TS2	435.6 [406.7 – 452.0]

Presented in Figure 93 are the average flow rate curves at the Endline for the BA and NoBA trials. Although the lines closely parallel each other as time progresses, the BA flow rate is consistently below that of the NoBA trials indicating that the impact of the BA was still felt after the pedestrians had passed through the BA.

Comparing the flow rate values at the BA line (see Table 81) with the flow rate values at the Endline (see Table 86) we note that the flow rate has increased by 5.0% in the case of the NoBA and 5.7% in the case of the BA by the time it has reached the Endline. This is consistent with the greater diffusion of pedestrians as they pass the Endline. As the density decreases, the population is more able to move at their personal desired speed and hence the flow rate increases.

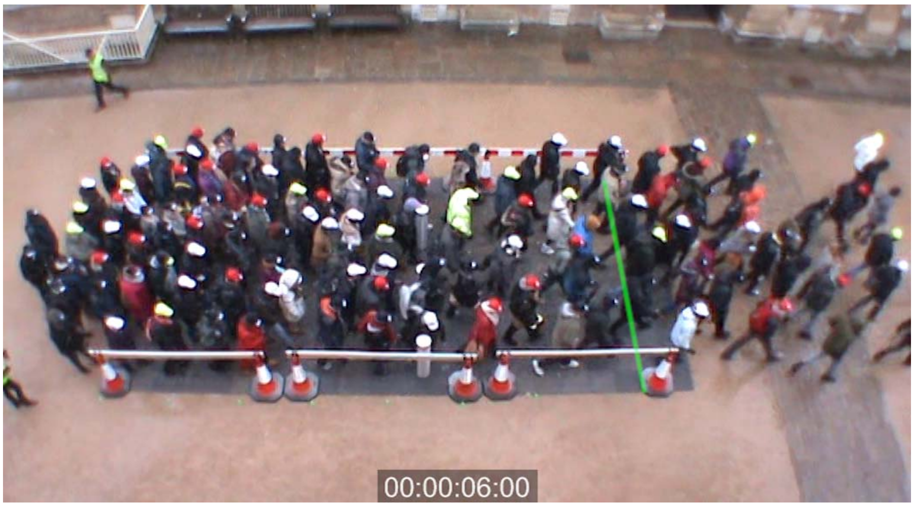


Figure 92: TS2 – Location of Endline in TS2 trials.

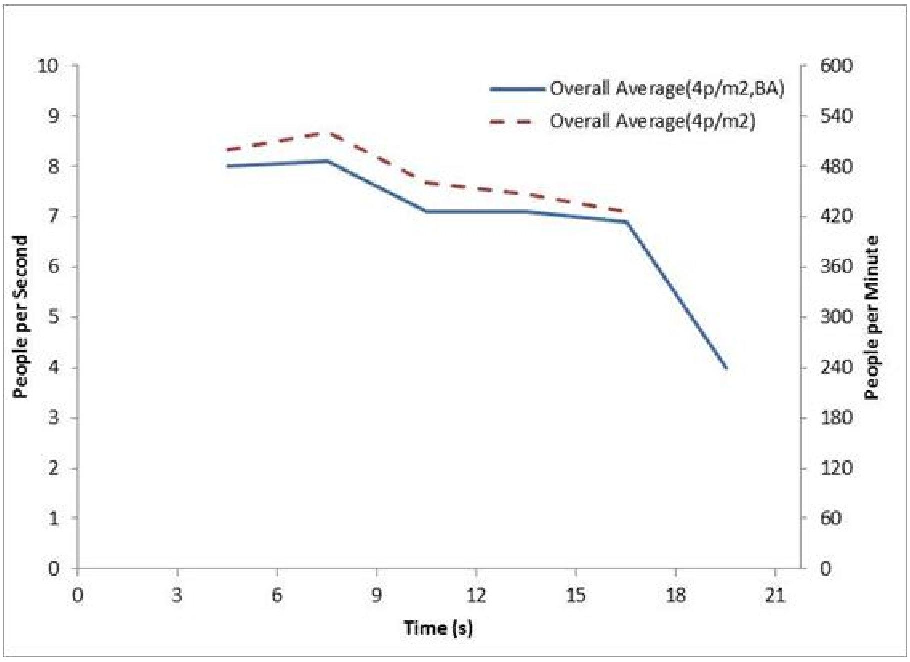


Figure 93: TS2 - Average peak flow rate at the Endline for NoBA and BA 4 p/m2 trials.

Key Findings - 4_BA_TS2: The BA trials produced Endline flow rates that were 7.5% lower than the equivalent NoBA flow rates. These are comparable with the differences evident at the BA line. The flow rate at the Endline is greater than that at the BA as the population is able to more easily travel at their desired speed due to greater diffusion of the population (leading to a reduction in density) once the BA has been passed.

4.3.1.4 ENDLINE DENSITY ANALYSIS

The population density was measured at the Endline during the TS2 trials where the population density was initially set to $4p/m^2$. The time interval for the density measurements in the $4p/m^2$ trials was 3 seconds. These measurements were made across the entire width of the space taking into account the area 1m before and 1m after the Endline. The manner in which the average density over each of the three trials for the NoBA and BA trials at the Endline changed over time is shown in Figure 94. It is apparent from Figure 94 that the average density across the Endline in both the BA and NoBA are similar, but that the trial with the BA present produced slightly lower densities than in the case without the BA.

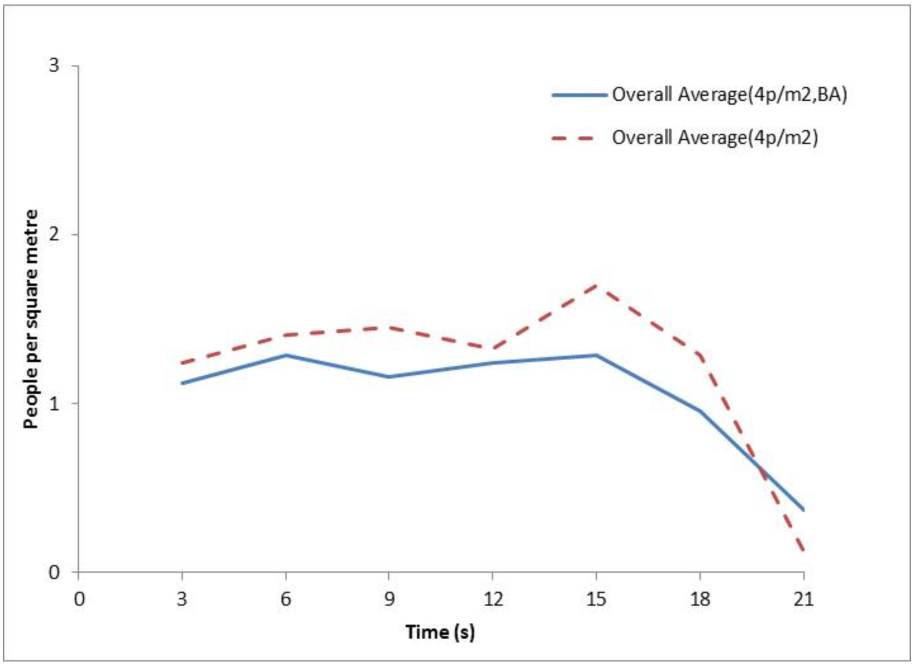


Figure 94: TS2 – Average population density in 3 sec intervals at the Endline for the NoBA and BA 4p/m^2 initial density trials.

Presented in Table 87 and Table 88 are the detailed density measurements recorded over each 3 second time interval from the start of the trial to near the end of the trial. In both cases the density sharply drops of from the initial 4 p/m^2. Unlike the density measured at the BA line, the densities at the Endline are more uniform and do not show a continuous downward trend. As stated earlier (see Section 4.3.1.2), the drop-off in densities is to be expected as the front of the pedestrian queue can rapidly move away from the BA line into unencumbered space.

Table 87: TS2: 4p/m^2 initial density, densities recorded over time at Endline, NoBA present

4_NoBA_TS2	**Time (sec)**					**Average (p/m^2)**
	6	**9**	**12**	**15**	**18**	
Trial 7 (p/m^2)	1.49	1.24	1.49	1.99	1.24	1.49
Trial 9 (p/m^2)	1.37	1.74	1.24	1.62	1.37	1.47
Trial 11 (p/m^2)	1.37	1.37	1.24	1.49	1.24	1.34
Average (p/m^2)	1.41	1.45	1.33	1.70	1.29	**1.44**

At the BA line, the density, for both the BA and NoBA cases was approximately 2.0 p/m^2, while at the Endline the density is 1.44 p/m^2 for the NoBA case and 1.19 p/m^2 for the BA case. As this measurement location is further away from the BA line, the crowd has further dispersed and so the density is lower than that at the BA line (compare Table 84 and Table 85 with Table 87 and Table 88). The density at the Endline in the BA case is also lower than the density in the NoBA case. This is a result of the flow rate at the BA line in the BA case being constrained by the presence of the BA and so fewer people can cross the BA line in a given period of time, resulting in the lower densities.

Table 88: TS2: 4p/m^2 initial density, densities recorded over time at Endline, BA present

4_BA_TS2	Time (sec)					Average (p/m^2)
	6	9	12	15	18	
Trial 1 (p/m^2)	1.37	1.12	1.37	1.12	--	**1.24**
Trial 3 (p/m^2)	1.37	1.24	1.37	1.24	0.62	**1.17**
Trial 5 (p/m^2)	1.12	1.12	1.00	1.49	1.00	**1.14**
Average (p/m^2)	1.29	1.16	1.24	1.29	0.81	**1.19**

Key Findings - 4_BA_TS2: In the BA and NoBA trials, the average density at the Endline was 1.19 p/m^2 and 1.44 p/m^2, a significant reduction from the initial 4.0 p/m^2. This result is consistent with expectation, where pedestrians are assumed to have more opportunity to disperse after crossing the BA line during actual egress from a station. The density at the Endline for the BA case was less than that for the NoBA case due to the reduction in flow rate at the BA line.

4.3.1.5 CROSS-WALK TRIALS

In this section the results for 4.0 p/m^2 crosswalk (CW) trials are presented. However, before these are discussed, a brief description of the underlying trial conditions is presented. This is necessary given that a key experimental factor present during the CW trials is a moving sub-population whose performance fluctuates during the trials. These trials involved both the BA and NoBA configuration. The same parameters as for the other TS2 experiments were measured; i.e. the flow rate at the BA and the flow rate at the Endline, just before the line of cross walkers. It must be emphasised that while the two lines of cross walkers attempted to maintain their initial line density of 1.11 p/m this was not always possible due to the disruption caused by the flow of people across their path. The initial set up is depicted in Figure 21. It was only possible to manage this density at the start of the trial as the interaction between the two flows disrupted the CW flow. As with the other TS2 results, the flow rates presented for the cross-walk trials represent peak flow rates. Unlike the other TS2 trials, only two trials were run for each condition.

For the CW trials observations were also made regarding the performance of the cross-walking group (as opposed to the participant population) in order to determine how consistent each of the CW trials were. The average line density achieved across all trials was estimated to be between 0.67 p/m and 0.88 p/m (down from 1.11 p/m). The lowest line density was 0.67 p/m for line 1 and 0 p/m for line 2 (where line 1 refers to the section of cross walkers closest to the arriving perpendicular flow). The average flow rate of CW in the BA trials was 40.9 ppm for line 1 and 44.6 ppm for line 2. The average flow rate of CW in the No BA trials was 44.6 ppm for line 1 and 48.2 ppm for line 2.

4.3.1.5.1 CONDITIONS AT THE BOLLARD ARRAY LINE

Presented in Table 89 are the flow rates produced at the BA line for the NoBA and BA trials with an initial density of 4p/m^2 during the CW trials. The results in Table 89 show that the trials with the BA present produced flow rates that were on average 15.9% lower than the equivalent NoBA trials. The NoBA trials produced an average flow rate of 387.5 ppm (with a standard deviation of 3.54 and a range of -0.6% to +0.6%) while the trials with BA present produced an average flow rate of 326.0 ppm (with a standard deviation of 3.14 and a range of -3.1% to +3.1%).

Table 89: TS2 – BA flows for the cross-walk trials at 4p/m^2.

Scenario	Flow (ppm)
4_NoBA_TS2_CW (2 trials)	387.5 [385.0 – 390.0]
4_BA_TS2_CW (2 trials)	326.0 [316.0 – 336.0]

The manner in which the average flow rate at the BA line changed over time is shown in Figure 95. It is apparent from Figure 95 that the flow rate with BA and cross-walkers is lower than that for the case without a BA but with cross-walkers for most of the duration of the trial.

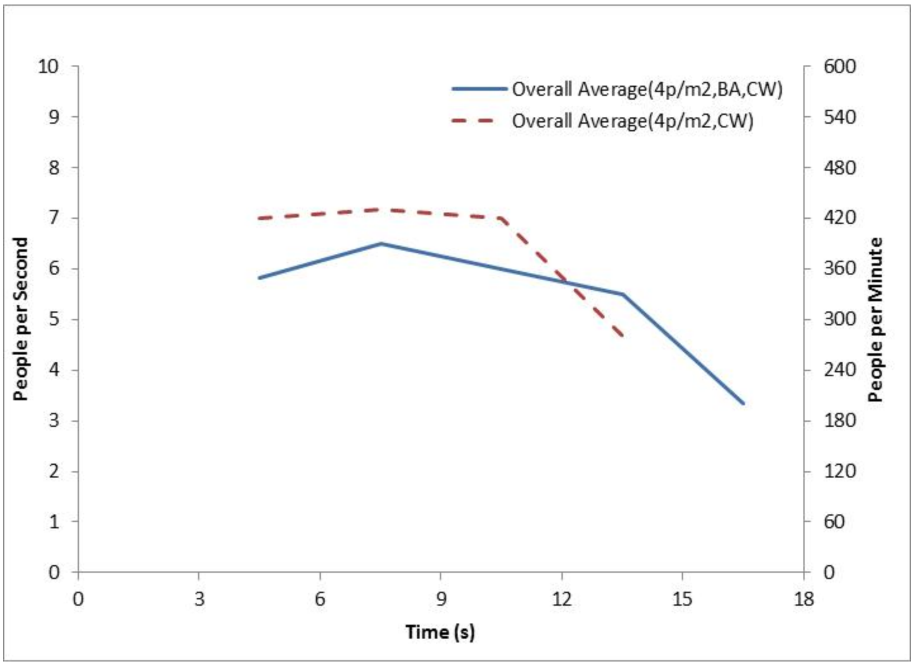


Figure 95: TS2 - Average peak flow rate at the BA line for NoBA and BA 4 p/m2 cross-walk trials

This comparison can be extended by examining Figure 96, where the CW trials are compared with those trials where no CW were present. It is apparent that where cross-walkers were present (i.e. during the CW trials), lower flow rates were typically produced – especially where both the BA and the cross-walkers were present.

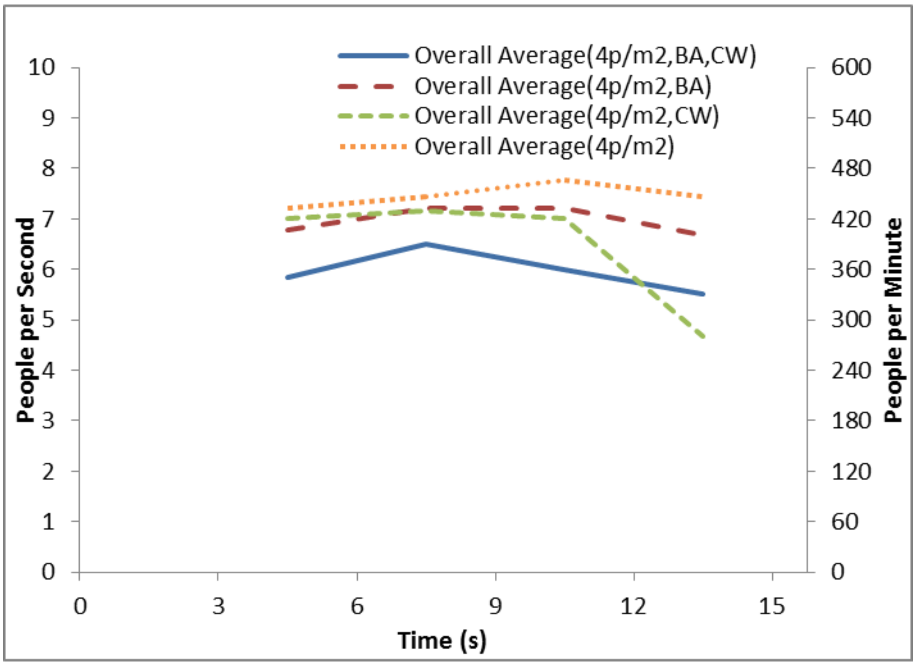


Figure 96: TS2 - Average peak flow rate at the BA line for the trials where the impact of the BA and Cross-Walkers were examined at an initial population density of 4 p/m^2.

The average flow rates with cross-walkers can be compared with the average flow rates produced without the cross-walkers present (see Table 90 which is derived from Table 81 and Table 89). It is apparent that the flow rates produced with the cross-walkers present are considerably lower than those produced without the cross-walkers. For the NoBA case, the flow rate at the BA line with cross-walkers is 60.8 ppm or 13.6% smaller than the corresponding case without cross-walkers, while the BA case is 86.0 ppm or 20.9% smaller than the corresponding case without cross-walkers. Clearly the cross-walkers had an additional negative effect on the flow rate at the BA line. Furthermore, the impact of the cross-walkers has a greater effect than the impact of the BA on the flow rate at the BA line. The presence of the BA alone reduced the flow rate at the BA line by 8.1% (see Table 90); however, the presence of the cross-walkers alone reduced the flow rate at the BA line by 13.6% (see Table 90). Furthermore, the combined impact of the cross-walkers and BA reduced the flow rate at the BA by 122.3 ppm or 27.3%. This is borne out in the curves produced in Figure 96.

Table 90: Comparison of average flow rates at the BA line for trials with and without BA and CW - 4p/m^2.

Scenario	NO CW (ppm)	CW (ppm)
NoBA (ppm)	448.3 (3 trials)	387.5 (2 trials)
BA (ppm)	412.0 (3 trials)	326.0 (2 trials)

Presented in Table 91 and Table 92 are the detailed density measurements at the BA line over each 3 second time interval from the start to near the end of the trial. In both cases the density drops off from the initial 4 p/m^2. However, we note that the densities in the NoBA case have increased as compared to the case without cross-walkers (see Table 84): the average density increasing from 2.00 p/m^2 without cross-walkers and NoBA (see Table 84) to

2.3 p/m^2 with cross-walkers (see Table 91). With BA present, the density at the BA has remained at approximately 2.0 p/m^2 (see Table 85 and Table 92).

Table 91: TS2 – Population density measured in 3 sec intervals at the BA line for the NoBA, cross-walk 4 p/m^2 trials.

4_NoBA_TS2_CW	**Time (sec)**					**Average (p/m^2)**
	3	**6**	**9**	**12**	**15**	
Trial B3 (p/m^2)	2.86	2.24	1.99	2.49	2.12	2.34
Trial B4 (p/m^2)	2.49	2.24	1.99	2.36	2.24	2.26
Average (p/m^2)	2.68	2.24	1.99	2.43	2.18	**2.30**

Table 92: TS2 – Population density measured in 3 sec intervals at the BA line for the BA, cross-walk 4 p/m^2 trials.

4_BA_ TS2_CW	**Time (sec)**						**Average (p/m^2)**
	3	**6**	**9**	**12**	**15**	**18**	
Trial B1 (p/m^2)	2.91	1.89	1.52	2.27	1.89	1.39	1.98
Trial B2 (p/m^2)	3.16	1.89	1.89	1.39	2.15	0.76	1.87
Average (p/m^2)	3.03	1.89	1.71	1.83	2.02	1.07	**1.93**

Key Findings - 4_BA_TS2_CW: The presence of the cross-flow had a greater impact on the flow rate at the BA line than the presence of the BA itself. A number of comparisons can be made with the previous results collected to demonstrate the impact of the crosswalk flow. Compared to a flow without a BA or cross-walking flow:

- The introduction of the BA reduces the flow rate at the BA line by **8%**
- The introduction of the cross-walkers reduces the flow rate at the BA line by **14%**
- The introduction of the BA /cross-walkers reduces the flow rate at the BA line by **27%**

Thus the cross-walkers have almost twice the impact of the BA on flow rate at the BA line and the combined impact of the BA and cross-walkers has more than three times the impact of the BA on the BA flow rate.

Compared to the flow with BA present:

- The introduction of the cross-walkers reduces the flow rate at the BA line by **21%**

This can then be compared to the flow when the cross-walkers are present:

- The introduction of the BA reduced the flow rate at the BA line by **16%**

This can be compared to the flow produced with a BA present:

- A flow with cross-walkers reduces the flow rate at the BA line by **6%.**

4.3.1.5.2 CONDITIONS AT THE ENDLINE

Presented in Table 93 are the average peak flow rates at the Endline of the trial geometry, a distance of 3.76 m beyond the BA line and just before the cross-flow.

Table 93: TS2 – Endline flow for cross-walk trials at 4p/m^2.

Scenario	Flow (ppm)
4_NoBA_TS2_CW (2 run)	246.4 [237.8 – 255.0]
4_BA_TS2_CW (2 run)	245.1 [237.8 – 252.5]

The results in Table 93 show that the BA trials produced flow rates that were on average 1.3 ppm or 0.5% lower than the equivalent NoBA case. The NoBA trials produced an average flow rate of 246.4ppm (with a standard deviation of 12.18 and a range of -3.5% to +3.5%) while the BA trials produced an average flow rate of 245.1ppm (with a standard deviation of 10.14 and a range of -3.0% to +3.0%). Unlike the trials without cross-walkers (see Table 86), it appears that the presence of the BA has little effect on the flow rates at the Endline.

The manner in which the average flow rate at the Endline changed over time is shown in Figure 97. It is apparent from Figure 97 that the flow rate at the Endline with BA and cross-walkers is equivalent to that without the BA. It is also apparent that the flow rate steadily decreased during the trial.

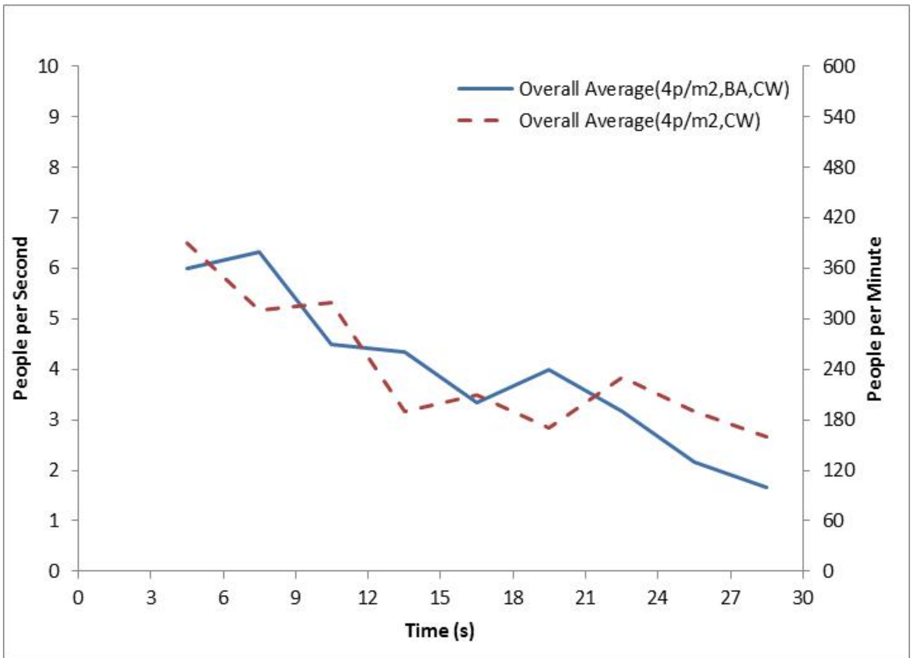


Figure 97: TS2 - Average peak flow rate at the Endline for NoBA and BA 4 p/m^2 cross-walk trials

This was due to the impediment caused by the cross-walkers preventing the participant population from freely exiting from the trial geometry. This also led to a steady increase in density at the Endline as shown in Table 95 and Table 96. This comparison can be extended by examining Figure 98, where the CW trials are compared with the NoCW trials. It is apparent that where cross-walkers were present (i.e. during the CW trials), then lower flow rates were always produced. However, when CW were present, there appears little difference in the flow rates produced in the BA and NoBA trials. As mentioned above, in all cases there was a downward trend in the flow rates produced.

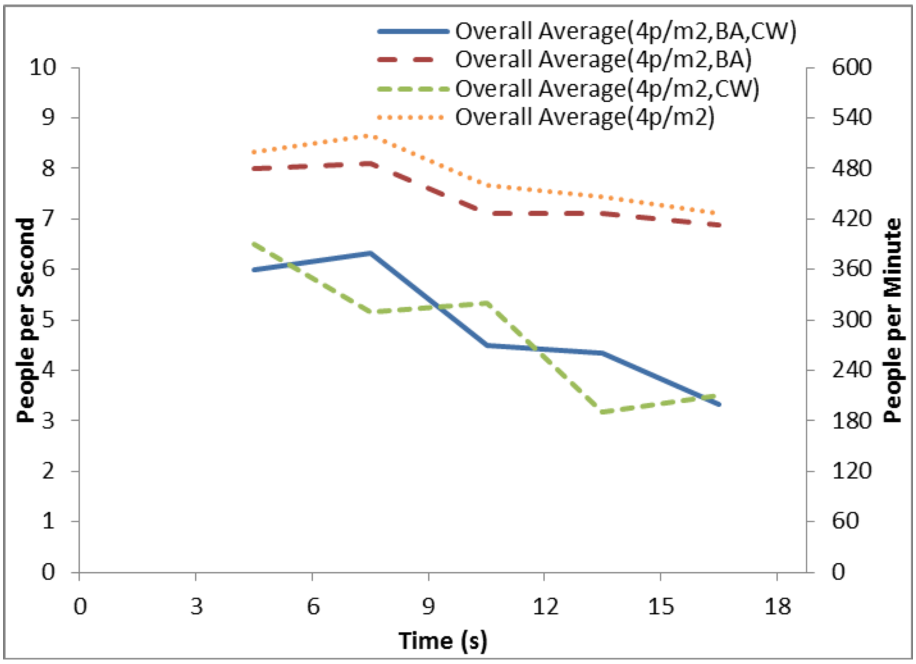


Figure 98: TS2 - Average peak flow rate at the Endline for the trials where the impact of the BA and CW fators were examined at an initial population density of 4 p/m^2.

The average flow rates at the Endline with cross-walkers can be compared with the average flow rates produced without the cross-walk present (see Table 94 which is derived from Table 86 and Table 93). It is apparent that the flow rates produced with the cross walkers present are considerably lower than those produced without the cross-walkers. For the NoBA case, the flow rate at the Endline with cross-walkers is 224.3 ppm or 47.7% smaller than the corresponding case without cross-walkers. The BA case is 190.5 ppm or 43.7% smaller than the corresponding case without cross-walkers. Clearly the cross-walkers had an additional negative effect on the flow rate at the Endline which was considerably more influential than that of the BA. The presence of the BA alone reduced the flow rate at the Endline by 7.4% (see Table 86 or Table 94); however, the presence of the cross-walkers alone reduced the flow rate at the Endline by 47.7% (see Table 94). Furthermore, the combined impact of the cross-walkers and BA reduced the flow rate at the BA by 225.6 ppm or 47.9%.

Table 94: Comparison of average flow rates at the EndLine for trials with and without BA and CW - 4p/m^2.

Scenario	NO CW (ppm)	CW (ppm)
NoBA (ppm)	470.7 (3 trials)	246.4 (2 trials)
BA (ppm)	435.6 (3 trials)	245.1 (2 trials)

Presented in Table 95 and Table 96 are the detailed density measurements at the Endline in 3 second time intervals from the start of the trial to near the end of the NoBA and BA trials respectively. In both cases the density is less than the initial 4 p/m^2. However, as already noted, the densities do not steadily fall. The flow rates increase due to the blocking effect of the cross-walkers. The density in NoBA case is 15.9% higher than that of the BA case, which is comparable to the difference in the case without cross-walkers (which was 17.4%). As in the case without cross-walkers this difference is due to the BA restricting the flow of pedestrians at the BA line and so there are fewer pedestrians at any given time at the Endline in the BA case. It is also apparent that in both the NoBA and BA cases that the densities with cross-walkers are higher than those without the cross-walkers (see Table 87 and Table 88). When cross-walkers are present, the NoBA case density is 74.3% higher and the BA case is 77.3% higher than the equivalent cases when the cross-walkers were absent. The higher density in the cross-walker cases is due to the blocking effect produced by the cross-walkers.

Table 95: Densities measured at the Endline during NoBA trials.

4_NoBA_TS2_CW	**Time (sec)**									**Average (p/m^2)**
	6	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	
Trial B3 (p/m^2)	2.24	2.24	2.49	2.61	3.24	3.11	2.99	1.74	--	2.58
Trial B4 (p/m^2)	2.12	2.36	2.86	3.11	2.86	2.61	2.61	2.12	1.24	2.43
Average (p/m^2)	2.18	2.30	2.68	2.86	3.05	2.86	2.80	1.93	1.24	**2.51**

Table 96: Densities measured at the Endline during BA trials.

4_BA_TS2_CW	**Time (sec)**									**Average (p/m^2)**
	6	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	
Trial B1 (p/m^2)	1.62	1.87	2.49	1.99	2.61	2.74	2.36	1.74	1.00	2.05
Trial B2 (p/m^2)	1.99	2.24	2.49	1.99	2.61	2.61	1.99	1.49	--	2.18
Average (p/m^2)	1.80	2.05	2.49	1.99	2.61	2.68	2.18	1.62	1.00	**2.11**

In evacuation situations from stations with a high throughput located on busy streets, it is possible that quite high cross-flows may exist which could have a significant impact on the evacuation flow. The cross-flow could be made up from pedestrians using the street or the flow from station being evacuated. In the trials the cross flow was imposed on the path flow at a stand-off of several metres. It is not clear how the stand-off distance may impact the flow rate at the BA line and the Endline. Furthermore, within the trials, the cross-flow consisted of a single, relatively high pedestrian line-density. It is thus not clear how the pedestrian line density in the cross-flow, may impact the path flow. It is likely that there is a critical line density below which the interference produced by the cross-flow is negligible. As these aspects were not was not tested in these trials they may warrant further analysis in future trials.

Key Findings - 4_BA_TS2_CW: The presence of the cross-flow had a significantly greater impact on the flow rate at the end line then the impact of the BA. A number of comparisons can be made with the previous results collected to demonstrate the impact of the crosswalk flow at the Endline. Compared to the Endline flow without a BA or cross-walking flow:

- The introduction of the BA reduces the flow rate at the end line by **7%**
- The introduction of the cross-walkers reduces the flow rate at the end line by **48%**

- The introduction of the BA/cross-walkers reduces the flow rate at the end line by **48%**

Thus the cross-walkers have almost seven times the impact of the BA on flow rate at the end line and the combined impact of the BA and cross-walkers is the same as the cross-walkers alone.

Compared to the flow at the Endline when the BA was present

- The introduction of the cross-walkers reduces the flow rate at the end line by **44%**

Compared to the flow at the Endline when the cross-walkers are present:

- The introduction of the BA reduced the flow rate at the end line by **1%**

Compared to a flow at the Endline when the BA is present:

- A flow with cross-walkers reduces the flow rate at the end line by **43%**

4.3.2 SUMMARY

A summary of the key results for the TS2 4p/m^2 trials are presented in Table 97. In the two basic trial conditions (4_NoBA_TS2 and 4_BA_TS2), there are numerical differences throughout, with the average peak exit flow rates produced affected by the presence of the BA and the location of the measurement taken: the flow rate at the BA line and the Endline was 8% lower when the BA was present than when it was absent; the flow rates at the Endline were greater than at the BA line with and without the BA. However, the reduction in the flow rate generated during the BA trials is not as pronounced as expected given the reduced width available with the presence of the BA. This is due to the BA producing an increase in the unit flow rate at the bollard array line. In the trials with the BA present, the unit flow rate at the BA line was some 15% higher than the case without the BA. It is unknown whether this improvement in unit flow rate will occur in situations with more passengers carrying luggage. As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

In the two crosswalk trial conditions (4_NoBA_TS2_CW and 4_BA_TS2_CW), a more complex relationship is apparent. Throughout, appreciably lower flow rates were produced compared to those cases where there were no cross-walkers: the presence of the cross-walkers reduces the flow rate achieved by up to 48% at the Endline and up to 21% at the BA line. The flow rates produced at the Endline during the CW trials were broadly comparable (246.4 and 245.1 ppm) and well below the values generated at the equivalent BA flow values (387.5 and 326.0 ppm). This is likely due to the dominant impact of the CW disrupting the flow significantly irrespective of whether the BA was in place or not.

Table 97: Summary average peak flow rates produced during the TS2 4p/m^2 trials.

	BA line with NoBA (ppm)	BA Line with BA (ppm)	% Difference	At Endline with NoBA (ppm)	At Endline with BA (ppm)	% Difference
Without Cross-walkers	448.3	412.0	8	470.7	435.6	8
With Cross-Walkers	387.5	326.0	16	246.4	245.1	1
% Difference	14	21	-	48	44	-

During the 4p/m^2 trials, the presence of the cross-walkers had a negative impact on the main trial flow, both at the BA line and at Endline. **The impact of the cross-walkers was more severe than the impact of the BA alone.** At the BA line, the BA and cross-walkers interacted to produce even more severe flow reductions, while at the Endline, the combined impact of the BA and the cross-walkers together broadly matched the effect of the cross-walkers on its own. It is apparent that the cross-walkers strongly influenced the results produced and that the positioning of BA should be mindful of the cross flows present.

The impact of the cross-walker flow on BA and Endline flow rate is likely to be affected by cross-walker stand-off distance and line density. As these parameters were not examined in these trials they may warrant further analysis in future trials.

4.3.3 POPULATION DENSITY: 3 p/m^2

In this section the results for 3_BA_TS2 trials are discussed and compared with the 3_NoBA_TS2 trials. The flow rates described in this section are peak flows flows during the steady-state period. This excludes the start-up period of the flow, where travel speeds, and hence flows, are low due to the crowd just starting to move and the slow-down period of the flow, where the flow is low due to the density dropping off at the very end. Presented in Figure 99 is a typical set of flow curves showing the start-up, peak flow and slow-down periods. In these trials, the peak period typically runs from 3 sec to 11 sec and the flow rate was measured in intervals of 2 seconds.

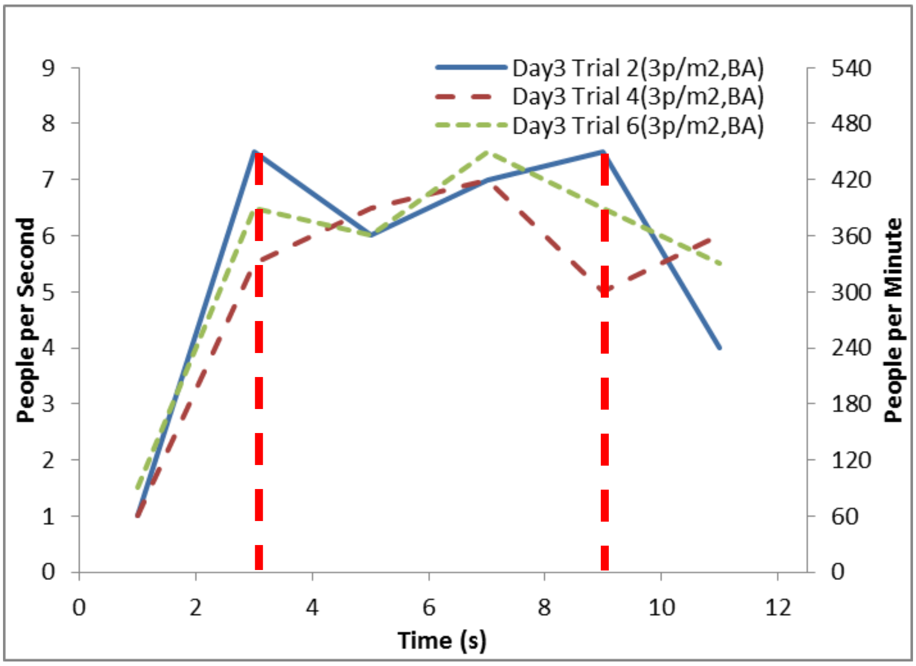


Figure 99: Example curve for entire duration of trial demonstrating the three phases of the flow identified.

4.3.3.1 BOLLARD ARRAY FLOW

Presented in Table 98 are the flow rates produced at the BA line for the NoBA and BA trials with an initial density of 3p/m^2. The results in Table 98 show that the BA trials produced flow rates that were on average 60.0 ppm or 13.3% lower than the equivalent NoBA trials. These are broadly comparable with the results produced during the 4p/m^2 trials (13.3% as opposed to 8.1%). The NoBA trials produced an average flow rate of 452.5 ppm (with a standard deviation of 11.46 and a range of -2.2% to +2.8%) while the BA trials produced an average flow rate of 392.5 ppm (with a standard deviation of 30.31 and a range of -8.3% to +7.0%).

Table 98: TS2 - BA flow for trials at 3p/m^2.

Scenario	Flow (ppm)
3_NoBA_TS2	452.5 [442.5 – 465.0]
3_BA_TS2	392.5 [360.0 – 420.0]

The manner in which the flow rates changed over time is shown in Figure 100 to Figure 102. From Figure 100 and Figure 101 it is clear that the three trials produced reasonably consistent results. The results from the three repeat trials were then averaged producing the average peak curves shown in Figure 102. It is apparent from Figure 102 that the curves are similar in nature, the BA curve is consistently below the NoBA curve, indicating that the flow rates produced were lower throughout the peak period.

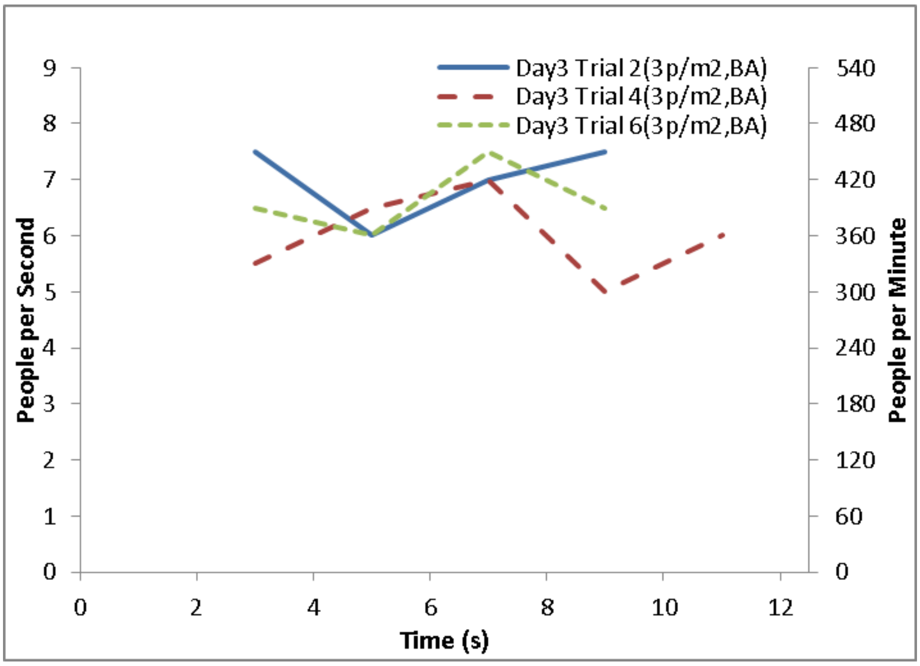


Figure 100: TS2 – Peak flow rate measured in 2 sec intervals at the BA line for the three BA, 3 p/m^2 trials.

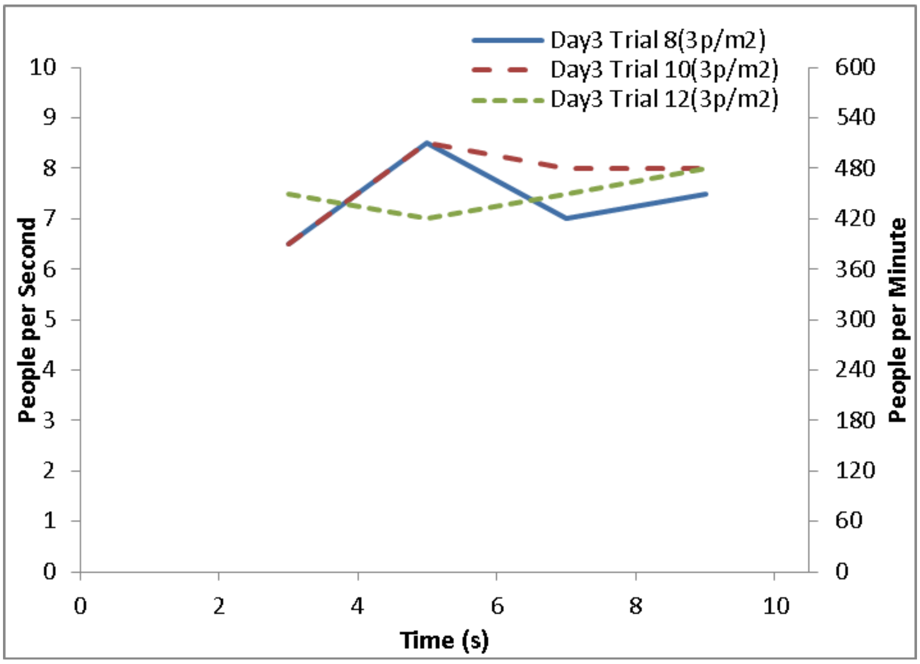


Figure 101: TS2 – Peak flow rate measured in 2 sec intervals at the BA line for the three NoBA, 3 p/m^2 trials.

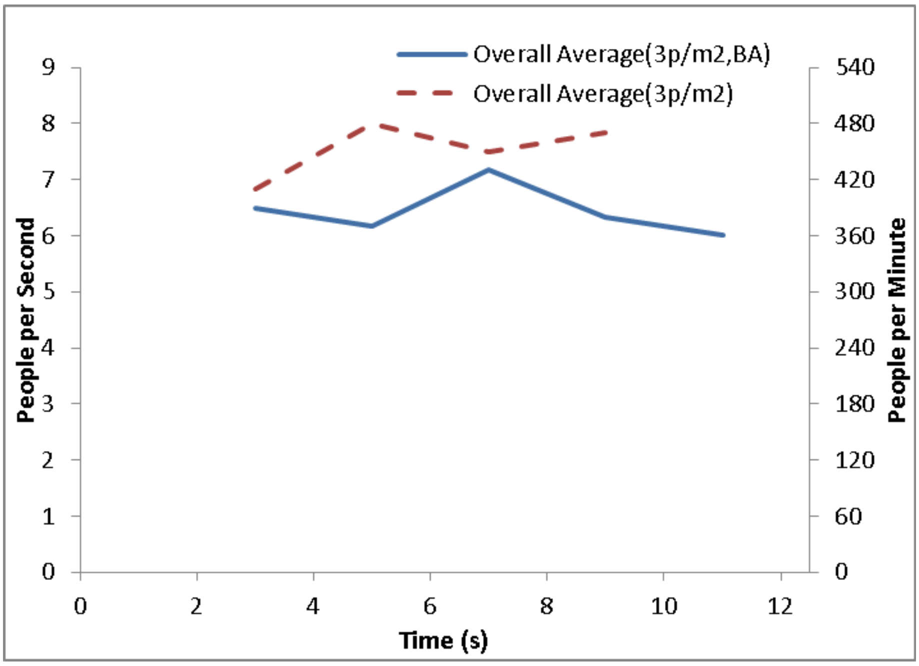


Figure 102: TS2 - Average peak flow rate at the BA line for NoBA and BA 3 p/m^2 trials.

From Table 99 it can be seen that in 0% of the comparisons, BA trials produced higher flow rates; in 100% of the comparisons they produced lower flow rates and in 0% of the comparisons they produced equal flow rates.

Table 99: TS2: Ranking of trials.

Scenario	Higher than 3_NoBA_TS2 Trials	Lower than 3_NoBA_TS2Trials	Equal to 3_NoBA_TS2Trials
3_BA_TS2 Trial 1	0	3	0
3_BA_TS2Trial 2	0	3	0
3_BA_TS2Trial 3	0	3	0
Total	0	9	0

Presented in Figure 103 are the average and range of the peak flow rates at the BA line produced during the NoBA and BA trials with an initial density of 3p/m^2. This demonstrates that the trials with the BA present produced a lower average flow rate (392.5 ppm compared with 452.5 ppm) with a wider range of flow rates produced (360.0-420.0 ppm compared with 442.5.0-465.0 ppm) than the case with no bollard array present. Furthermore, the difference in the average flow rates is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate.

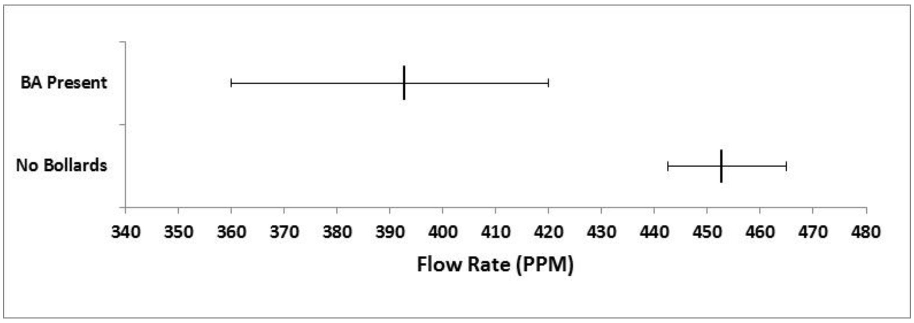


Figure 103: TS2 - Average and range of peak flow rates at the BA line for the BA and NoBA trials at $3p/m^2$.

While the BA case produced a flow rate which was 13.3% lower than the NoBA case, the flow rate achieved in the BA case was greater than expected given the reduction in available width associated with positioning of the BA. As with the 4.0 p/m^2 case, the presence of the BA across the pedestrian movement path results in a 20% reduction in the available exit width. As a result, we would expect the flow rate to be 20% lower with the BA present. However, it is measured to be only 13.3% lower – greater than expected. This difference can be explained by considering the unit flow rate for the exit path.

Using the available free exit width, the average unit flow rate for the exit path without BA is 1.68 p/m/sec while that for the exit path with the BA is 1.82 p/m/sec. Therefore, we note that with the BA present the unit flow rate for the exit is 8.4% higher than without the BA present (see Table 100). As before, it is suggested that the improvement in unit flow rate is due to the reduction of conflicts between pedestrians at the BA line resulting from the presence of the BA. The bollards act as a barrier, preventing left-right conflicts from occurring between pedestrians at the BA line. This reduction in conflicts results in a more ordered flow through the BA line that in turn produces a higher than expected flow rate. Thus, the 20% reduction in flow rate produced by the reduction in effective width of the exit path due to the presence of the BA is partially compensated by the 8.4% improvement in unit flow rate achieved by the ordered flow generated by the presence of the BA. It is noted that the improvement in unit flow rate for the 3.0 p/m^2 initial density crowd (i.e. 8.4%), is less than the 15.1% improvement in the unit flow rate achieved in the equivalent 4.0 p/m^2 trial (see Section 4.3.1.1). The difference is likely due to individuals within the higher density crowd experiencing a greater number of conflicts (due to the closer proximity of the individuals in the crowd) and hence the shielding effect offered by the barrier has a proportionally greater impact.

As with the 0m bollard case (TS1) and the $4p/m^2$ TS2 trial, it must be noted that the improvement in unit flow rate was achieved with pedestrians with little or no luggage. It is unclear if this mechanism will be as effective in situations involving passengers carrying significantly more luggage or larger luggage as may be found in a busy station. In this case the BA may exert a greater negative impact on the BA flow rate. As this aspect was not tested in these trials it may warrant further analysis in future trials.

Table 100: Flow and Unit flow at the BA line for the NoBA and BA trials at peak flow for $3p/m^2$.

Scenario	Flow (ppm)	Unit Flow (p/m/min)	Unit Flow (p/m/sec)
No Bollards (3_NoBA)	452.5 [442.5 – 465.0]	100.56 [98.3 – 103.3]	1.68 [1.64 – 1.72]
Bollard Array (3_BA)	392.5 [360.0 – 420.0]	109.03 [100.0 – 116.7]	1.82 [1.67 – 1.94]

Key Findings - 3_BA_TS2: For the 3.0 p/m^2 initial crowd density, the presence of the BA produced a flow rate at the BA location that was on average 13.3% lower than the NoBA trials. This reduction in flow rate is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate. However, the reduction in flow rate due to the presence of the BA was not as great as would be expected due to the reduction in effective width of the exit path. The better than expected flow rate with the BA present is due to an 8.4% improvement in the unit flow rate for the exit path with the BA present. The reduction in flow rate due to the reduction in exit path width was partially compensated by the improvement in unit flow rate. The improvement in unit flow rate offered by the BA is greater the higher the density of the crowd. However, the improvement in unit flow rate may not occur in situations with more passengers carrying luggage.

4.3.3.2 DENSITY ANALYSIS

The population density was measured at the BA line during the TS2 trials where the initial population density was initially set to $3p/m^2$. The time interval between density measurements for the $3p/m^2$ trials was **two seconds** to ensure a representative sample of densities. (Elsewhere time periods of three and five seconds were used given the longer trial times.) These measurements were made across the entire width of the BA taking into account the area 1m before and 1m after the BA.

The three trials in each case produced reasonably consistent results. The results from the three repeat trials were then averaged producing the average curves shown in Figure 104. It is apparent from Figure 104 that the average density across the BA line in both the BA and NoBA are similar, but that the trial with the BA present produced slightly lower densities than in the case with the no bollards.

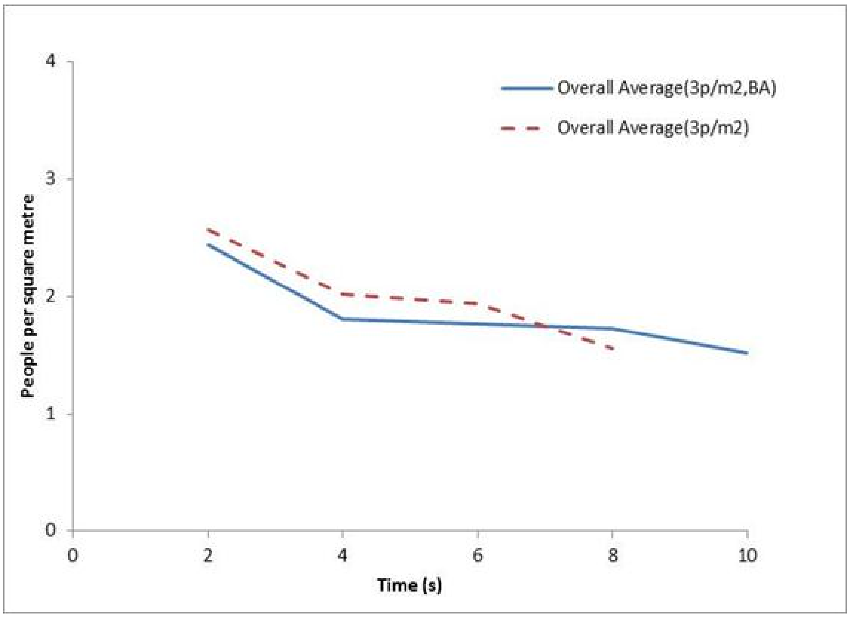


Figure 104: TS2 – Average population density in 2 sec intervals at the BA line for the NoBA and BA 3p/m^2 initial density trials.

Presented in Table 101 and Table 102 are the detailed density measurements at 2 second time intervals from the start of the trial to near the end of the trial. In both cases the density drops of from the initial 3 p/m^2, with the highest densities being recorded at the start of the trial, although the drop is less pronounced than in the 4 p/m^2 trials.

Table 101: TS2: 3p/m^2 initial density, densities recorded over time at BA line, NoBA present

3_NoBA_TS2	**Time (sec)**				**Average (p/m^2)**
	2	**4**	**6**	**8**	
Trial 8 (p/m^2)	2.40	2.02	2.15	1.52	2.02
Trial 10 (p/m^2)	2.65	2.02	1.52	1.64	1.96
Trial 12 (p/m^2)	2.65	2.02	2.15	1.52	2.08
Average (p/m^2)	2.57	2.02	1.94	1.56	**2.02**

The drop off in densities is to be expected as the front of the pedestrian queue can rapidly move away from the BA line into unencumbered space. This result is consistent with what may happen in actual situations on site where it is reasonable to assume that pedestrians are free to disperse after crossing the BA line.

Table 102: TS2: 3p/m^2 initial density, densities recorded over time at BA line, BA present

3_BA_TS2	Time (sec)					Average (p/m^2)
	2	4	6	8	10	
Trial 2 (p/m^2)	2.53	2.02	1.77	1.64	1.39	1.87
Trial 4 (p/m^2)	2.40	1.89	1.64	1.77	1.64	1.87
Trial 6 (p/m^2)	2.40	1.52	1.89	1.77	1.52	1.82
Average (p/m^2)	2.44	1.81	1.77	1.73	1.52	**1.85**

Key Findings - 3_BA_TS2: In both the BA and NoBA trials, the average density at the BA line was approximately a third less than the initial packing density (i.e. approximately 2.0 p/m^2 rather than the 3.0 p/m^2), although the fall in densities is not as pronounced as in the 4.0 p/m^2 case. This result is consistent with what may happen in actual situations on site where it is reasonable to assume that pedestrians are free to disperse after crossing the BA line.

4.3.3.3 ENDLINE FLOW

Presented in Table 103 are the average peak flow rates at the Endline (or exit point of the trial geometry), a distance of 3.76 m beyond the BA line for the NoBA and BA trials with an initial density of $3p/m^2$. The results in Table 103 show that the BA trials produced flow rates that were on average 44.7 ppm or 9.3% lower than the equivalent NoBA trials. This is comparable to the equivalent conditions produced during the $4p/m^2$ trials (4_BA_TS2) where the reduction was 7.5%. This is also comparable to the 13.3% drop off evident at the BA line (see Table 98).

Table 103: Endline Flow for at $3p/m^2$.

Scenario	Flow (ppm) at BA
3_NoBA_TS2	482.5 [472.5 – 495.0]
3_BA_TS2	437.8 [396.0 – 487.5]

The NoBA trials produced an average flow rate of 482.5ppm (with a standard deviation of 11.46 and a range of -2.1% to +2.6%) while the BA trials produced an average flow rate of 437.8ppm (with a standard deviation of 46.25 and a range of -9.5% to +11.4%).

Presented in Figure 105 are the average flow rate curves at the Endline for the BA and NoBA trials. Although the curves are similar to each other as time progresses, the BA flow rate is typically below that of the NoBA trials indicating that the impact of the BA was still felt after the pedestrians had passed through the BA.

Comparing the flow rate values at the BA line (see Table 98) with the flow rate values at the Endline (see Table 103) we note, as with the 4 p/m^2 case, that the flow rate has increased at the Endline. In the case of the NoBA the flow rate has increased by 6.6% and for the BA case by 11.5%. This is consistent with the greater diffusion of pedestrians as they pass the BA line. As the density decreases, the population is more able to move at their personal desired speed and hence the flow rate increases.

Comparing the NoBA cases with 3p/m^2 and 4p/m^2 initial population densities, the flow rate at the BA line was slightly greater for the 3p/m^2 case. Here, the lower initial density was compensated for by greater travel speed producing a higher flow rate. During the BA trials, the higher density 4p/m^2 case results in greater percentage increase in UFR and in greater UFR, resulting in greater flow rate. Table 104 shows a summary of these results. The flow rates produced at the BA during the 3p/m^2 trials was lower than the comparable 4p/m^2 condition (392.5 and 412.0 respectively). The reverse is true with the NoBA trials. The relationship between the density and achieved flow rate then changes between the trial conditions. At the Endline, the 3p/m^2 cases produce higher rates during both the BA and NoBA trials.

Table 104: TS2: 4p/m^2 and 3p/m^2 initial density results

Condition	3.0 p/m^2	4.0 p/m^2	% Difference
NoBA at BA line (ppm)	452.5	448.3	-1.0%
BA at BA line (ppm)	392.5 (-13%)	412.0 (-8%)	+15.3%
BA at BA line (p/m/sec)	1.82 (8%)	1.91 (15%)	+5.0%
NoBA at Endline (ppm)	482.5	470.7	-2.5%
BA at Endline (ppm)	437.8 (-9%)	435.6 (-8%)	-0.5%

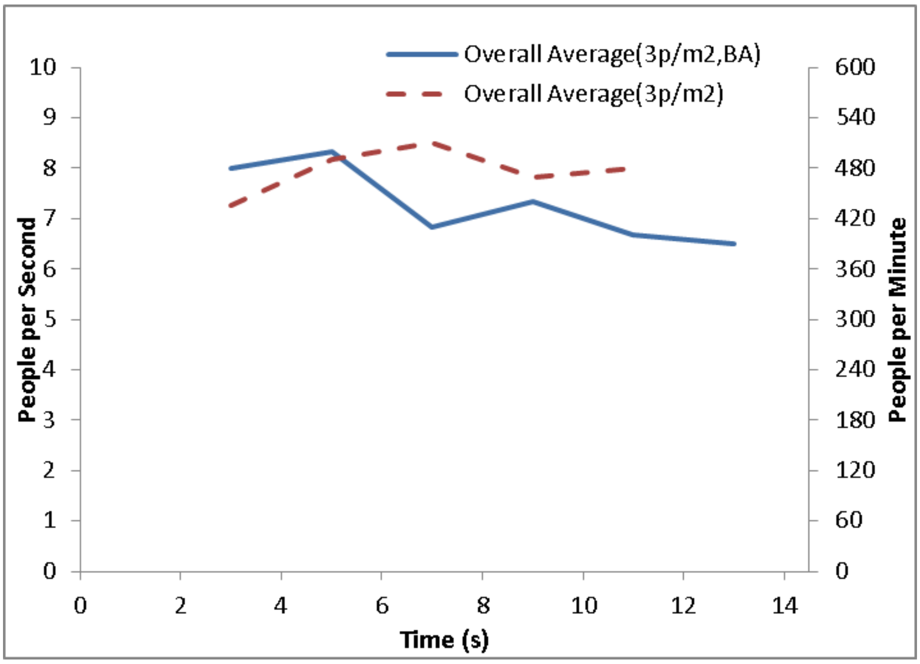


Figure 105: TS2 - Average peak flow rate at the Endline for NoBA and BA 3 p/m2 trials

Key Findings - 3_BA_TS2: The BA trials produced Endline flow rates (downstream of the BA) that were 9.3% lower than the equivalent NoBA flow rates. These are comparable with the differences evident at the BA line. The flow rate at the Endline is greater than that at the BA as the population is able to more easily travel at their desired speed due to greater diffusion of the population (leading to a reduction in density) once the BA has been passed.

4.3.3.4 ENDLINE DENSITY ANALYSIS

The population density was measured at the Endline during the TS2 trials where the population density was initially set to 3p/m^2. The time interval between density measurements in these trials was two seconds, in order to ensure a representative sample of results. These measurements were made across the entire width of the space taking into account the area 1m before and 1m after the Endline.

The manner in which the average density over each of the three trials for the NoBA and BA trials at the Endline changed over time is shown in Figure 106. It is apparent from Figure 106 that the average density across the Endline in both the BA and NoBA are similar, but that the BA trial typically produced slightly lower densities than in the NoBA case.

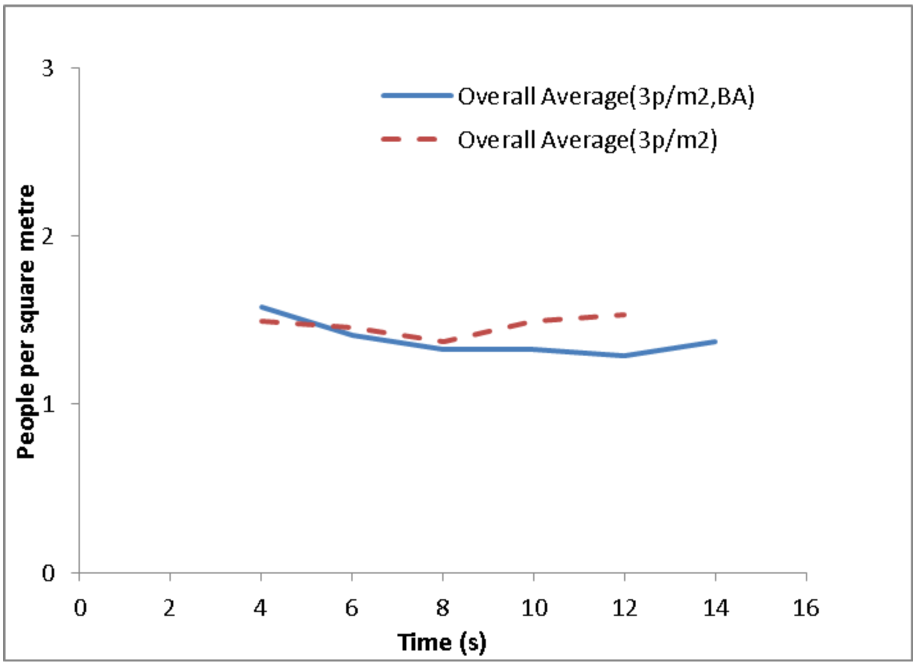


Figure 106: TS2 – Average population density in 2 sec intervals at the Endline for the NoBA and BA 3p/m2 initial density trials.

A more detailed analysis is possible from examining Table 105 and Table 106. It is apparent that the densities produced at the Endline during the BA trials were lower. In both cases, the conditions at the BA line dropped off quickly from the original 3p/m^2; however, this fall was more severe in the BA trials. The difference is broadly similar to that experienced at the BA line (see Table 101-Table 102), where the 3_NoBA_TS2 trials produced an average density of 2.02 p/m^2 and the 3_BA_TS2 produced an average density of 1.85p/m^2 at the BA line.

Presented in Table 105 and Table 106 are the detailed density measurements over each 2 second time interval from the start of the trial to near the end of the trial. In both cases the density drops of from the initial 3 p/m^2. Unlike the density measured at the BA line, the densities at the Endline are more uniform and do not show a continuous downward trend. As stated earlier (see Section 4.3.1.2) the drop-off in densities is to be expected as the front of the pedestrian queue can rapidly move away from the BA line into unencumbered space. At the BA line the density, for both the BA and NoBA cases, was approximately 2 p/m^2, while at the Endline the density is 1.47 p/m^2 for the NoBA case and 1.39 p/m^2 for the BA case. As this measuring location is further away from the BA line, the crowd has further dispersed and so the density is considerably lower than that at the BA line (compare Table 101 and Table 102 with Table 105 and Table 106). The density at the Endline in the BA case is also lower than the density in the NoBA case. This is a result of the flow rate at the BA line in the BA case being constrained by the presence of the BA and so fewer people can cross the BA line in a given period of time, resulting in the lower densities. These observations are consistent with those for the 4 p/m^2 case (see Section 4.3.1.4).

Table 105: TS2: 3p/m^2 initial density, densities recorded over time at Endline, NoBA present

3_NoBA_TS2	**Time (sec)**					**Average (p/m^2)**
	4	**6**	**8**	**10**	**12**	
Trial 8 (p/m^2)	1.37	1.37	1.37	1.49	1.49	1.42
Trial 10 (p/m^2)	1.62	1.24	1.49	1.37	1.49	1.44
Trial 12 (p/m^2)	1.49	1.74	1.24	1.62	1.62	1.54
Average (p/m^2)	1.49	1.45	1.37	1.49	1.53	**1.47**

Table 106: TS2: 3p/m^2 initial density, densities recorded over time at Endline, BA present

3_BA_TS2	**Time (sec)**						**Average (p/m^2)**
	4	**6**	**8**	**10**	**12**	**14**	
Trial 2 (p/m^2)	1.74	1.49	1.24	1.12	1.12		1.34
Trial 4 (p/m^2)	1.49	1.24	1.37	1.37	1.37	1.37	1.37
Trial 6 (p/m^2)	1.49	1.49	1.37	1.49	1.37		1.44
Average (p/m^2)	1.58	1.41	1.33	1.33	1.29	1.37	**1.39**

Key Findings - 3_BA_TS2: In the BA and NoBA trials, the average density at the Endline was 1.39 p/m^2 and 1.47 p/m^2, a significant reduction from the initial 3.0 p/m^2. This result is consistent with what may happen in actual situations on site where it is reasonable to assume that pedestrians are free to disperse after crossing the BA line. The density at the Endline for the BA case was less than that for the NoBA case due to the reduction in flow rate at the BA line. These results are consistent with those for the 4.0 p/m^2 initial density.

4.3.3.5 CROSS-WALK with 3.0 p/m^2 INITIAL DENSITY

In this section the results for 3.0 p/m^2 cross walk trials are presented. However, before these are discussed, a brief description of the underlying trial conditions is presented. This is necessary given that a key experimental factor present during the CW trials is a moving sub-population whose performance fluctuates during the trials.

These trials only involved the NoBA setup and only involved two repeat trials. The reason for only two repeat trials in this case is that these were additional unplanned trials that were included upon the conclusion of the planned TS2 trials since they were completed earlier than anticipated. The same parameters as for the TS2 experiments were measured, in particular the flow rate at the BA and the flow rate at the Endline (a distance of 3.76 m beyond the BA line just before the line of cross walkers). It must be emphasised that while the two lines of cross walkers attempted to maintain their initial line density of 1.11 p/m this was not always possible due to the disruption caused by the flow of people across their path. The initial set up is depicted in Figure 21. It was only possible to manage this density at the start of the trial as the interaction between the two flows disrupted the CW flow. As with the other TS2 results, the flow rates presented for the cross-walk trials represent peak flow rates.

For the cross walking trials some calculations were also made regarding the performance of the cross walking group in order to establish how consistent the trial conditions were. As far as possible it was attempted to maintain consistency between trials. However, the very nature of the trial meant that the interaction between the perpendicular flows affected performance.

The average line density achieved across all trials was estimated to be between 0.67 p/m and 0.88 p/m (down from 1.11 p/m). The lowest line density was 0.67 p/m for line 1 and 0 p/m for line 2 (where line 1 refers to the section of cross walkers closest to the arriving perpendicular flow). The average flow rate of CW in the No BA trials was 42.5 ppm for line 1 and 43.75 ppm for line 2.

4.3.3.5.1 BOLLARD ARRAY LINE

Presented in Table 107 are the flow rates produced at the BA line for the NoBA trials with an initial density of 3p/m^2. The results show that the trials with NoBA present produced an average peak flow rate of 405.0 ppm, which varied from a low of 382.5 ppm to a high of 427.5 ppm.

Table 107: Flow rates produced at the BA line during cross-walk trials at 3p/m^2.

Scenario	Flow (ppm) at BA
3_NoBA_TS2_CW (2 run)	405.0 [382.5 – 427.5]

The manner in which the average flow rate at the BA line changed over time is shown in Figure 107 for the following cases: with cross-walkers and NoBA; without cross-walkers and BA; and finally, without cross-walkers and NoBA. It is apparent from Figure 107 that the effect of the cross-walkers on the flow rate at the BA line was broadly equivalent to that of the BA.

The average flow rates at the BA line with cross-walkers can be compared with the average flow rates produced without the cross-walk present for the 3.0 p/m^2 and 4.0 p/m^2 initial densities (see Figure 86, Table 89, Table 98 and Table 107). A summary of the data is presented in Table 108.

For the 3.0 p/m^2 initial density, it is apparent that the average flow rate at the BA line produced with the cross-walkers present is comparable to that produced by the presence of the BA. For the NoBA case, the flow rate at the BA line with cross-walkers is 47.5 ppm or

10.5% smaller than the corresponding case without cross-walkers. The presence of the BA reduced the flow rate at the BA line by 60.0 ppm or 13.2%. Clearly the impact of cross-walkers and BA on the flow rate at the BA line is comparable. This is different to the observation for the 4.0 p/m^2 population, where the effect of the cross-walkers on the BA line flow rate was almost double that of the BA (see Table 108). From Table 108 we note that the BA had a greater impact on the low density population while the cross-walkers had a greater impact on the high density population.

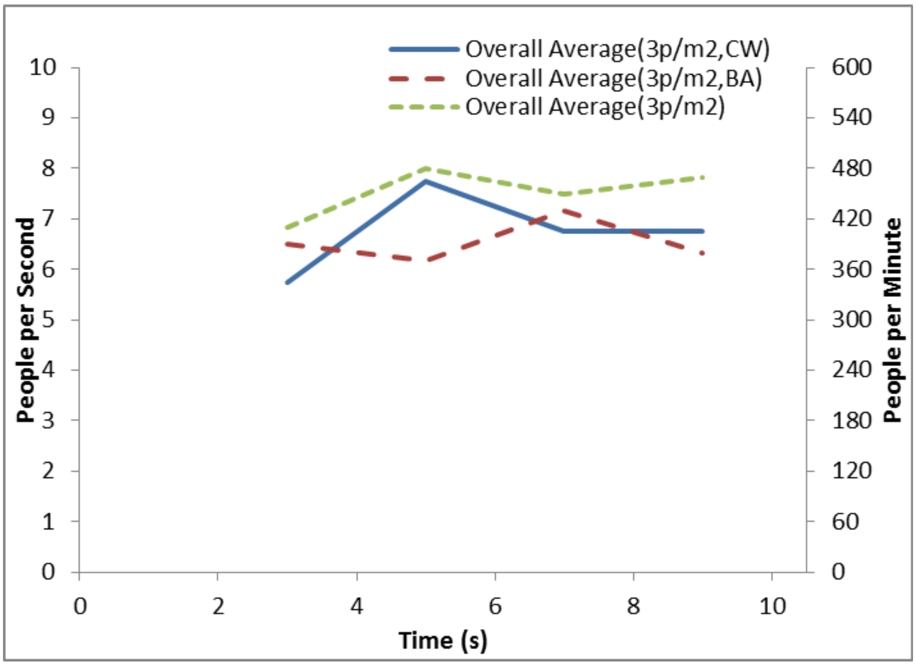


Figure 107: TS2 - Average peak flow rate at the BA line for NoBA cross-walk, the BA trials and the NoBA trials at an initial density of 3 p/m^2.

Table 108:Average flow rates at the BA line for the 3.0 p/m^2 and 4.0 p/m^2 initial populations

Condition	3.0 p/m^2	4.0 p/m^2	% Difference
NoBA (ppm)	452.5	448.3	-1.0%
BA (ppm)	392.5 (-13%)	412.0 (-8%)	+15.3%
Cross-Walkers and NoBA (ppm)	405.0 (-10%)	387.5 (-14%)	-4.4%
Cross-Walkers and BA (ppm)	--	326.0 (-21%)	--

Furthermore, the flow at the BA line with cross-walkers present and NoBA is 3.2% greater than the flow without cross-walkers with BA. This is opposite to the observation for the higher density population in which the introduction of the cross-walkers resulted in a flow at the BA line 21% smaller than the case with the BA present and no cross-walkers. This suggests that the 3p/m^2 density conditions provided sufficient space for participants to avoid the cross-walkers (given the cross-walker line density examined) and subsequently reduce the impact the cross-walkers have on the flow rates achieved. This is not the case for the 4p/m^2 density conditions where the cross-walkers had a larger impact on the flow rates produced, indicating that there was insufficient room for the participants to avoid the cross-walkers.

The densities produced at the bollard array line, for the NoBA trials, were calculated from the collected data in 2 second time intervals from the start of the trial to near the end of the trial. These are presented in Table 109. It is apparent that the densities are slightly lower than those present during the equivalent TS2 trials without the crosswalk population (see Table 101).

As can be seen, the density drops off sharply from the initial 3 p/m^2. We note that the average density at the BA line in the case with cross-walkers and NoBA (1.9 p/m^2, see Table 109), is less than that for the case without cross-walkers and NoBA (2.0 p/m^2, see Table 101).

Table 109: Densities measured at the bollard array location during NoBA cross-walk trials.

3_NoBA_TS2_CW	**Time (sec)**					**Average (p/m^2)**
	2	**4**	**6**	**8**	**10**	
Trial B5 (p/m^2)	2.49	1.87	1.74	1.74	1.74	1.92
Trial B6 (p/m^2)	2.24	2.24	1.49	1.49	1.74	1.84
Average (p/m^2)	2.36	2.05	1.62	1.62	1.74	1.88

It is apparent that the densities at the BA line are not as anticipated; i.e., it was expected that the presence of the cross-walkers would increase the densities at the BA line (see Table 101 and Table 102). However, the effect can be understood by examining Figure 108 and Figure 109. In Figure 108(a), the population has just started to move during the 3p/m^2 trials. At this stage people are crossing the BA line (just before the third set of cones from the left) and the Endline (just before the cone on the right). When all of the population has moved off, it is apparent that they are able to fit beyond the BA line at a higher population density (see Figure 108(b)). Visually, the new population density approximates 4p/m^2; in effect the initial smaller population is able to compress into the smaller space before the cross-walkers, moving from 3p/m^2 density spread over the original larger space to a 4p/m^2 density over a smaller space. Therefore, the congestion has no impact upon the densities present at the BA line given that the 3p/m^2 population can pack into a relatively small space. This then allows for the densities at the BA to rapidly tail off after a reservoir of people develops between the BA and the CW.

(a) (b)

Figure 108: Congestion produced during cross walk trials with 3p/m^2 as (a) population initiates movement, (b) congestion builds at cross-walker position.

(a) (b)

Figure 109: Congestion produced during cross walk trials with 4p/m^2 as (a) population initiates movement, (b) congestion builds at cross-walker position.

These conditions were not replicated during the 4p/m^2 trials (see Figure 109). Here, the initial conditions were similar (see Figure 109(a)); however, when all of the population have moved off the opportunity for the population to compress within the space between the BA and the CW is not available given the initial density of 4p/m^2. Therefore the flow rate through the BA does not tail off as dramatically as in the 3p/m^2 conditions (see Figure 109(b)). This will then affect the densities recorded.

Key Findings - 3_BA_TS2_CW: For the 3.0 p/m^2 population, the presence of the cross-flow had a smaller impact on the flow rate at the BA line then the impact of the BA. A number of comparisons can be made with the previous results collected to demonstrate the impact of the crosswalk flow. Compared to a flow without a BA or cross-walkers:

- The introduction of the BA reduces the flow rate at the BA line by **13%**
- The introduction of the cross-walkers reduces the flow rate at the BA line by **10%**

This is different to the 4.0 p/m^2 population, in which case the cross-walkers had a more pronounced effect than the BA on flow rates at the BA line.

Compared to the flow with BA present:

- The introduction of the cross-walkers increases the flow rate at the BA line by **3%.**

This result is again different to that observed in the 4.0 p/m^2 population, in which case the introduction of the cross-walkers decreased the flow rate at the BA by 21%. This is likely due to the population being able to compress into a smaller area, with the resultant population density approximating 4p/m2, leading to the tailing off of the flow at the BA.

4.3.3.5.2 ENDLINE

Presented in Table 110 are the average peak flow rates at the Endline of the trial geometry, a distance of 3.76m beyond the BA line and just before the cross-flow for the 3.0 p/m^2 population. The results in Table 110 show that the NoBA trials produced an average flow rate of 254.2 ppm, with a minimum of 253.3 ppm and a maximum of 255.0 ppm.

Table 110: Flow rates produced at the Endline during cross-walk trials at 3p/m^2.

Scenario	Flow (ppm) at Endline
3_NoBA_TS2_CW (2 run)	254.2 [253.3 – 255.0]

The manner in which the average flow rate at the BA line changed over time is shown in Figure 111 for the following cases; with cross-walkers and NoBA (also shown in Figure 110), without cross-walkers and BA, and finally, without cross-walkers and NoBA. It is apparent from Figure 111 that the effect of the cross-walkers on the flow rate at the BA line is more pronounced than the other conditions examined.

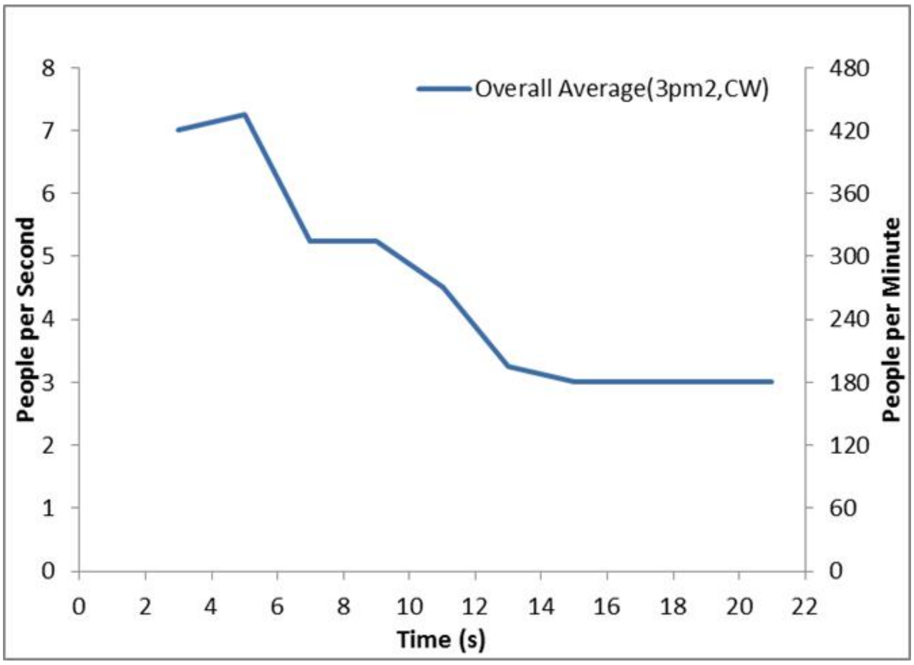


Figure 110: TS2 - Average peak flow rate at the Endline for NoBA cross-walk, at an initial density of 3 p/m^2.

The average flow rates at the Endline with cross-walkers can be compared with the average flow rates produced without the cross-walkers present for the 3.0 p/m^2 and 4.0 p/m^2 initial densities (see Table 86, Table 93, Table 103 and Table 110). A summary of the data is presented in Table 111.

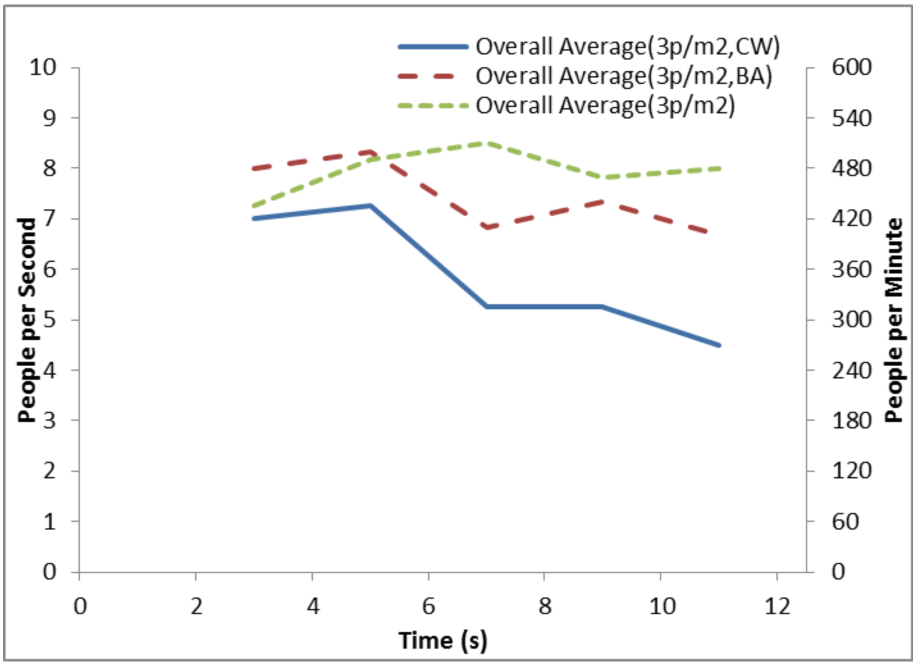


Figure 111: TS2 - Average peak flow rate at the Endline for NoBA cross-walk, the BA trials and the NoBA trials at an initial density of 3 p/m^2 .

For the 3.0 p/m^2 initial density, it is apparent that the average flow rate produced at the Endline with the cross-walkers present is considerably smaller than that produced by the presence of the BA. For the NoBA case, the flow rate at the Endline with cross-walkers is 254.2 ppm or 47% smaller than the corresponding case without cross-walkers. The presence of the BA reduced the flow rate at the Endline by 44.7 ppm or 9.3%. Clearly the impact of cross-walkers on the Endline flow rate is significantly greater than that of the BA. The impact of the cross-walkers and the BA on the end-line flow rate is identical for both the 3.0 p/m^2 and 4.0 p/m^2 populations. In both cases the impact of the cross-walkers on the Endline flow rate was almost seven times the impact of the BA (see Table 111).

Table 111: Average flow rates at the Endline for the 3.0 p/m^2 and 4.0 p/m^2 initial populations

Condition	3.0 p/m^2	4.0 p/m^2	% Difference
NoBA (ppm)	482.5	470.7	-2.5%
BA (ppm)	437.8 (-9%)	435.6 (-8%)	-0.5%
Cross-Walkers and NoBA (ppm)	254.2 (-47%)	246.4 (-48%)	-3.1%
Cross-Walkers and BA (ppm)	--	245.1 (-48%)	--

Presented in Table 112 are the detailed density measurements at the Endline determined every 2 seconds from the start of the trial to near the end of the trial. It is apparent that the densities are higher than those present during the equivalent TS2 trials without the crosswalk population (see Table 105). As can be seen, the densities at the Endline are larger than those at the BA line (see Table 109 and see Figure 108, Figure 109, and associated discussion) and following an initial drop are closer to the initial 3.0 p/m^2 than the corresponding densities at the BA line. The average density at the Endline is 2.1 p/m^2 compared with 1.9 p/m^2 (Table

109) at the BA line and 1.5 p/m^2 at the Endline without cross-walkers and NoBA (see Table 105). The higher density at the Endline in the cross-walker case is due to the blocking effect produced by the cross-walkers.

Table 112: Densities measured at the Endline during NoBA trials.

3_BA_TS2_CW	Time (sec)										Average (p/m^2)
	4	6	8	10	12	14	16	18	20	22	
Trial B5 (p/m^2)	1.74	2.49	2.49	2.36	2.49	2.49	2.86	2.49	1.74	1.12	2.23
Trial B6 (p/m^2)	1.49	2.24	2.36	2.49	2.24	2.86	2.24	1.99	1.24	0.62	1.98
Average (p/m^2)	1.62	2.36	2.43	2.43	2.36	2.68	2.55	2.24	1.49	0.87	2.10

Key Findings - 3_BA_TS2_CW: For the 3.0 p/m^2 population, the presence of the cross-flow had a more pronounced impact on the flow rate at the Endline then the impact of the BA. A number of comparisons can be made with the previous results to demonstrate the impact of the cross-walkers on the flow at the Endline.

Compared to the Endline flow without a BA or cross-walking flow:

- The introduction of the BA reduces the flow rate at the end line by **9%.**
- The introduction of the cross-walkers reduces the flow rate at the end line by **47%.**

Compared to the flow with BA present:

- The introduction of the cross-walkers decreases the flow rate at the Endline by **42%.**

This is likely due to the population being able to compress into a smaller area, with the resultant population density approximating 4p/m^2, leading to the tailing off of the flow at the BA.

These results are broadly similar to the effect that the cross-walkers had on the 4.0 p/m^2 population.

4.3.4 SUMMARY

A summary of the key results for the TS2 3p/m^2 trials are presented in Table 113. In the two basic trial conditions (3_NoBA_TS2 and 3_BA_TS2), there are numerical differences throughout, with the average peak exit flow rates produced affected by the presence of the BA and the location of the measurement: the flow rate at the BA line and the Endline was 13% and 9% lower respectively when the BA was present than when it was absent; the flow rates at the Endline were greater than at the BA line with and without the BA. However, the reduction in the flow rate generated during the BA trials is not as pronounced as expected given the reduced width available with the presence of the BA. This is due to the BA producing an increase in the unit flow rate at the bollard array line. In the trials with the BA present, the unit flow rate at the BA line was some 8% higher than the case without the BA. This improvement in unit flow rate may not occur in situations with passengers carrying luggage. As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

Table 113: Summary average peak flow rates produced during the TS2 3p/m^2 trials.

	BA line with NoBA (ppm)	BA Line with BA (ppm)	% Diff	At Endline with NoBA (ppm)	At Endline with BA (ppm)	% Diff
Without Cross-walkers	452.5	392.5	13	482.5	437.8	9
With Cross-Walkers	405.0	-	-	254.2	-	-
% Diff	10	-	-	47	-	-

In the crosswalk trial condition (3_NoBA_TS2_CW), significantly lower flow rates are produced than in the comparable case where there are no cross-walkers: the presence of the cross-walkers reduces the flow rate achieved by 47% at the Endline and 10% at the BA line.

Unlike the trials without cross-walkers, the flow rates produced at the BA with cross-walkers were numerically higher than at the Endline. As with the higher density flow, it is apparent that the cross-walkers strongly influenced the results produced and that the positioning of BA should be mindful of the cross flows present. The impact of the cross-walker flow on BA and Endline flow rate is likely to be affected by cross-walker stand-off distance and line density. As these parameters were not examined in these trials they may warrant further analysis in future trials.

5 DISCUSSION

The key findings from the analysis of the trial results were highlighted at the end of each results section and are collected together and presented in ANNEX J: KEY FINDINGS. These findings are now briefly discussed. The discussion will first focus on the TS1 trials, where on exiting the trial participants encountering a BA at various stand-off distances; and then the TS2 trials, where the participants were initially positioned around a BA at two initial population densities.

During this discussion the results are presented broadly in order of the influence that they exerted over other factors; e.g. that the participant use of the gaps in the BA will influence the densities produced, which in turn influences the flow rates achieved. Obviously, some of these issues influence each other and so the order is only a simple representation of this process.

Key findings are highlighted throughout in bold. Each finding is labelled ((1.1.0), (1.1.1), …(1.2.0), (1.2.1), etc.), making it easier to identify and cross-reference.

5.1 DISCUSSION: TS1

During the TS1 trials participants moved from a holding area adjacent to an exit and then moved out into the courtyard towards an objective immediately opposite the exit. During these trials a number of variables were examined: the presence of a BA, the BA stand-off of distance from the exit, the initial population density within the holding area.

A number of parameters were recorded and measured during these trials. The parameters reported here are:

- *Gap Use* – the routes adopted by the participants as they approached the BA line
- *Population Densities* at the BA line – the densities produced by the participants at the BA line given the routes adopted
- *Flow rates* produced at the Exit and the BA – these are the primary results and indicate the achieved flow rates at the two measurement locations

In addition, several parameters were derived from the observations collected:

- (Derived) *Unit Flow Rates* (UFR) produced at the exit – these flow rates were derived for the 0m BA and NoBA trials and compared against the flow produced at the exit
- (Derived) *Travel Speeds* – once the UFR had been derived then it was possible to make some simple comparisons between the speeds produced primarily to verify the credibility of the underlying conditions present during the trials

5.1.1 GAP USE: TS1

The manner in which the bollard array line was used during the trials has been established where possible. The proportion of participants selecting to use each of the five gaps in the full bollard array and the gap locations in the case of no bollard array has been established. The average percentages of the participant population using each of these gap locations are described in Table 114, while in Table 115 the average usage of the central gaps (gaps 2-4) are presented. From this data it is apparent that:

- **(1.1.0) Participants disproportionately used the central gaps, irrespective of initial population density or presence/absence of the array (e.g. an average of 91% used gaps 2-4 (see Table 115));**

- **(1.1.1) The use of the central gaps decreases as the stand-off distance increases, irrespective of initial population density or presence/absence of the array (e.g. an average of 96% used gaps 2-4 at 3m, while 87% used the gaps at 6m (see Table 115)).**

- **(1.1.2) With no BA present there is a slight tendency for greater use of the central gaps compared to the case with BA irrespective of initial density and stand-off distance (e.g. With BA an average of 89% used gaps 2-4, while with NoBA an average of 93% used gaps 2-4 (see Table 115))**

- **(1.1.3a) With the BA present there is a slight tendency for greater use of the central gaps as the population density increases irrespective of stand-off distance (e.g. at 3p/m^2 an average of 88% used gaps 2-4, while at 4p/m^2 an average of 90% used gaps 2-4 (see Table 115)).**

- **(1.1.3b) With no BA present there is a slight tendency for less use of the central gaps as the population density increases irrespective of stand-off distance (e.g. at 3p/m^2 an average of 94% used gaps 2-4, while at 4p/m^2 an average of 93% used gaps 2-4 (see Table 115)).**

Note: If there was equal usage of the gaps, gaps 2-4 would have on average 60% of the population using these gaps.

It is postulated that as the stand-off distance is reduced and/or the population density increases, so the participant has fewer opportunities to use the more peripheral gaps and so use the more central gaps. Furthermore, it is suggested that the BA behaves like a divergent lens, encouraging pedestrians to modify their paths and diverge slightly from the central paths.

It should be noted that 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. In this case, the width of the exit was 2.4m and at a distance of 3m from the exit, 93% of the population had spread out to occupy 3.6m of the BA with only 7% of the population spread out further; by 6m from the exit 86% of the population had spread out to occupy 3.6m of the BA with 14% of the population spread further out. So for initial exit flow densities of up to 4p/m^2, the flow width has expanded by 50% at 3m from the exit.

Thus for high density flows, for a given width of exit and stand-off distance the expanse of BA utilised by the exiting population will be some multiple of the exit width. Furthermore, for a given width of exit, the extent of the BA utilised by the flow will decrease with decreasing stand-off distance (down to a distance of 3m from the exit which was the smallest stand-off distance considered in these trials). These results suggest that for a given exit flow population density there is a relationship between the exit width, stand-off distance and expanse of BA required to ensure that there is no detrimental effect on the exit flow.

As a result, for wide exits it is necessary to ensure that there is a sufficiently wide expanse of BA. For example, assuming the above relationship scales, for a 5m exit the BA would need to be at least 7.5m wide if placed at 3m from the exit for exit flows of up to 4p/m^2. If a smaller expanse of BA is available, it is possible that the flow would back up and impinge on the exit flow. It is suggested that as the relationship between exit width and stand-off distance was not examined in these trials it may warrant further analysis in future trials.

- **(1.1.4a) For a given exit flow population density there is a relationship between the exit width, stand-off distance and expanse of BA required to ensure that there is no detrimental effect on the exit flow. Furthermore, for a given width of exit, the extent of the BA utilised by the flow will decrease with decreasing stand-off distance up to a distance of 3m from the exit.**
- **(1.1.4b) Assuming that the relationship between exit width, stand-off distance and extent of BA usage scales for other exit widths, for a given exit width, the BA should be at least 50% wider than the exit at a 3m stand-off distance; i.e. BA Width /Exit Width > 1.5m at 3m.**

Table 114: TS1: Gap Usage

		% Gap Use				
Stand-Off	**Initial Population Density (p/m^2)**	**1**	**2**	**3**	**4**	**5**
6m BA	3	9.4	27.3	31.9	24.7	6.6
	4	6.7	25.2	36.4	25.7	6.0
3m BA	3	3.2	28.3	37.4	27.1	3.9
	4	3.6	28.7	37.3	27.1	3.2
6m NoBA	3	7.7	26.2	36.5	26.7	3.0
	4	6.5	29.0	32.4	27.0	5.1
3m NoBA	3	1.0	29.1	42.7	26.4	0.7
	4	0.9	30.8	40.8	26.3	1.1

Table 115: TS1: Central Gap (gaps 2-4) Usage (%)

Stand-Off	**NoBA**			**BA**		
	3 p/m^2	**4 p/m^2**	**Average**	**3 p/m^2**	**4 p/m^2**	**Average**
6m	89.4	88.4	88.9	83.9	87.3	85.6
3m	98.3	98.0	98.1	92.9	93.2	93.0
Average	93.8	93.2	93.5	88.4	90.2	89.3

5.1.2 POPULATION DENSITIES: TS1

The values for the average densities across all sections and in the central section (in parentheses) calculated for the TS1 trials are summarised in Table 116. It should be remembered that the methods employed to identify the densities would have tended to produce lower density estimates than those actually experienced by the participants (refer to Section 4.2.1.7). The densities produced were broadly similar; however, when the BA was placed at the 3m line, it produced (15%) higher densities than when there was NoBA during the 4p/m^2 trials. Overall, however,

- **(1.2.0) The density incident on the BA at 3m and 6m stand-off distances, was significantly lower than the initial population density in the exit flow. This was due to diffusion of the population as they exited from the starting location.**

It is instructive to examine the density conditions in the central 'gate' given the tendency for it to be disproportionately used and that the rest of the population was otherwise spread across a relatively wide plane. This was the most direct path and might therefore be assumed the route typically selected had other factors not intervened (e.g. availability, surrounding population, etc.). In this situation,

- **(1.2.1) With one exception (with the BA at 3m for the 4 p/m^2 initial population) the central gate densities increased as the measurement location was reduced (see Table 116).**

This observation is as expected given that the degree of population diffusion increases with increased distance from the exit.

Table 116: TS1: Population densities at BA according to density and BA location. Density is presented as: average (central section) in p/m^2.

BA Stand - Off	Location of measurement	Initial Population Density	
		3p/m^2	4p/m^2
NoBA	6m	0.42 (0.62)	0.46 (0.69)
	3m	0.46 (0.74)	0.39 (0.72)
	0m	3	4
BA	6m	0.44 (0.53)	0.49 (0.77)
	3m	0.42 (0.66)	0.45 (0.69)
	0m	3	4

5.1.3 FLOW RATES: TS1

The flow rates produced at the bollard array line and the point of exit are summarised in Table 117. It is apparent that;

- **(1.3.0) The presence of a bollard array at a stand-off distance of 3m or 6m from a 2.4m wide exit, or a single bollard placed within the centre of the exit (0m stand-off) had little impact (approximately +/-1%) on the average peak exit flow rates, irrespective of initial population density (for densities not exceeding 4 p/m^2).**

- Table 117: TS1: Key Flow rates (ppm)

BA Stand - Off	Location of measurement	Initial Population Density				
		$3p/m^2$		$4p/m^2$		
		Flow (ppm)	% Diff (BA vs NoBA)	Flow (ppm)	% Diff (BA vs NoBA)	%Diff in Flow Given Initial Density
NoBA (6m)	BA line	230.7 [221-246]	-	246.2 [238-250]	-	-6.7
	Exit	233.3 [224-252]	-	247.1 [242-252]	-	-5.9
NoBA (3m)	BA line	235.2 [224-250]	-	248.7 [246-250]	-	-5.7
	Exit	233.3 [224-252]	-	247.1 [242-252]	-	-5.9
6m BA	BA	230.9 [221-246]	-0.1%	246.4 [242-254]	+0.1%	-6.7
	Exit	230.7 [224-235]	-1.1%	248.7 [242-252]	+0.6%	-7.8
3m BA	BA	238.7 [234-248]	+1.5%	243.4 [235-255]	-2.1%	-2.0
	Exit	235.2 [228-245]	+0.8%	245.5 [237-260]	-0.6%	-4.4
0m BA	BA	-		-		
	Exit	232.9 [226-242]	-0.2%	244.6 [243-245]	-1.0%	-5.0

The difference in the average peak exit flow rate values for the various bollard locations is smaller than the variation in the trial results for each case. The small differences noted in the exit flow rates are thus likely to be due to the natural variation in trial conditions. An exception is for the 0m bollard location at $4p/m^2$, where the difference between the average flow rate for the 0m bollard case and the no bollard case is greater than the variation in the 0m bollard cases. In this case the small reduction noted in the exit flow is unlikely to be due to variations in experimental conditions.

It should also be noted that, for the 0m case, the decrease in exit flow rate due to the presence of the bollard is partially compensated by the increase in exit unit flow rate due to the presence of the bollard and so the reduction in exit flow rate is not as large as would be expected (see Table 118 and the more detailed discussion below).

- **(1.3.1) For the 4 p/m^2 population, as the BA is brought closer to the exit i.e. from 6m to 3m, the average exit flow rate decreases and becomes less than that for the no bollard case. However, the difference in average flow rates is less than the natural variation within each of the cases.**

However, in the 3 p/m^2 case, the opposite trend is noted. It is again emphasised that the variations in exit flow rate that are noted are small (approximately +/-1%) and are less than the natural variation within the cases. It is unclear what may occur if the bollard array was brought closer to the exit (e.g. between 0m and 3.0m). As this aspect was not was not tested in these trials it may warrant further analysis in future trials.

As expected, the initial population density within the exit area has an impact on the achieved flow rates at both the exit and the BA line:

- **(1.3.2) The flow rates produced during the 4p/m^2 trials were consistently (albeit marginally) higher than those produced during the 3p/m^2 trials.**

The averages produced across the 3p/m^2 trials range from 230.7ppm to 239.8ppm, while the range produced during the 4p/m^2 trials is 234.4ppm to 248.7ppm. The 3p/m^2 trials therefore produced flow rates 2% to 7.8% lower than the 4p/m^2 trials (see Table 117).

The flow rates produced at the bollard array and the exit point are broadly consistent within each of the two density initial conditions:

- **(1.3.3) There is no obvious correlation between the location of measurement and the flow rate measured during the TS1 trials for each of the initial population density conditions assumed**.

For the 3p/m^2 trials, the flow at the BA ranged from 230.7ppm to 238.7ppm, while the flow at the Exit ranged from 230.7ppm to 235.3ppm. For the 4p/m^2 trials, the flow at the bollard ranged from 243.4ppm to 248.7ppm, while the flow at the Exit ranged from 244.6ppm to 248.7ppm. The similarities in the results are apparent.

An analysis of the unit flow rate at the exit was undertaken to explain the better than expected performance of the 0m bollard case (see Table 118). During the 3p/m^2 and 4p/m^2 0m trials, flow rates at the exit when the BA was present were 0.2% and 1.0% lower than the equivalent NoBA trials respectively. However, given the reduced width available due to the presence of the bollard, the flow was expected to be reduced by 9.4%.

With the bollard located in the centre of the exit, the exit unit flow rates are greater than those for the exit without the bollard (see Table 118). In both cases the presence of the bollard generated unit flow rates that were approximately 10% higher.

- **(1.3.4) The 0m bollard case benefited from an increase in the exit unit flow rate which partially compensated for the reduction in exit flow rate resulting from the reduction in clear exit width**.

- Table 118: TS1: Unit flow rates produced at exit – p/m/min (p/m/s)

BA Stand - Off	Initial Population Density	
	3p/m^2	4p/m^2
0m	107.08 (1.78)	112.45 (1.87)
NoBA	97.21 (1.62)	102.94 (1.72)
HMSO	80 (1.33)	
Fruin	120 (2.0)	

It is suggested that the improvement in unit flow rate is the result of the segregation of the exit flow into lanes which in turn results in fewer conflicts between the pedestrians as they pass through the constrained space of the exit. It must be noted that the improvement in unit flow rate was achieved with participants typically not carrying luggage. It is unclear if this mechanism will be as effective in situations involving passengers with luggage such as brief cases, suit cases, pushchairs, etc. In this case the bollard may exert a greater negative impact on the exit flow rate. As this aspect was not was not tested in these trials it may warrant further analysis in future trials (see Section 7). Further information may provide better understanding of this effect and how it might be exploited/addressed in future designs.

The unit flow rates can be compared with existing flow rates presented in the research literature and in guidance documents [4,5]. It is apparent that the unit flow rates produced when the bollard array is in place are greater than the (deliberately conservative) flow rates assumed in regulatory guidance documents (HMSO), but lower than those presented elsewhere in research literature (FRUIN) (see Table 118).

Given the assumed relationship between unit flow, density and achieved speed, an estimate of the average travel speeds maintained across the population can also be derived from the unit flow rate data [3]. This relationship is based on the following equation:

$$F_U = vD$$

Where F_u is the unit flow, v is the travel speed and D is the population density [3]. The results are shown in Table 119. As would be expected, the speeds maintained at 3p/m^2 are slightly higher than at the 4p/m^2 conditions. They are also higher than expected in engineering models (e.g. SFPE) where conservative assumptions are made. For instance, at 3p/m^2 a travel speed of 0.28m/s would be assumed using the SFPE calculation, while at 4p/m^2 no movement would be assumed. However, these models are deliberately conservative, and higher rates have been recorded in field observations [6]. The speeds produced are within expectation for data-sets describing the relationship between speed and density [7], somewhat verifying the conditions produced during the trials themselves as being reasonably representative of expected conditions.

Table 119: TS1: derived speeds (m/s)

BA Stand - Off	Location of measurement	Initial Population Density	
		3p/m^2	4p/m^2
0m	BA/Exit Point	0.60	0.47
NoBA	BA/Exit Point	0.54	0.43

In summary, in the trials representing the movement of pedestrians, with initial population densities of 3 p/m^2 and 4 p/m^2, out of an exit measuring 2.4m in width, and onto a BA, with stand-off distances of 0m, 3m and 6m, the presence of the BA had a small impact on the pedestrian dynamics, in particular the exit flow rates.

5.2 DISCUSSION: TS2

During the TS2 trials participants were assembled around the bollard line and allowed to move in one direction into the courtyard towards an objective immediately opposite them. During these trials a number of variables were examined: the presence of a BA, the initial population density and the presence/absence of cross-walkers (CW).

A number of parameters were recorded during these trials. The parameters reported here are as follows:

- *Population Densities* at the BA line – the densities produced by the participants at the BA line given the routes adopted
- *Flow rates* produced at the BA and the Endline – these are the primary results and indicate the achieved flow rates at the two measurement locations

In addition, several parameters were derived from the observations:

- (Derived) *Unit Flow Rates* produced at the BA – these flow rates were derived throughout as these trials allowed the available width to be taken into account enabling the UFR to be established at the BA line
- (Derived) *Travel Speeds* – once the UFR had been derived then it was possible to make some simple comparisons between the speeds produced primarily to verify the credibility of the underlying conditions present during the trials.

5.2.1 POPULATION DENSITIES: TS2

The population densities produced at the bollard array were summarised in Table 120. It is apparent that

- **(2.1.0) The population densities measured at both the BA line and the Endline throughout the TS2 trials were lower than the initial densities.**

The reduction in density occurs for both the 3p/m^2 initial population density (where the BA line densities ranged from 1.9p/m^2 to 2.0 p/m^2 and the Endline densities ranged from 1.4p/m^2 to 2.1p/m^2) and the 4 p/m^2 initial population density (where the BA line densities ranged from 1.9p/m^2 to 2.3 p/m^2 and the Endline densities ranged from 1.2 p/m^2 to 2.1p/m^2). The drop off in densities is to be expected as the front of the pedestrian queue can rapidly move away from the BA line into unencumbered space. This result is considered representative of what may happen in an actual situation where the crowd can rapidly disperse after they cross the BA line. The reduction in population density at the BA line is less severe than that noted in TS1.

Table 120: Average densities produced during the TS2 trials.

Condition	Location of measurement	Initial Population Density	
		3p/m^2	4p/m^2
NoBA	BA Line	2.0	2.0
	EndLine	1.5	1.4
BA	BA Line	1.9	2.0
	EndLine	1.4	1.2
NoBA CW	BA Line	1.9	2.3
	EndLine	2.1	1.9
BA CW	BA Line	-	1.9
	EndLine	-	2.1

5.2.2 FLOW RATES: TS2 with BA

As part of the TS2 trials, the flow rates were measured at the BA line and at the Endline 3.76m beyond the BA.

- **(2.2.0) The flow rate generated at the BA line is consistently lower than at the Endline (see Table 121).**

The average BA flow rate was 5.4% and 10.4% lower than the equivalent flow rate produced at the Endline location for the BA trials at 4p/m^2 and 3p/m^2 respectively. This is to be expected given the ability of the participant population to spread out and move more freely beyond the array. This suggests that the impact that the BA might have upon the movement of the population might be rectified in a short period of time after crossing the BA should sufficient space be available.

- **(2.2.1a) The presence of the BA reduces the flow rate at the BA line by 13% and 8% for the 3p/m^2 and 4p/m^2 respectively compared to the equivalent case without BA (NoBA).**

- **(2.2.1b) The presence of the BA reduces the flow rate at the Endline by 9% and 8% for the 3p/m^2 and 4p/m^2 respectively compared to the equivalent case without BA (NoBA).**

Table 121: TS2: Average flow rates during peak flow (ppm)

Condition	Location of measure	Initial Population Density				
		3p/m^2		4p/m^2		
		Flow (ppm)	% Diff BA-NoBA	Flow (ppm)	% Diff BA-NoBA	%Diff in Flow Given Initial Density
NoBA	BA	452.5 [443-465]	0	448.3 [440-465]	0	-1.0%
	Endline	482.5 [473-495]	0	470.7 [460-480]	0	-1.4%
BA	BA	392.5 [360-420]	-13%	412.0 [396-425]	-8%	+5.0%
	Endline	437.8 [396-488]	-9%	435.6 [407-452]	-8%	-0.5%

This reduction in flow rate is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate. However, the reduction in flow rate due to the presence of the BA was not as great as would be expected due to the 20% reduction in effective width of the path. The better than expected flow rate produced with the BA present is due to an improvement in the unit flow rate for the exit path with the BA present (see Table 122).

- **(2.2.2a) The presence of the BA increases the unit flow rate of the flow by 15% for the 4p/m^2 population. The reduction in flow rate due to the reduction in path width was partially compensated by the improvement in unit flow rate, resulting in a better than expected flow rate at the BA.**

- **(2.2.2b) The presence of the BA increases the unit flow rate of the flow by 8% for the 3p/m^2 population. The reduction in flow rate due to the reduction in path width was partially compensated by the improvement in unit flow rate, resulting in a better than expected flow rate at the BA.**

Table 122: TS2: Average unit flow rates during peak flow – p/m/min (p/m/s)

Condition	Location of	Initial Population Density

	measure	3p/m^2		4p/m^2	
		Unit Flow	% Diff BA-NoBA	Unit Flow	% Diff BA-NoBA
NoBA	BA	100.6 (1.7)	0	99.6 (1.7)	0
BA	BA	109.0 (1.8)	8%	114.4 (1.9)	15%
HMSO [4]	80 (1.33)				
Fruin [5]	120 (2.00)				

The improvement in unit flow rate is likely due to the reduction of conflicts between pedestrians at the BA line resulting from the presence of the BA. The bollards act as a barrier, preventing lateral conflicts from occurring between pedestrians at the BA line. This effect leads to a more ordered flow through the BA line which, in turn, produces a higher than expected flow rate. Thus, the 20% reduction in flow rate produced by the reduction in effective width of the exit path due to the presence of the BA is partially compensated by the 15.1%/8.4% improvement in unit flow rate achieved by the ordered flow generated by the presence of the BA.

It is noted that the improvement in unit flow rate for the 3.0 p/m^2 initial density crowd (i.e. 8.4%), is less than the 15.1% improvement in the unit flow rate achieved in the equivalent 4.0 p/m^2 trial. The difference is likely due to individuals within the higher density crowd experiencing a greater number of conflicts (due to the closer proximity of the individuals in the crowd) and hence the shielding effect offered by the barrier has a proportionally greater impact. The unit flow rates achieved can be compared with unit flow rates quoted in the research literature and in guidance documents [4,5]. It is apparent that, in all cases, the unit flow rates produced when the bollard array is in place are slightly higher than the flow rates assumed in regulatory guidance documents (HMSO) and lower than those produced elsewhere in research (FRUIN) (see Table 118).

As with the 0m bollard case (TS1), it must be noted that the improvement in unit flow rate was achieved with pedestrians typically without luggage. It is unclear if this mechanism will be as effective in situations involving many more passengers with luggage. In this case the BA may exert a greater negative impact on the BA flow rate. As this aspect was not tested in these trials it may warrant further analysis in future trials.

Given the assumed relationship between unit flow, density and achieved speed, an estimate of the average travel speeds maintained across the population can also be derived from the unit flow rate data [5]. This relationship is based on the following equation:

$$F_u = vD$$

where F_u is the unit flow, v is the travel speed and D is the population density [3]. The results are shown in Table 123. As expected, the speeds maintained at 3p/m^2 are slightly higher than at the 4p/m^2 conditions. However, the results collected at 3p/m^2 and 4p/m^2 are higher than expected in engineering models (e.g. SFPE, where conservative assumptions are made), although conform to data-sets collected to investigate the relationship between speed and density [7]. As with the TS1 trials, this result somewhat supports the contention that the conditions produced during the trials were representative of their real-world counterparts.

Table 123: TS2: derived speeds (m/s)

BA	Location of	Initial Population Density

Stand - Off	measurement	3p/m^2	4p/m^2
0m	BA	0.55	0.42
NoBA	BA	0.60	0.48

5.2.3 FLOW RATES: TS2 with CW

The final conditions examined in the TS2 trials involved the presence of cross-walkers (participants moving perpendicular to the main flow beyond the BA location, denoted as CW). Given the significance of these results, they are presented in conjunction with the other TS2 flow rates presented previously to allow direct comparison (see Table 124).

- **(2.3.0) The presence of the CW results in significantly lower flow rates at the BA line and the Endline compared to cases without the CW.**

The complex relationship between the presence of the CW and the other factors examined is discussed in more detail in the next section, however several points are immediately apparent:

- **(2.3.1a) The presence of the CW reduces the flow rate produced at the BA line by up to 21% and at the Endline by up to 48% for the 4 p/m^2 initial density.**

- **(2.3.1b) The presence of the CW reduces the flow rate produced at the BA line by 10% and at the Endline by 47% for the 3 p/m^2 initial density NoBA trials.**

- **(2.3.2a) The impact of the CW on the flow rate at the BA line and the Endline is more severe than the impact of the BA alone for the 4 p/m^2 initial population density. This suggests that where the CW is present, it is the dominant factor.**

- **(2.3.2b) The impact of the CW on the flow rate at the Endline is more severe than the impact of the BA alone for the 3 p/m^2 initial population density. However, at the BA line, the impact of the BA and CW are approximately equivalent. This suggests that at the lower density, where the CW is present, it will be the dominant factor on the Endline flow.**

Table 124: Average flow rates produced during the TS2 trials.

Condition	Location of measurement	Initial Population Density	
		3p/m^2	4p/m^2
NoBA	BA Line	452.5 [443-465]	448.3 [440-465]
	EndLine	482.5 [472-495]	470.7 [460-480]
BA	BA Line	392.5 [360-420]	412.0 [396-425]
	EndLine	437.8 [473-495]	435.6 [407-452]
NoBA CW	BA Line	405.0 [383-428]	387.5 [385-390]
	EndLine	254.2 [253-255]	246.4 [238-255]
BA CW	BA Line	-	326.0 [316-336]
	EndLine	-	245.1 [238-253]

From Table 120, the population densities produced through the presence of the CW are broadly in line with the other TS2 trials conducted.

A detailed comparison between the various factors examined and the flow rates produced at the various locations of measurement during the TS2 trials is presented below:

- **Population Density: 4 p/m^2 – BA Line flow rates.**

Compared to a flow without a BA or cross-walking flow:

- The introduction of the BA reduces the flow rate at the BA line by **8%**
- The introduction of the cross-walkers reduces the flow rate at the BA line by **14%**
- The introduction of the BA+cross-walkers reduces the flow rate at the BA line by **27%**

- **(2.3.3) For the 4 p/m^2 population, the cross-walkers have almost twice the impact of the BA on the flow rate at the BA line and the combined impact of the BA and the cross-walkers has more than three times the impact of the BA on the BA flow rate.**

Compared to the flow with BA present:

- A flow without BA but with cross-walkers reduces the flow rate at the BA line by **6%**
- The introduction of the cross-walkers reduces the flow rate at the BA line by **21%**

This can then be compared to the flow when the cross-walkers are present:

- The introduction of the BA reduced the flow rate at the BA line by **16%**

- **Population Density: 4 p/m^2 – Endline flow rates.**

Compared to the Endline flow without a BA or cross-walking flow:

- The introduction of the BA reduces the flow rate at the Endline by **7%**
- The introduction of the cross-walkers reduces the flow rate at the Endline by **48%**
- The introduction of the BA+cross-walkers reduces the flow rate at the Endline by **48%**

- **(2.3.4) For the 4 p/m^2 population, the cross-walkers have almost seven times the impact of the BA on the flow rate at the Endline and the combined impact of the BA and the cross-walkers is the same as the cross-walkers alone.**

Compared to the flow at the end line when the BA was present:

- A flow without BA but with cross-walkers reduces the flow rate at the Endline by **43%**
- The introduction of the cross-walkers reduces the flow rate at the Endline by **44%**

Compared to the flow at the end line when the cross-walkers are present:

- The introduction of the BA reduced the flow rate at the Endline by **1%**

- **Population Density: 3 p/m^2 – BA Line flow rates.**

Compared to a flow without a BA or cross-walkers:

- The introduction of the BA reduces the flow rate at the BA line by **13%**
- The introduction of the cross-walkers reduces the flow rate at the BA line by **10%**

- **(2.3.5) For the 3 p/m^2 population, the BA has an almost equivalent impact to the cross-walkers on the flow rate at the BA line.**

Compared to the flow with BA present:

- The introduction of the cross-walkers increases the flow rate at the BA line by **3%.**

- **Population Density: 3 p/m^2 – End line flow rates.**

Compared to the Endline flow without a BA or cross-walking flow:

- The introduction of the BA reduces the flow rate at the Endline by **9%.**
- The introduction of the cross-walkers reduces the flow rate at the Endline by **47%.**

- **(2.3.6) For the 3 p/m^2 population, the cross-walkers have more than five times the impact of the BA on the flow rate at the Endline.**

Compared to the flow with BA present:

- The introduction of the cross-walkers decreases the flow rate at the Endline by **42%.**

The impact of the cross-walker flow on BA and Endline flow rate is likely to be effected by cross-walker stand-off distance and line density. As these parameters were not examined in these trials they may warrant further analysis in future trials.

6 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, how does BA stand-off distance impact exit flow and how does the BA impact flow passing through the BA. As these effects were expected to be dependent on population density, two initial population densities were examined, 3 p/m^2 and 4 p/m^2. These densities were selected as they reflected the recommended maximum engineering design population densities and so were deemed representative of the conditions that may be encountered during evacuation situations at peak periods.

The exit flow results were generated for a 2.4m wide exit, with initial crowd densities of 3 p/m^2 and 4 p/m^2 and BA stand-offs of 3m and 6m with 6 bollards being used in the BA. Additional trials were conducted using a single bollard placed in the centre of the exit. For the BA flow trials, the width of the exit path was 4.5m and the BA consisted of 4 bollards. For the BA flow trials involving cross-walkers, the cross-walkers were in two rows a distance of 3.76m beyond the BA. The cross-walkers attempted to maintain their initial line density of 1.11 p/m per row and flow rate of 60 ppm per row. This was not always possible due to the disruption caused by the flow of people across their path. On average they managed a flow rate of 44.6 ppm across all the trials. In each set of trials, the bollards were 0.225m wide, 1.0m high and were spaced 1.2m apart.

In describing the main conclusions, reference is made to Section 5 and the specific observations made are used to support the concluding statements.

- On passing through the confines of the exit, a high density exit flow tends to spread out (or diffuse) into the available space as it approaches the BA. The BA acts as a divergent lens and encourages the population to spread out slightly more than would be the case without the BA. The degree of population diffusion is greater, the smaller the initial exit population density and the further away from the exit point. For a given exit flow population density there is a relationship between the exit width, stand-off distance and expanse of BA required to ensure that there is no detrimental effect on the exit flow. Furthermore, for a given width of exit, the extent of the BA utilised by the flow will decrease with decreasing stand-off distance up to a distance of 3m from the exit *(see 1.1.0 to 1.1.4 in Section 5).*
    - *Assuming that the relationship between exit width, stand-off distance and extent of BA usage scales for exit widths not considered in this work, for a given exit width, the BA should be at least 50% wider than the exit at a 3m stand-off distance i.e.* BA width/Exit Width > 1.5 at 3m *(see 1.1.0 to 1.1.4b in Section 5).*

- The exit population density will influence the flow rates achieved at the BA and beyond, with higher densities producing marginally higher flow rates *(see 1.3.2 in Section 5).*
    - *Suggests that the approach to the exit can be operated at engineering design levels (up to 4p/m^2) without experiencing a negative effect on flow rates produced at the BA location for a BA placed at a stand-off of 3m or 6m.*

- The densities at the BA fell sharply from those at the exit given the diffusion of the population. However, there was no obvious relationship between the densities produced at the BA location and the presence of the BA (see 1.2.0 and 2.1.0 in Section 5).
  - *Due to population diffusion, beyond a critical stand-off distance, the exit density will not be reflected at the BA. The minimum BA stand-off distance considered was 3m but the critical distance may be considerably less than this.*

- Assuming that the population densities at the exit are controlled (do not exceed 4 p/m^2) and there is sufficient width of BA for the exit, and the BA is not placed closer than 3m from the exit, the impact of the BA upon the exit flow rates and the BA flow rate is negligible and inconsistent (see 1.3.0 in Section 5).
  - *Given that the BA is not constraining the width available to the population, the presence of the BA does not appear to hinder the movement of the population.*

- Typically, the flow produced at the BA and the exit is comparable given BA stand-off distances of between 3m and 6m (see 1.3.3 in Section 5).

- Assuming that a single bollard is placed at the centre of a 2.4m wide exit and that the population densities at the exit are controlled (do not exceed 4 p/m^2), the impact of the bollard upon the exit flow rate is negligible. This case benefited from an increase in the exit unit flow rate brought about by a more ordered flow resulting from lane formation generated by the presence of the bollard. This partially compensated for the reduction in exit flow rate resulting from the reduction in clear exit width due to the presence of the bollard (see 1.3.0 and 1.3.4 in Section 5).
  - *It must be noted that the improvement in unit flow rate was achieved with the vast majority of participants not carrying luggage. It is unclear if this mechanism will be as effective in situations involving a greater proportion of pedestrians with luggage such as brief cases, suit cases, pushchairs, etc. In this case the bollard may exert a greater negative impact on the exit flow rate.*

- Where the densities are controlled at the BA location (do not exceed 4 p/m^2) (TS2), the presence of the BA reduces the flow rate at the BA line and at a distance 3.76m beyond the BA (see 2.2.1 in Section 5).
  - *This again points to the benefits of ensuring that the BA stand-off is at a prescribed location (e.g. 3m or beyond) to encourage population diffusion and ensure that the densities at the BA do not reach engineering design maxima.*

- Assuming initial population densities of 3 p/m^2 and 4 p/m^2 incident on the BA, the BA reduces the flow rate at the BA line by 13% and 8% respectively compared to the equivalent case without BA. At a distance 3.76m beyond the BA, the BA reduces the flow rate by 9% and 8% for the 3p/m^2 and 4p/m^2 respectively. This case benefited from an increase in the unit flow rate through the BA brought about by a more ordered flow resulting from lane formation generated by the presence of the BA. This partially compensated for the reduction in flow rate resulting from the reduction in clear path width due to the presence of the BA (see 2.2.1 and 2.2.2 in Section 5).

- *It must be noted that the improvement in unit flow rate was achieved with the vast majority of participants not carrying luggage. It is unclear if this mechanism will be as effective in situations involving many more pedestrians with luggage such as brief cases, suit cases, pushchairs, etc. In this case the BA may exert a greater negative impact on the flow rate.*

- The presence of the cross-walkers in the BA flow trials resulted in significantly lower flow rates at the BA line and at a distance 3.76m beyond the BA, just before the line of cross-walkers (see 2.3.0 in Section 5).

- For the 4 p/m^2 population, the cross-walkers have almost twice the impact of the BA on the flow rate at the BA line (representing a reduction in flow rate of 14%) and the combined impact of the BA and the cross-walkers has more than three times the impact of the BA on the BA flow rate (representing a reduction in flow rate of 27%). The cross-walkers have almost seven times the impact of the BA on the flow rate a distance 3.76m from the BA line (representing a reduction in flow rate of 48%), just before the line of cross-walkers and the combined impact of the BA and the cross-walkers is the same as the cross-walkers alone. For the lower main flow density (3 p/m^2), the impact of the cross-walkers while less severe was still considerable. The impact of cross-walker stand-off distance from the exiting flow and the cross-walker line density on flow rate was not examined (see 2.3.3 to 2.3.6 in Section 5).
    - *Suggests that it is extremely important for station management to understand and, if possible, manage the pedestrian flow immediately outside of the station during an incident. This might be achieved by the use of procedural measures (e.g. staff and notification systems) to cordon off the exit path from the station and divert non-evacuating pedestrians and through co-ordination with authorities managing the conditions outside the station.*

These concluding remarks reflect the complexity of the impact of the BA upon performance. It is clear that the presence of a BA of sufficient width located at least 3m from an exit will have little impact on the exit flow. This is due to the diffusion of the population into the available space significantly reducing the population density by the time the crowd comes into contact with the BA. If a single bollard is placed within the centre of the exit, the exit flow rate will be reduced due to the reduction in available exit width; however, the results suggest that the presence of the bollard generated a more ordered flow through the exit which resulted in an improved exit unit flow rate that somewhat compensated for the loss in exit width due to the presence of the bollard. A balance may therefore be reached where the two effects effectively cancel out (for example by decreasing the width of the bollard).

Should the initially high population densities be maintained at the BA location (e.g. up to 4 p/m^2, where the initial densities within the exit flow greatly exceeded engineering design or where the BA stand-off was reduced such that population diffusion was diminished or there was insufficient BA width to accommodate the diffusion of the population), then the presence of the BA will have a more pronounced impact – resulting in approximately a 10% reduction in flow rate at the BA location and approximately an 8% reduction 3m beyond the BA location.

However, the most significant impact on the BA flow rate was generated by the presence of the cross-walkers – a line of pedestrians walking across the main exit path up to 4m from the

BA. The cross-walkers had twice the impact on the BA flow rate as the BA and the BA and cross-walkers combined had three times the impact of the BA alone.

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 and through the management of external flows around the exit point. Further work however is required to identify the impact of stand-off distances less than 3m; the relationship between exit width, stand-off distance and full width of the BA; the impact of pedestrians with luggage upon unit flow rate; the impact of cross-flow stand-off distance and flow rate upon BA flow rate; and the impact of alternate pedestrian targets on exit flow rate.

7 FUTURE WORK

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 five are considered the most important in framing our understanding of how evacuation flows interact with the BA. The numbers of trials suggested in each case is indicative: fewer trials could be conducted in most cases by simply reducing the number of options.

1) Exit Flow Trials with BA stand-off distances between 0m and 3m.

The exit flow trials conducted as part of this study placed the BA at 0m (in the exit) and at stand-offs of 3m and 6m. The results suggested that there was no appreciable effect on the exit flow rate as the BA moved from 6m to 3m. However, it was noted that there was a slight reduction (less than 1%) in flow rate 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 may amplify the impact of the BA on the exit flow. The impact of the BA at 0m is complex as there is a reduction in effective width due to the presence of the BA leading to a reduction in the exit flow rate and a corresponding increase in the unit flow rate at the exit due to the influence of the BA resulting in an increase in the exit flow rate. Thus, it is not clear what impact a BA positioned between 0m and 3m from the exit may have on the exit flow rate. Furthermore, if additional stand-off distances are examined it will be possible to determine the required expanse of BA required for a given exit width for stand-off distances less than 3m (the current work has postulated that BA width/Exit Width > 1.5 at 3m).

To determine the impact it is suggested that an additional series of exit flow rate trials are conducted with the BA positioned at 2m, 1m and 0.5m from the exit. The 0.5m stand-off distance is considered important as it may also benefit, to some degree from the unit flow rate effect. These trials should be conducted at $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require:

2 (densities) x 3 (stand-off distances) x 3 (repeats) = 18 trials.

2) Exit Flow Trials with varying exit width and stand-off distances between 0m and 6m.

Analysis of the trial results suggests 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. 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 this study only considered a single exit width and suggests, assuming that the relationship between exit width, stand-off distance and extent of BA usage scales for exit widths not considered in this work, that:

BA width/Exit Width > 1.5 at 3m

By examining one or two additional exit widths we will be able to determine if the above expression is valid for a range of different situations. 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 as in TS2. It is suggested that two additional widths be examined

3.5m and 4.5m. These could be run at only one density – 4 p/m^2. Note that the wider width will require more people then were used in the TS1 trials to ensure that the flow is maintained for sufficient time. Assuming that the above relationship is correct, then for the 4.5m wide exit trial, a BA of at least 6.75m is required at 3m from the exit. As the courtyard is 12.75m wide these trials can easily be accommodated.

Three stand-off distances could be considered 3m, 2m and 1m. This would require:

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

It is also suggested that some of the trials be repeated with a smaller expanse of BA to investigate the impact of a smaller array. It is suggested that the two BA widths are considered at a stand-off of 3m, generating the following additional trials:

1 (density) x 2 (widths) x 1 (stand-off distance) x 3 (repeats) = 6 trials.

3) Exit Flow Trials involving people carrying luggage at the 0m stand-off.

The exit flow trials involving a BA placed at 0m stand-off produced complex flow dynamics. The reduction in exit flow rate 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 rate resulting from the more ordered flow generated by two lanes of exit flow. This increase in the unit flow rate 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 UoG trials the vast majority of participants were not carrying luggage or baggage (occasionally some participants very small handbags, umbrellas, books, etc.). If the pedestrians were encumbered by luggage/baggage, strollers etc., it is unknown whether the improvement in unit flow rate would have been as significant, if it indeed occurs at all. If this is so, then the presence of the 0m BA would have a more negative impact on the exit flow rate.

To determine the impact of pedestrians carrying baggage/luggage it is suggested that an additional series of exit flow rate trials are conducted with and without the BA at 0m with pedestrians carrying luggage. These trials would be conducted at $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require:

2 (densities) x 2 (BA conditions 0m stand-off and no BA) x 3 (repeats) = 12 trials.

4) BA Flow Trials involving people carrying luggage.

The BA flow trials, like the exit flow trials with a BA placed at 0m stand-off produced complex flow dynamics. The reduction in BA flow rate resulting from the reduction in effective passage width brought about by the presence of the BA was partially compensated for by the increase in the unit flow rate resulting from the more ordered flow generated by the multi-lanes of passage flow. This increase in the unit flow rate partially compensated for the reduction in effective passage width and as a result, the impact of the BA was not as significant as it could have been. The UoG trials were conducted using pedestrians who were not carrying luggage or baggage as may be expected at a rail or underground station. If the pedestrians were encumbered by luggage/baggage, strollers etc, it is unlikely that the improvement in unit flow rate would have been so significant, if it indeed occurs at all. If this is so, then the presence of the BA would have a more negative impact on the passage flow rate.

To determine the impact of pedestrians carrying baggage/luggage it is suggested that an additional series of BA flow rate trials are conducted with and without the BA with pedestrians carrying luggage. These trials would be conducted at $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require:

2 (densities) x 2 (with BA and without BA) x 3 (repeats) = 12 trials.

5) Cross-Flow stand-off distances and line density.

The BA flow trials with cross-flow produced the smallest path flow rate, with path flows being reduced by almost 50%. Thus the cross-walkers had a significantly greater impact on the flow than the BA. In real evacuation situations from busy stations located on busy streets, it is possible that quite high cross-flows may exist which could have a significant impact on the evacuation flow. However, the cross flow was imposed on the path flow at a stand-off of several metres. It is not clear how the stand-off distance may impact the flow rate at the BA line and the Endline. Furthermore, the cross-flow consisted of a single, relatively high pedestrian line-density. It is thus not clear how the pedestrian line density in the cross-flow, may impact the path flow. It is likely that there is a critical line density below which the interference produced by the cross-flow is negligible.

To determine the impact of cross-flows on the path flow it is suggested that an additional series of BA flow rate trials are conducted with and without the BA with cross-flows. These trials would be conducted at $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require:

2 (densities) x 2 (BA without CF and no BA with CF) x 3 (CF stand-off distances) x 3 (repeats) = 36 trials.

For a given CF stand-off distance, several CF line densities could be explored. This would require

2 (main flow densities) x 2 (BA without CF and no BA with CF) x 3 (line densities) x 1 (CF stand-off distance) x 3 (repeats) = 36 trials.

In addition, some or all of these may need to be repeated with participants carrying luggage, depending on the outcome of the luggage trials.

6) 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 TS2 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 TS2 due to the two interacting populations. This would require the following number of trials:

2 (Pop1 densities) x 2 (Pop2 densities) x 3 (repeats) = 12 trials.

7) BA height

The height of the BA may influence the manner in which people approach the BA and the flow rate 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. 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 both exit flow rate trials and the BA flow rate trials to be repeated. For the exit flow rate trials, it is perhaps only likely that a higher BA would be used in the exit (0m stand-off). If so, then only one BA condition would need to be explored. In this case the required trials would consist of densities at $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require the following exit flow rate trials:

2 (densities) x 1 (portal BA at 0m stand-off) x 3 (repeats) = 6 trials.

In addition, it is suggested that the BA flow rate trials could be repeated with portal type BA. This case would also be run at densities of $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require the following exit flow rate trials:

2 (densities) x 1 (with portal BA) x 3 (repeats) = 6 trials.

In addition, some or all of these may need to be repeated with participants carrying luggage, depending on the outcome of the luggage trials.

8) Exit and BA Flow Rate trials in low lighting.

All of the Exit and BA flow rate 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 rate.

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:

2 (densities) x 3 (0m and 3m stand-off and no BA) x 3 (repeats) = 18 trials.

In addition, it is suggested that the BA flow rate trials could be repeated with reduced illumination. This case would also be run at densities of $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require the following exit flow rate trials:

2 (densities) x 2 (with portal BA and without BA) x 3 (repeats) = 12 trials.

9) Exit Flow Rate trials with alternate Target Point.

In the exit flow rate 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 rate.

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 $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require:

2 (densities) x 4 (0m, 3m and 6m stand-off and no BA) x 3 (repeats) = 24 trials.

10) Exit Flow Rate trials with multiple Target Points.

In the exit flow rate 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 them 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 rate.

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 $4p/m^2$ and $3p/m^2$ to be consistent with the earlier trials. This would require:

2 (densities) x 4 (0m, 3m and 6m stand-off and no BA) x 3 (repeats) = 24 trials.

11) 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.

To determine the impact of running pedestrians it is suggested that an additional series of exit flow rate trials are conducted with and without the BA at stand-offs of 0m, 1m and 3m. If the trials with pedestrians encumbered with luggage are undertaken, it would also be necessary to repeat a selection of these trials with pedestrians carrying luggage. These trials would be conducted at $1p/m^2$ and $0.5p/m^2$ to provide pedestrian with an opportunity to run. This would require:

2 (densities) x 3 (stand-off conditions 0m, 1m and 3m) x 3 (repeats) + 1 (without BA) x 3 (repeats) = 21 trials.

In addition, some or all of these may need to be repeated with participants carrying luggage, depending on the outcome of the luggage trials.

8 REFERENCES

[1] CPNI Statement of Requirement (SoR) for FY2012/13, 17 August 2012.
[2] Galea, E.R., and Gwynne, S., Impact of Hostile Vehicle Mitigation Measures (Bollards) on Pedestrian Crowd Movement, Research Proposal, Fire Safety Engineering Group, University of Greenwich, 6 November 2012.
[3] Gwynne, S.M.V. and Rosenbaum, E.R., "Employing the Hydraulic Model in Assessing Emergency Movement," SFPE Handbook of Fire Protection Engineering, 4th Edition, DiNenno et al. (eds.), National Fire Protection Association, Quincy, MA, 2009, pp3-373 – 3-396.
[4] HMSO, The Building Regulations 1991 - Approved Document B, section B1, HMSO Publications, London.
[5] Fruin, J., Pedestrian planning and design, Metropolitan Association of Urban Designers and Environmental Planners, New York, 1971.
[6] Fahy RF, Proulx G (2001) Towards creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling. In: Proceedings of the second international symposium on human behavior in fire, 26/28 March 2001, Massachusetts Institute of Technology, USA. Interscience Communications (London, UK), pp175 – 179.

9 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.

10 ANNEX B: PLANNING TIMELINE

Two types of trials will be conducted:

- TS1 – at the south arch of Queen Anne Court (at point [E] in Figure 112)
- TS2 – in the centre of the courtyard in Queen Anne Court (at point [F] in Figure 112)

These will involve slightly different trial scenarios and physical configurations. These will be described in more detail after the pilot study. The pilot study will be conducted on the 1-2/2/13. On the 1/2/13, the experimental procedure and people management issues will be examined; on the 2/2/13 the equipment involved in the experimental scenarios will also be examined.

The main actions and events before, during and after the experiment are presented in the timeline shown in Table 125. The roles adopted by those involved are described in Table 126. A schematic of the experimental area is shown in Figure 112.

Table 125: Experimental Timeline. RED – COMPLETE. ORANGE – IN PROGRESS. BLUE – TO BE COMPLETED.

Time Step	People Management	Data Collection	Resources	Physical Environment
-18			Ensure storage area in courtyard available [EG]	
-17	Send out FSEG/Gre e-mail [EG – 15/2]		Finalise participant briefing [SG – 18/2]	
-16			Develop card system that allows participants to be given a numbered card on their arrival that they exchange for a cap.[SG]	
-15			Organise first aiders [EG – 15/2]	
-14			Confirm insurance / safety requirements [EG – 18/2]	
-13	Allot arrival times to groups (of 60/70) [XH]	Ensure cameras / still camera / walkie-talkies / clamps/laptops available [DC]	Identify (C1/C2) locations [EG]	
-12	Assign number / groups to each individual when all responses are in [XH]	Ensure rooms/space available [DC]	Purchase hats [EG – 15/2] Purchase water [EG]	
-11			Develop group / trial allocation [SG – 8/2]	
-10			Develop numbering system that carries through from registration to payment [SG – 8/2]. Produce participant roster, withdrawal forms and registration documents for cross checking [SG/EG – 15/2]	

-9		Identify footage numbering for output [XH/AV]	Develop script for greeters/meeters [SG – 18/2]	
-8			Get payment bags [KJ]	Ensure barriers are available [EG]
-7		Charge Batteries [DC]	Prepare hats / numbers. Get tape measure, masking tape, pencils, markers, paper. [DC]	Ensure cones are available. [SD]
-6			Meeters to learn script [AH/MP]. Ensure First Aiders on site [EG]	Mark out 2m sections in two pens: (E) or (F) [DC]
-5			[DC, XH, AV, SD] collect equipment: cameras, laptop, clamps, walkie-talkies. Pass on walkie-talkie to [KJ/EG/AH/SG]	
-4			Ensure accessibility of safe / money [EG]	
-3		[DC] camera to also have laptop to allow review of footage by [EG]	Check water provisions [EG]	Ensure cones are in place. [SG]
-2		Position cameras. Test quality of footage. Test longevity[XH/AV/DC/SD]	Prepare registration [KJ] / distribution [V/A/ AH/MP]	Ensure barriers in place to delimit pen. [DC]
-1		Take stills / test footage from camera positions [XH/AV/DC/SD]	Set up holding area [LH]	Arrange furniture in cafeteria area. Two stations required (C1,C2).
0	Participants arrive. Met at (A) and (B) by [AH/MP]. Arrivals scheduled in groups of 60/70 at 15 minute intervals. [EG] to meet and collect visitors at pre-determined location.			
1	Moved to cafeteria (C) in groups (MP/AH) from (A) and (B). Ensure that either [MP] or [AH] is also available to meet people. [EG] takes visitors to (V1) and (V2). Monitor and record number of arrivals [A / V] (C). Report to [LH] to confirm.			
2	Registered at (C1) by [KJ]. Documents, numbered cards and pencil provided. [KJ] keeps [EG] informed of registration process. [KJ]calls [EG] every 15 mins or when 25%, 50%, 75%, 100% have registered			
3	Move to distribution area (C2 - [V/A] present) where participants hand over numbered cards and are given hats / water by [LH]. Hat numbers also associated with group allocation of 15.		Briefing document for [EG]	
4	Briefing in cafeteria (C) of each group [EG].			
5	While still within (C), participants complete documentation and return to [V/A] who collect and pass onto [KJ]. Participants then go to holding area. If participants want to withdraw at this stage, they are taken to [V/A] take them to [LH] where hat is returned. [LH] notes withdrawal on a withdrawal form, thanks them for their time, and gives card to [V/A] which they pass onto [KJ]. [KJ] assigns free hat number to one of the spare participants in buffer group. [KJ] provides EG with updates of number of drop outs.			

6	In the holding area, participant numbers are logged ready for the trial [SG]. This ensures that those actually taking part can be distinguished from those withdrawing. [SG] will check with [KJ] that his list corresponds to her list		[SG] will need a walkie-talkie from the registration period onwards.	
7	Assessment of viable participants made [SG]. Number of sections to be used established.			
8	When all of the group members have arrived, move to pen (E or F). [MP] [AH] still moving between (a) and (B) to meet latecomers.	Operate Cam1 [DC] Operate Cam2 [XH] Operate Cam3 [AV] Operate Cam4 [SD]		
9	Complete loading of pen (E) into the 9 sections of (15) people for TS1 and 4 sections of (15) people for TS2. Groups will be loaded into allocated pen section, according to participant management document. Where 20 participants are required in each section, secondary groups will be split into five person sub-groups by [SG] and then inserted into the allocated pen section, again defined in the participant management document. These will be inserted into the section from different sides to ensure that they more effectively mingle with the rest of the population. Each group instructed to remain in allocated section [SG]. [MP] assists [SG] in this process. [LH] and [KJ] should remain in (C) to process any late arrivals. [AH] remains on road to direct late arrivals until last moment.	Confirm density condition inside arch [DC] All camera positions confirm active to [DC] who then confirms with [EG]		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], [AH]. [AH] and [MP] then move into F stand under opposite arch to act as target and ensure path adopted by participants, [A] moves to between (A) and (B) for latecomers and withdrawals, [V] at door of (C) for withdrawal processing, [SG] stands at back of pen and walks with crowd. [DC] starts cameras rolling,		[EG] has load hailer and emergency stop horn.	
11	[EG] final check with [DC], [SG] and [AH]. [EG] starts trial [DC] and [SG] monitor crowd while in arch and if anyone in distress, they call [EG] who sounds horn to stop.			
12	On completion, [AH/MP] move participants to holding area (D), through side or end arch. Sarah Ragab may be on site from 1pm, 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.			Check status of trial area [SG / DC]
13	Participants held at (D) by [AH/MP] while allocation of participants for next trial resolved by [SG], who will have moved to [D] on completion of trial. Participants either moved to café [A/V]until next required, or taken back to the pen when appropriate participant in hold[AH/MP]. [SG] will need to communicate with [A/V] to retrieve appropriate people from cafeteria.		Distribute water from cafeteria as and when [A / V]	Adjust trial area as required [XH / AV]
14	After first trial, [EG/DC] to check the video footage on a laptop at camera positions {1,2,3}. Must be done before start of next trial. Go to time step <8>.			[KJ] prepares (C) for post-trial processing.
15	Cafeteria furniture returned to normal positions			

	for lunch.			
16	Cafeteria furniture positioned for one station for participant departure.			
17	On completion of trials, [AH/MP] return to (C) administration.			
18	[SG] returns to (C) provides [KJ] with withdrawal lists.			
19	[KJ] prepares payment lists, taking into account no shows, non-starting 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	Distribute Payments [KJ / DC and SG] [V] moves to [DC] camera position to guard position. [KJ] 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. [EG] escorts visitors from (V1) and (V2), off-site.	Pack Cam1 [DC] Pack Cam2 [XH] Pack Cam3 [AV] Pack Cam4 [SD]		

Table 126: Staff roles.

STAFF	ROLE
EG	Coordinator
AH	People Management
MP	People Management
DC	Camera / Resources
AV	Camera / Resources
XH	Camera / Resources
SD	Camera / Resources
LH	People Management / Admin
KJ	Admin
V	People Management
A	People Management
SG	People Management

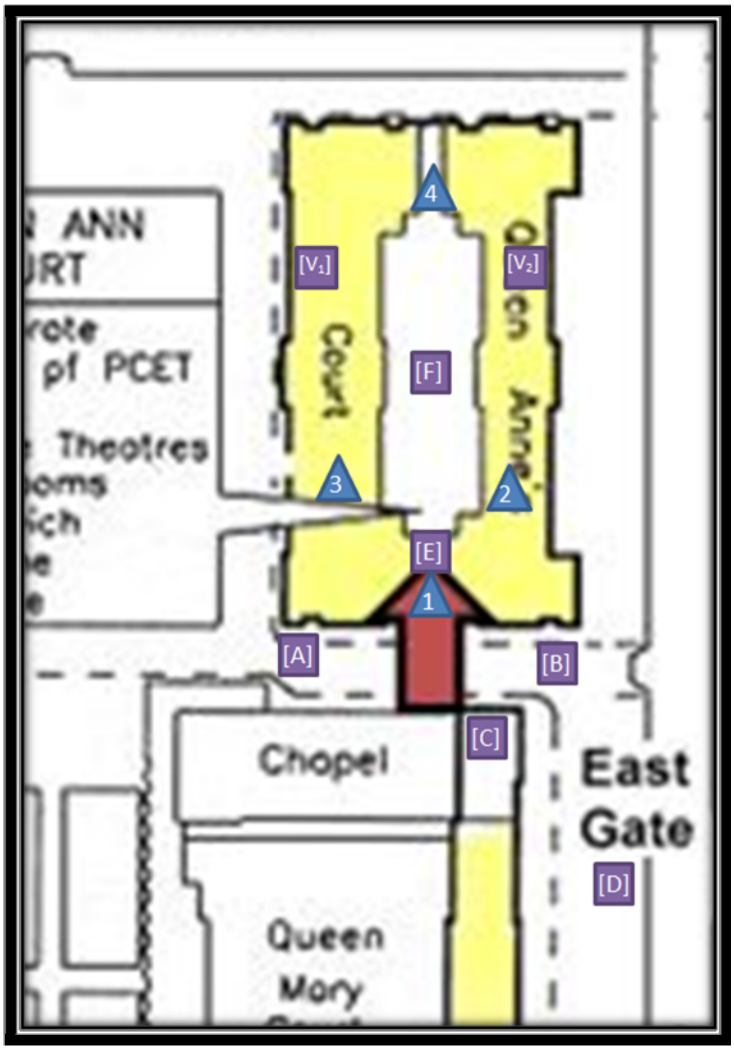


Figure 112: Experimental area. Triangles indicate camera positions. Squares indicate locations of interest.

11 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.

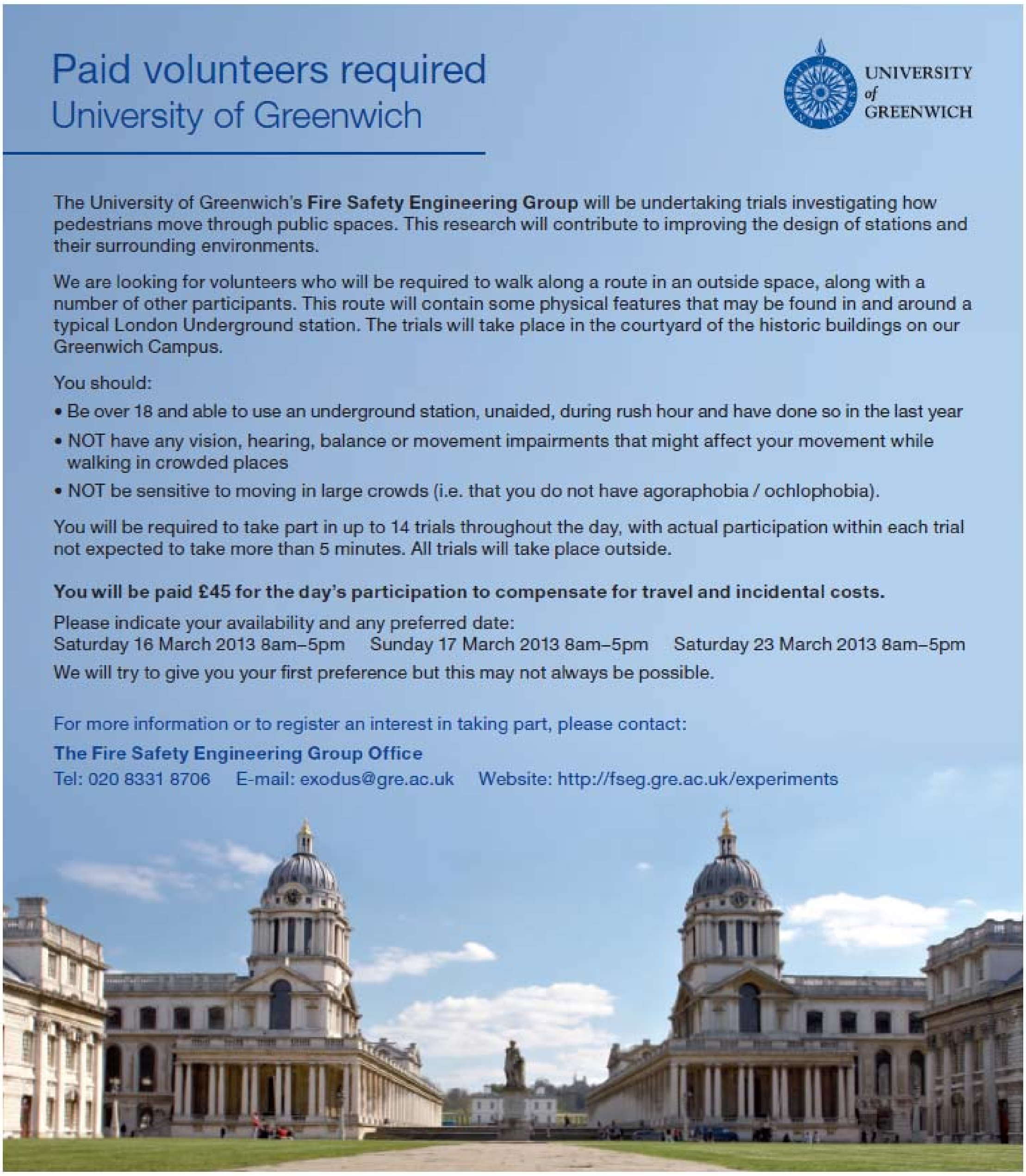
Environmental risks
*The weather may interfere with the experimental schedule. **HIGH***
- Five day weather forecasts will be examined to avoid extreme weather conditions. The facility has been booked for more dates than required and so the trial could be rescheduled for a later date. It is thus essential 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.

12 ANNEX D: ADVERTISEMENT



13 ANNEX E: WEB ADVERTISEMENT

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

14 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.

15 ANNEX G: PARTICIPANT DETAILS

Date	Participants booked	Participants attended	Breakdown of attendees				
			Male	Female	18-30	31-50	51+
16.03.13	198	149	79	70	60	58	31
17.03.13	248	170	76	94	89	51	30
23.03.13	184	139	72	67	76	38	25

Date	Participants booked	Participants attended	Breakdown of non-attendees				
			Male	Female	18-30	31-50	51+
16.03.13	198	149	22	34	38	16	2
17.03.13	248	170	38	40	52	15	11
23.03.13	184	139	22	29	29	15	7

Date	Participants booked	Participants attended	Drop-outs during trial				
			Male	Female	18-30	31-50	51+
16.03.13	198	149	1	1	1	1	0
17.03.13	248	170	0	0	0	0	0
23.03.13	184	139	0	0	0	0	0

16 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 127: Itemised contents of Case 1

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

Table 128: Itemised contents of Case 2

Equipment	Quantity
Super Clamp	6
Long Arm	6
Camera Mount	6

Table 129: Equipment carried separately

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

17 ANNEX I: RESULTS

17.1 TS1: 4p/m²

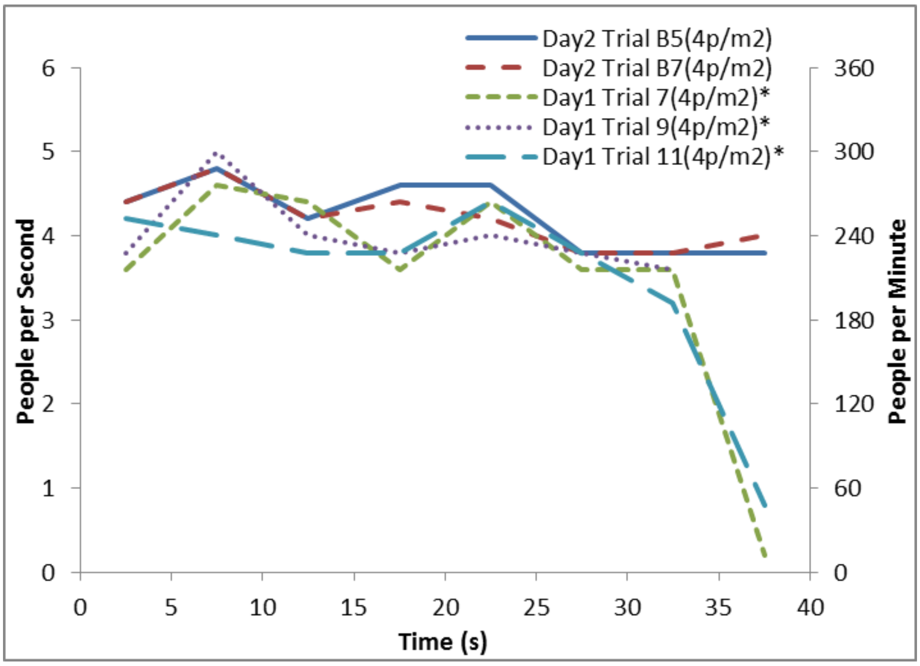


Figure 113: TS1 – Exit flow rate measured in 5 sec intervals for the five NoBA 4 p/m^2 trials

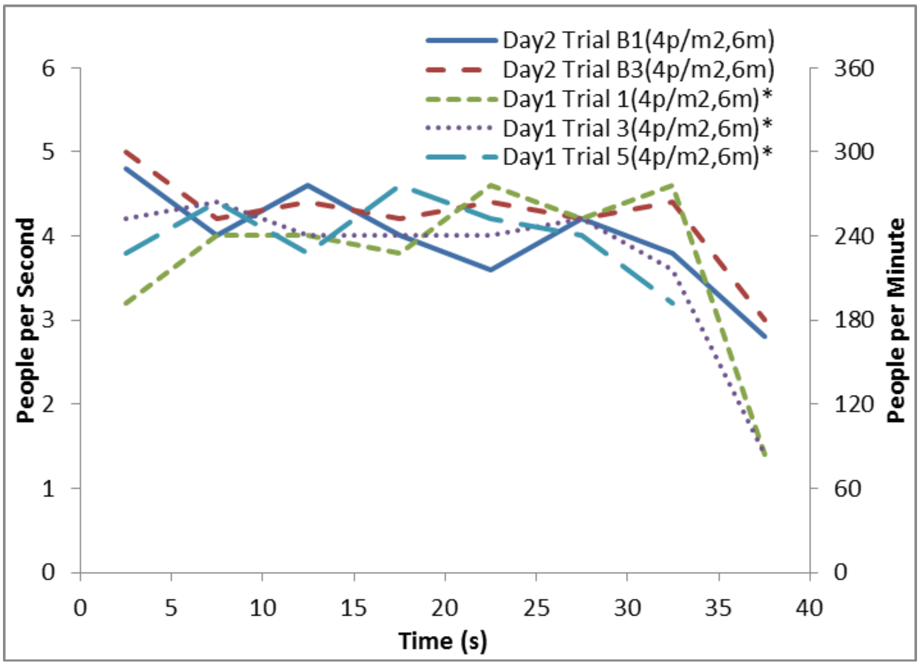


Figure 114: TS1 – Exit flow rate measured in 5 sec intervals for the five 6m BA 4 p/m^2 trials

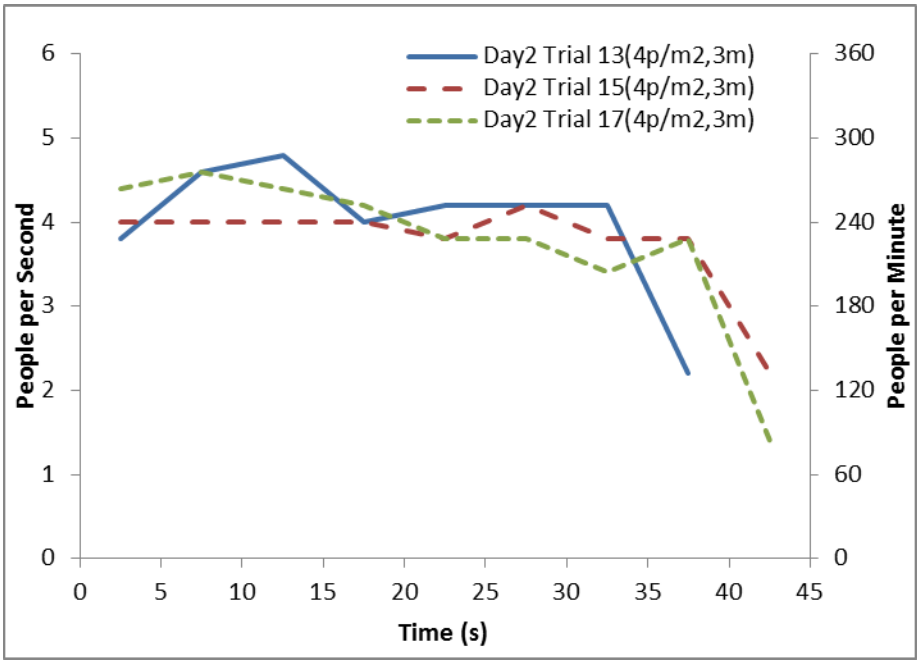


Figure 115: TS1 – Exit flow rate measured in 5 sec intervals for the three 3m BA 4 p/m^2 trials

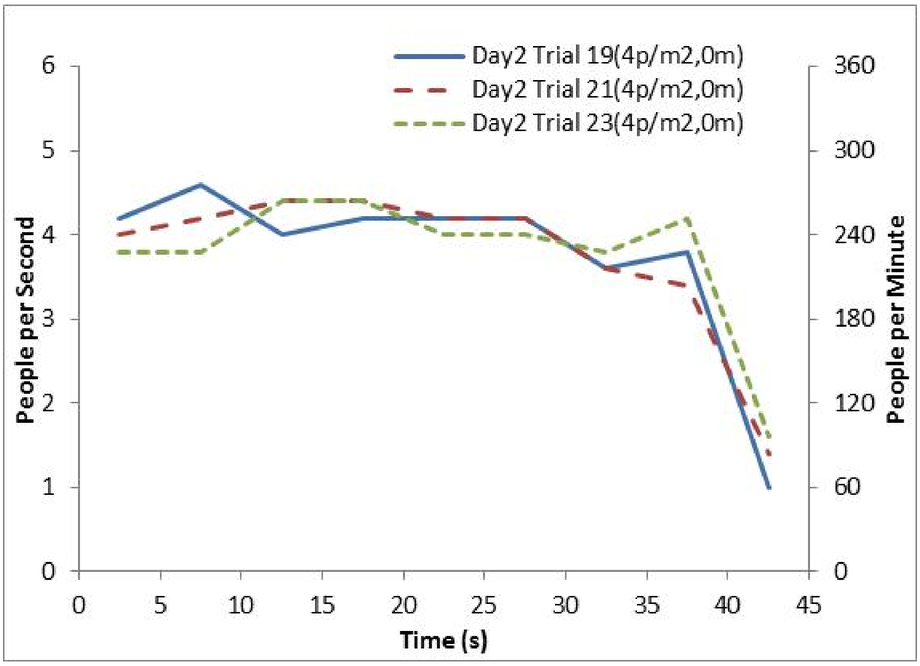


Figure 116: TS1 – Exit flow rate measured in 5 sec intervals for the three 0m BA 4 p/m^2 trials

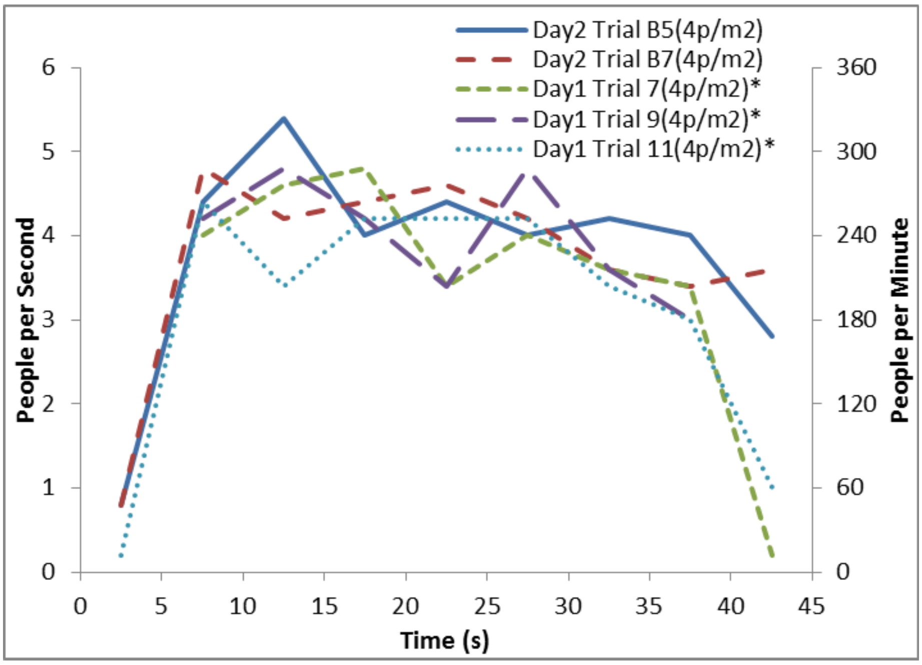


Figure 117: TS1 – BA flow rate measured in 5 sec intervals for the five 6m NoBA 4 p/m^2 trials

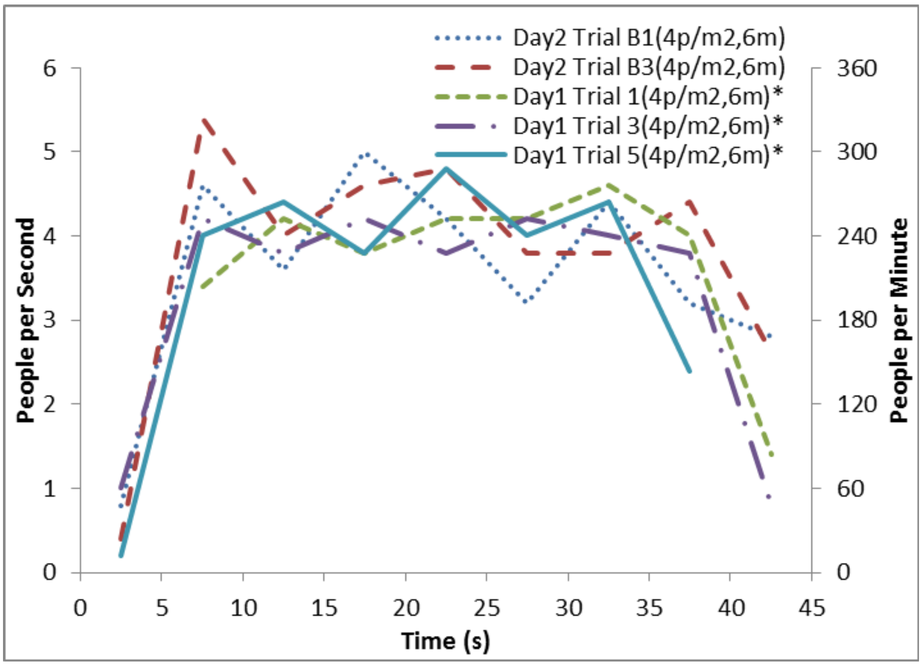


Figure 118: TS1 – BA flow rate measured in 5 sec intervals for the five 6m BA 4 p/m^2 trials

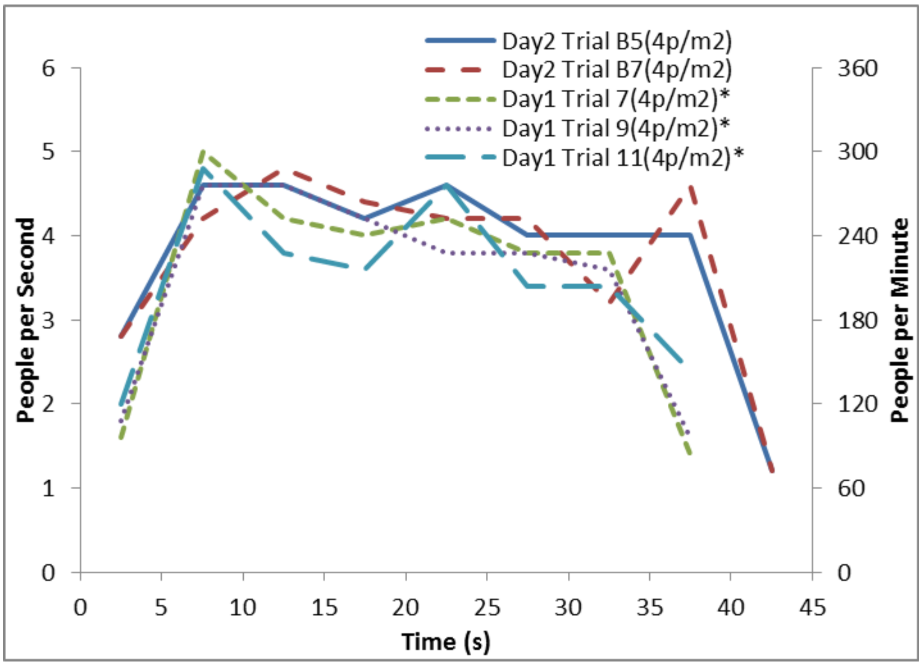


Figure 119: TS1 – BA flow rate measured in 5 sec intervals for the three 3m NoBA 4 p/m^2 trials

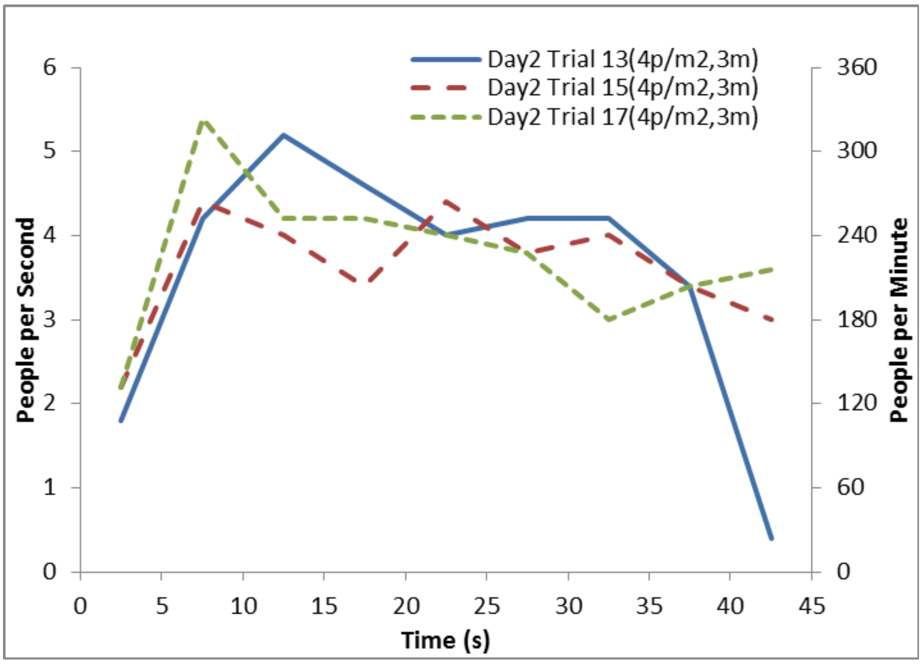


Figure 120: TS1 – BA flow rate measured in 5 sec intervals for the three 3m BA 4 p/m^2 trials

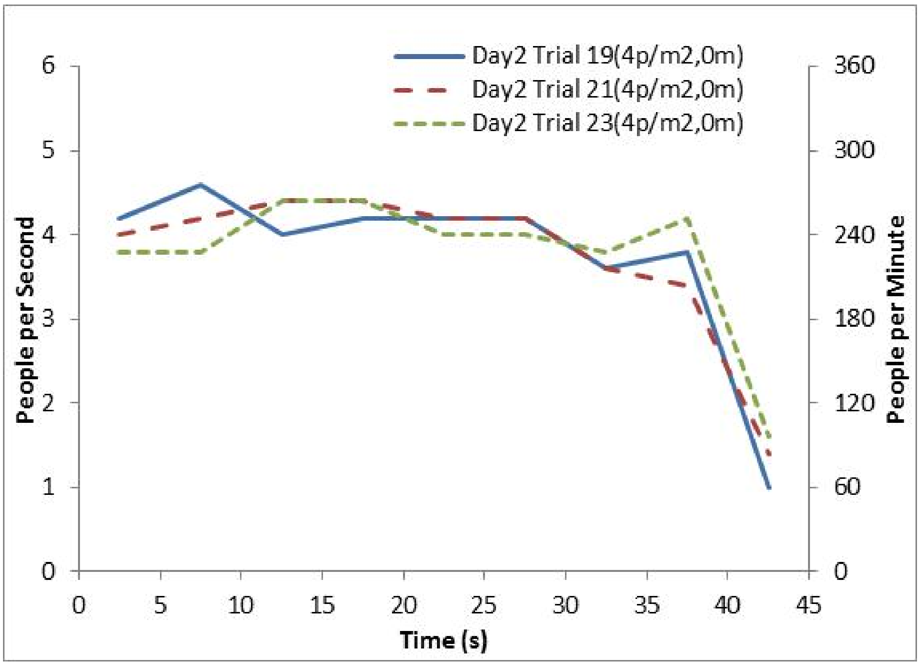


Figure 121: TS1 – BA flow rate measured in 5 sec intervals for the three 0m BA 4 p/m² trials

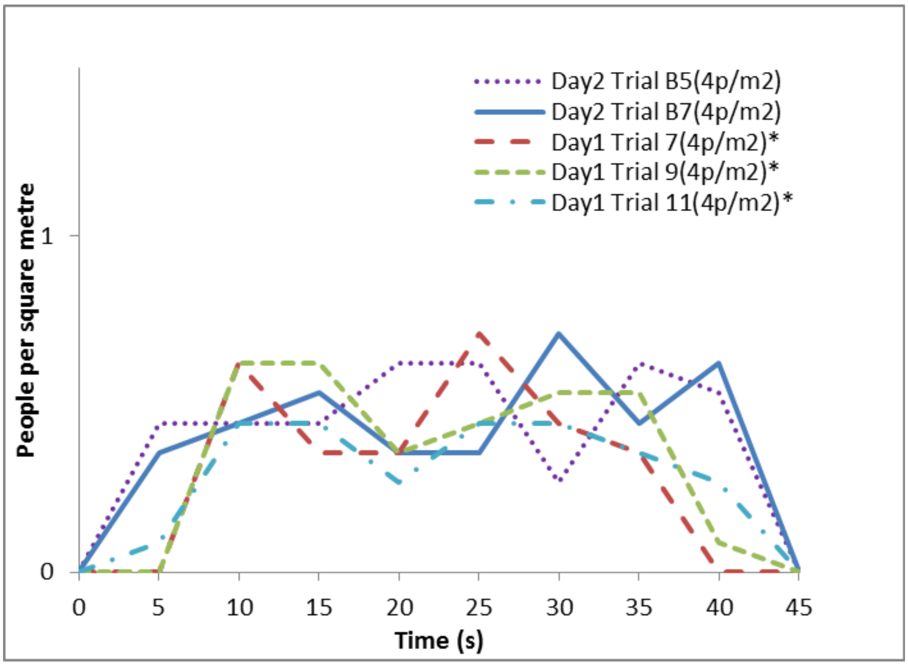


Figure 122: TS1 – BA density measured in 5 sec intervals for the five 6m NoBA 4 p/m² trials

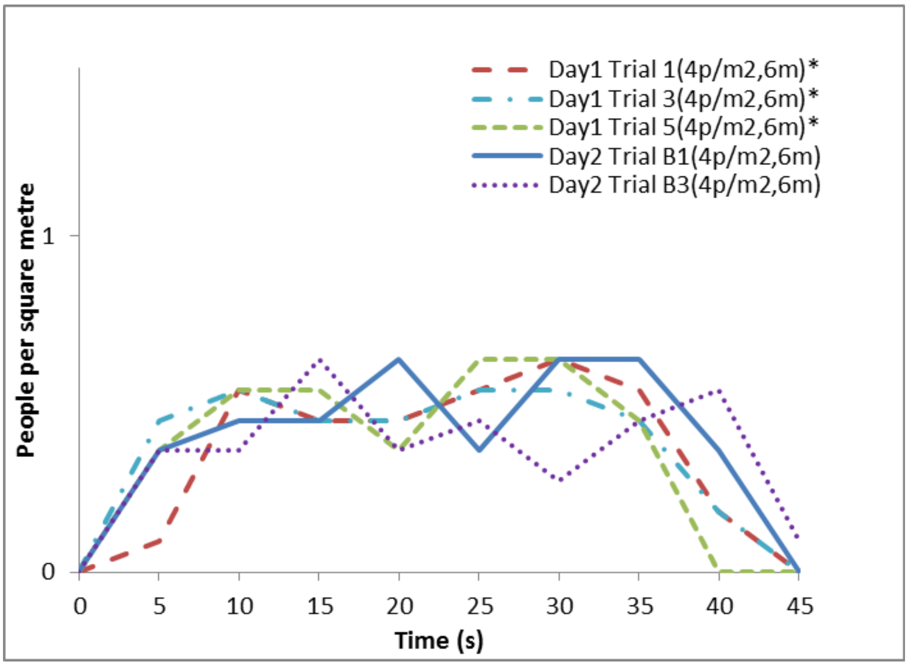


Figure 123: TS1 – BA density measured in 5 sec intervals for the five 6m BA 4 p/m^2 trials

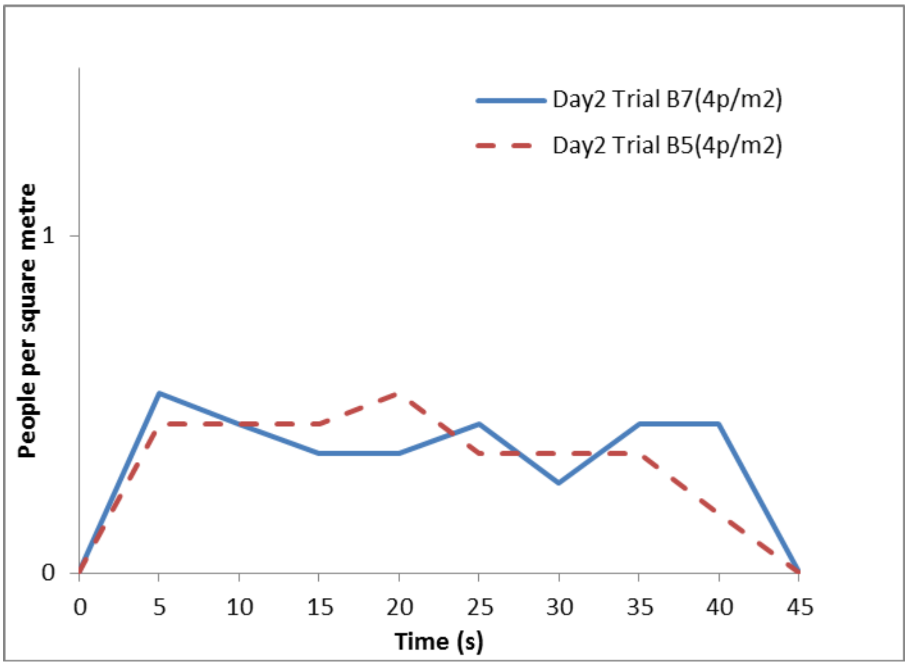


Figure 124: TS1 – BA density measured in 5 sec intervals for the two 3m NoBA 4 p/m^2 trials

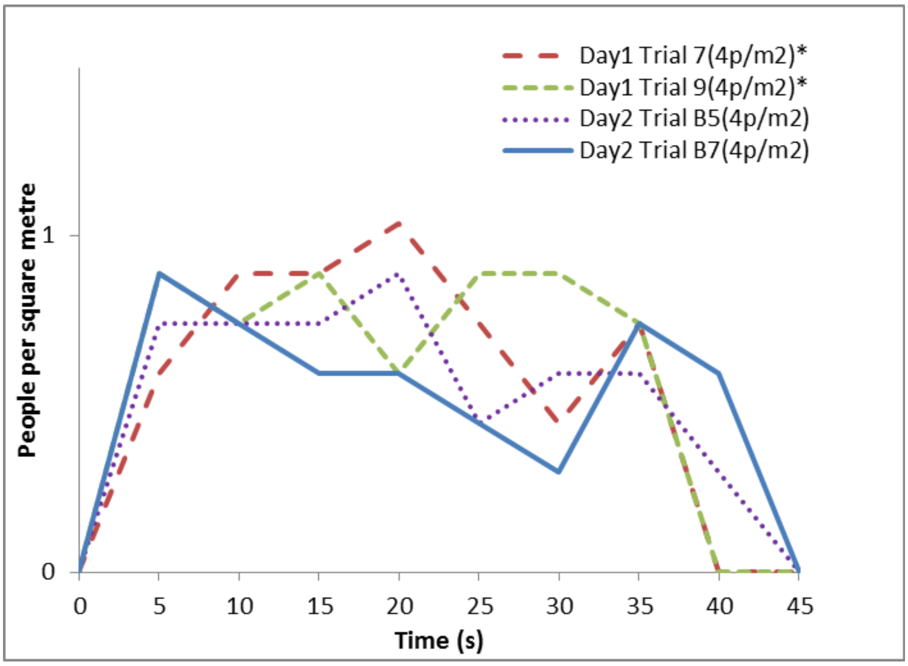


Figure 125: TS1 – BA density of region B, measured in 5 sec intervals for the four 3m NoBA 4 p/m^2 trials

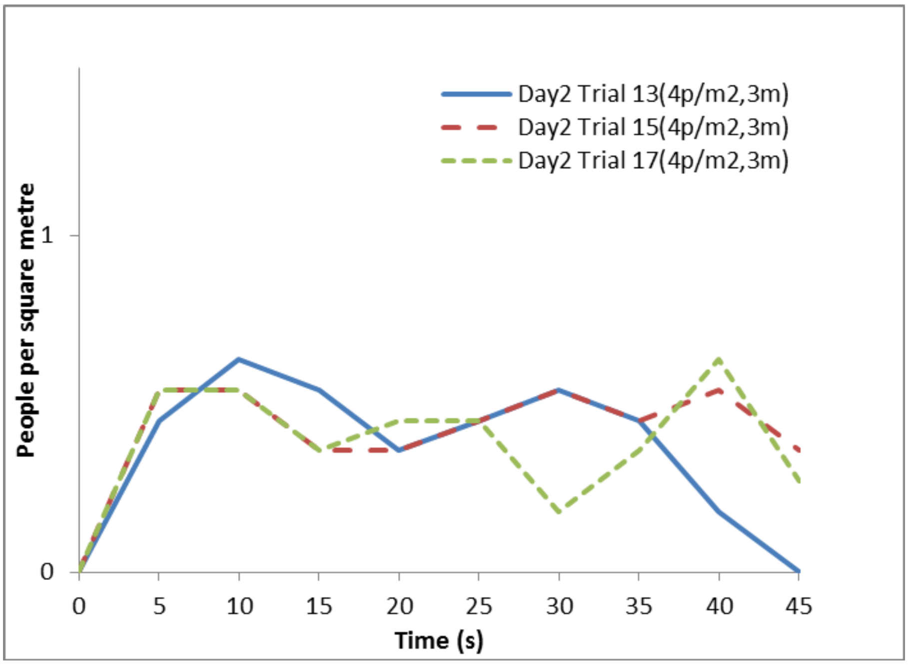


Figure 126: TS1 – BA density measured in 5 sec intervals for the three 3m BA 4 p/m^2 trials

17.2 TS1: 3p/m^2

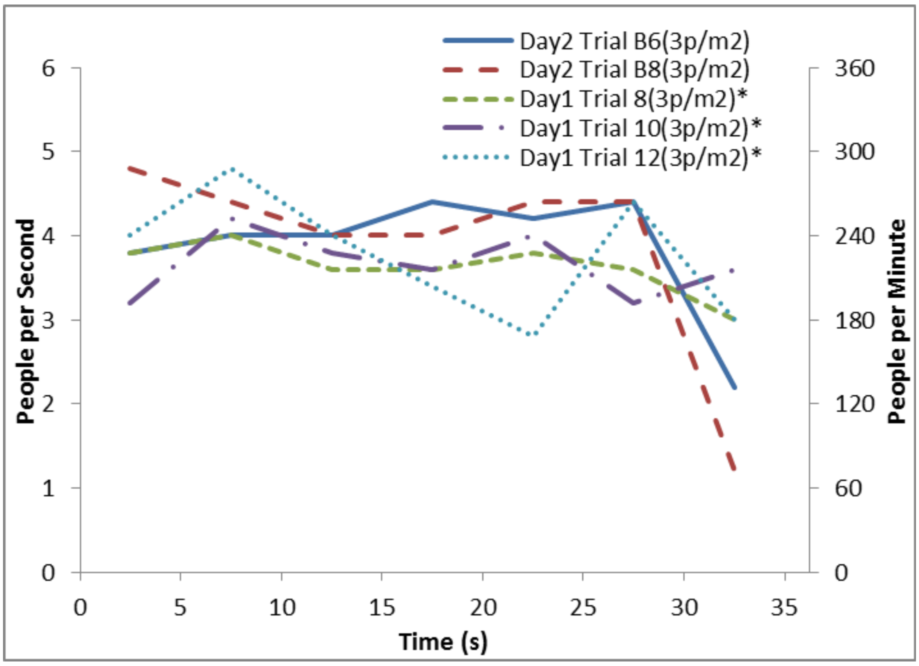


Figure 127: TS1 – Exit flow rate measured in 5 sec intervals for the five NoBA 3 p/m^2 trials

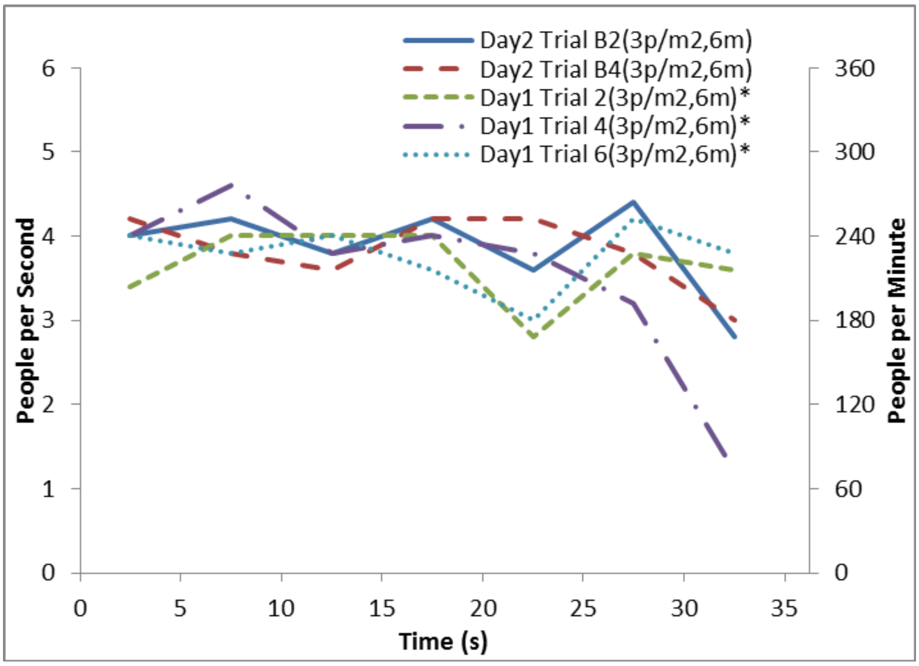


Figure 128: TS1 – Exit flow rate measured in 5 sec intervals for the five 6m BA 3 p/m^2 trials

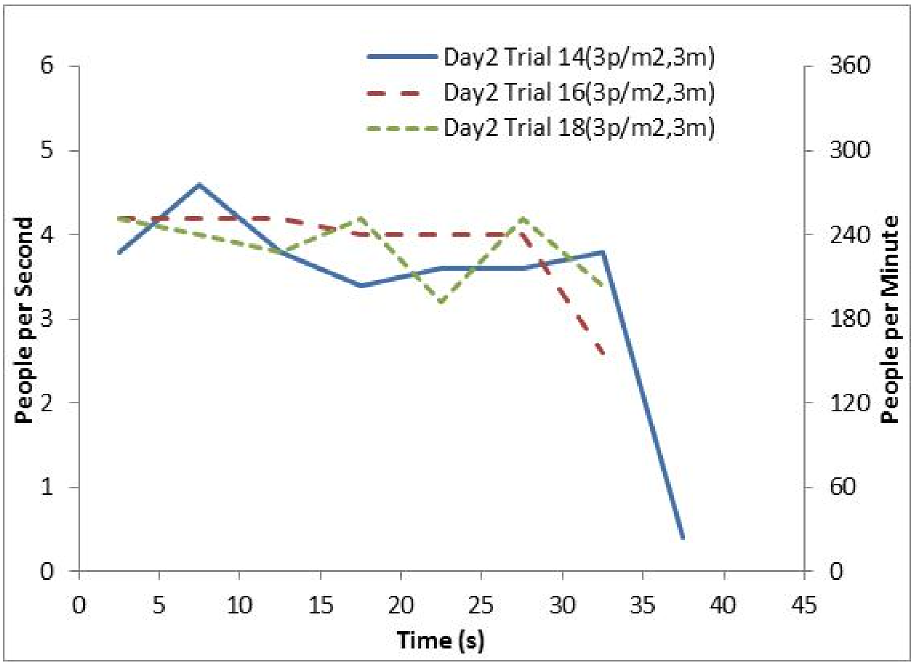


Figure 129: TS1 – Exit flow rate measured in 5 sec intervals for the three 3m BA 3 p/m^2 trials

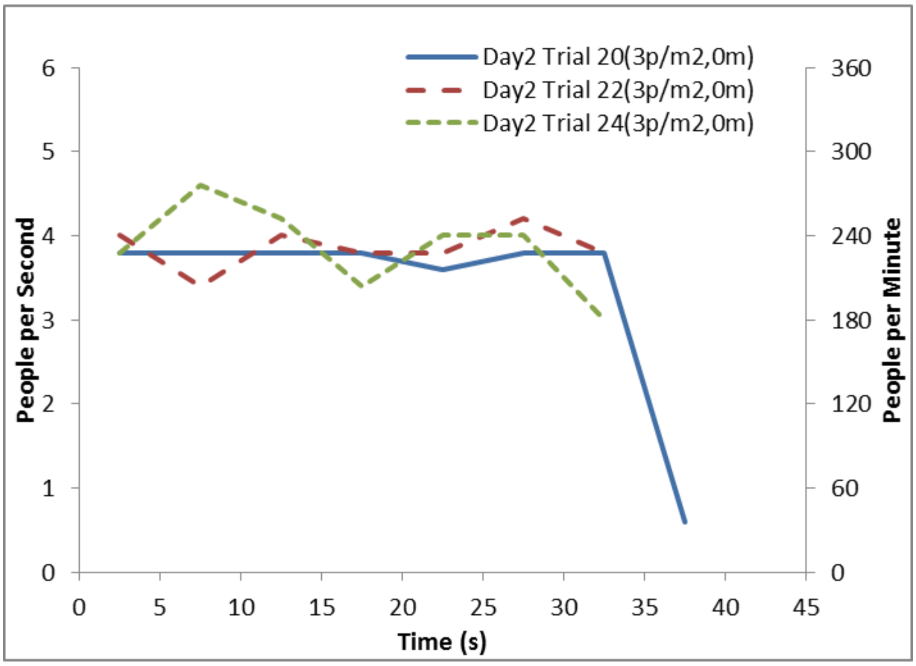


Figure 130: TS1 – Exit flow rate measured in 5 sec intervals for the three 0m BA 3 p/m^2 trials

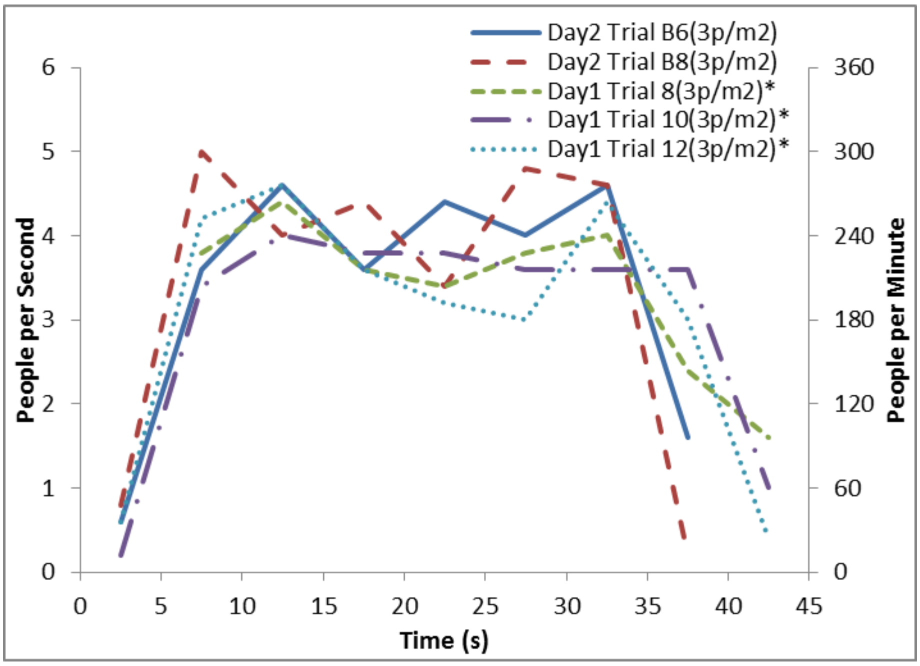


Figure 131: TS1 – BA flow rate measured in 5 sec intervals for the five 6m NoBA 3 p/m^2 trials

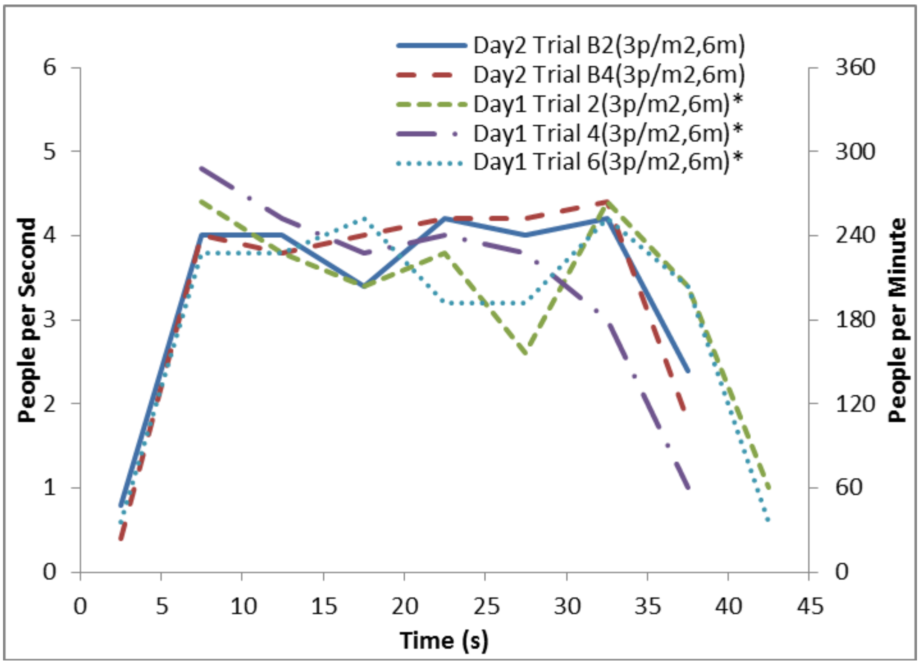


Figure 132: TS1 – BA flow rate measured in 5 sec intervals for the five 6m BA 3 p/m^2 trials

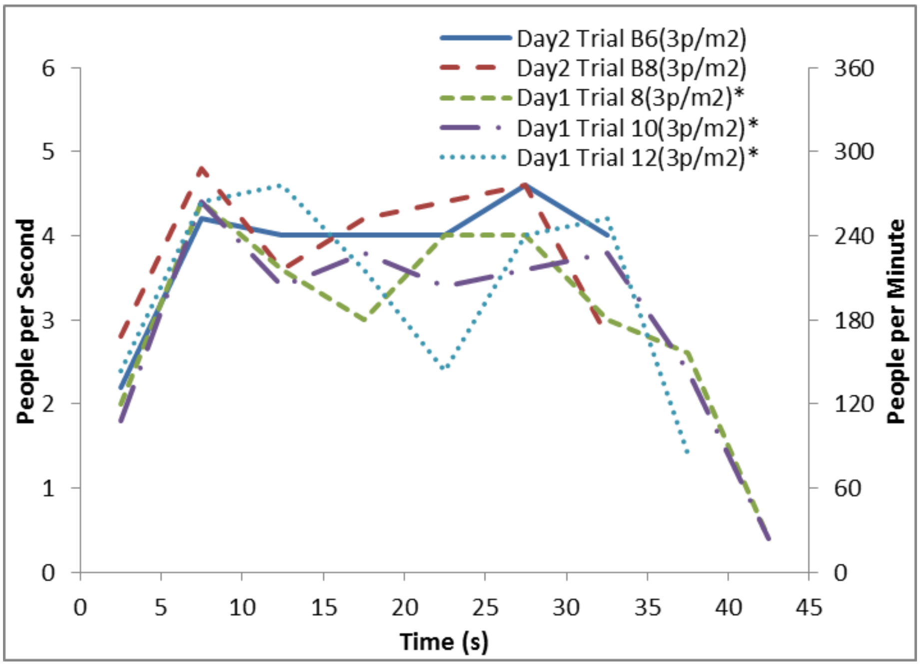


Figure 133: TS1 – BA flow rate measured in 5 sec intervals for the three 3m NoBA 3 p/m^2 trials

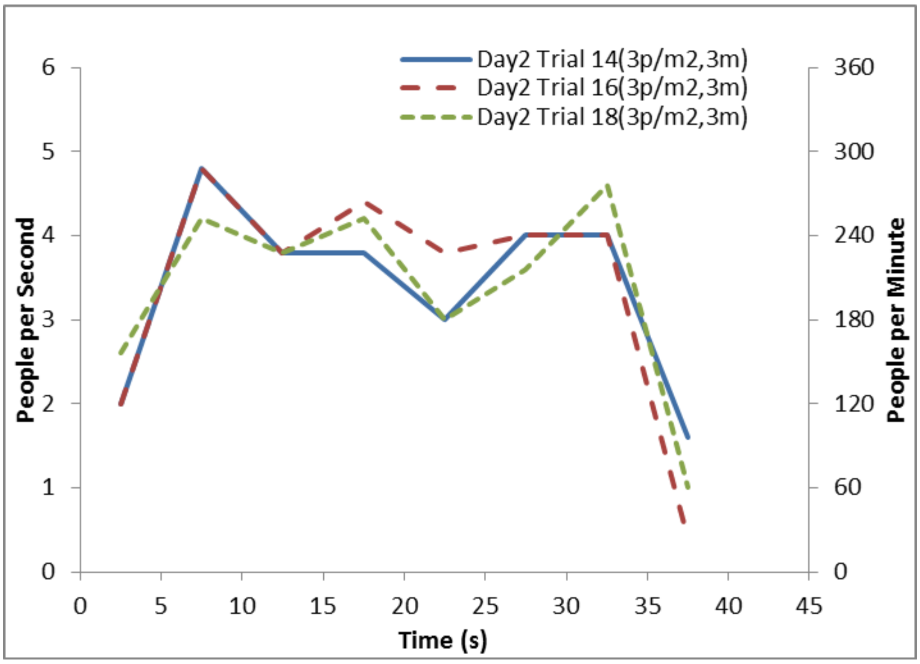


Figure 134: TS1 – BA flow rate measured in 5 sec intervals for the three 3m BA 3 p/m^2 trials

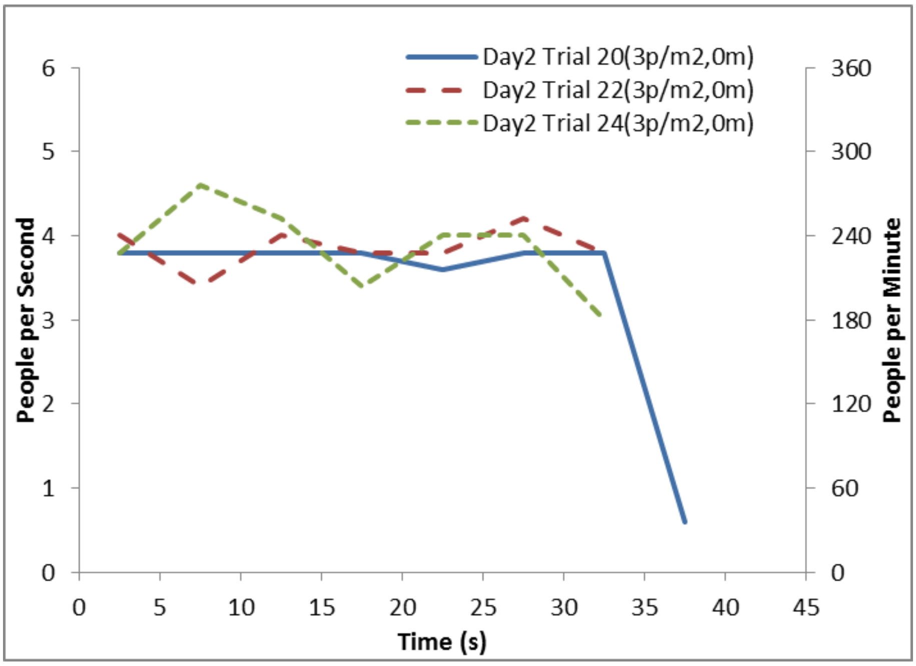


Figure 135: TS1 – BA flow rate measured in 5 sec intervals for the three 0m BA 3 p/m^2 trials

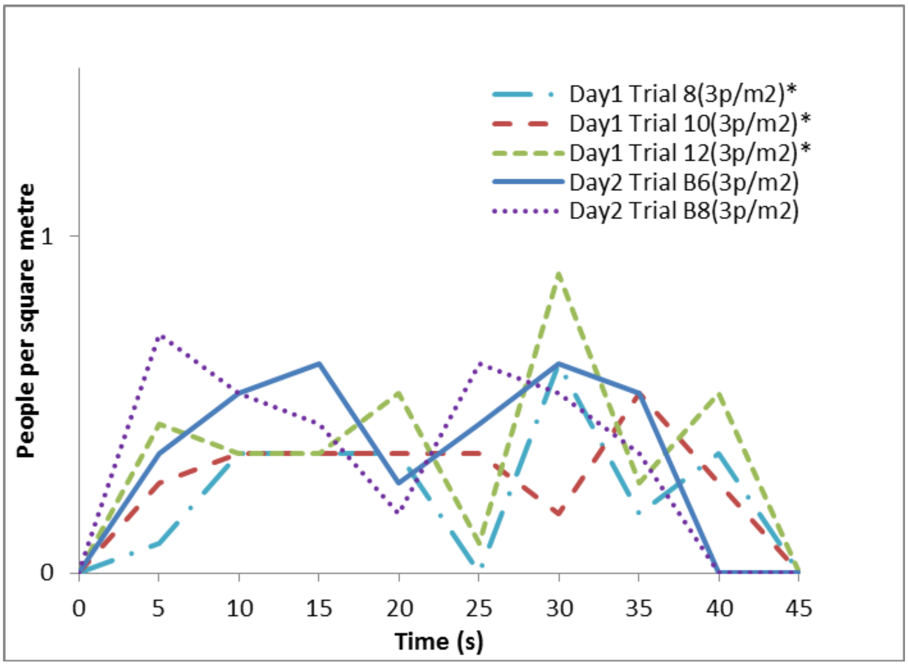


Figure 136: TS1 – BA density measured in 5 sec intervals for the five 6m NoBA 3 p/m^2 trials

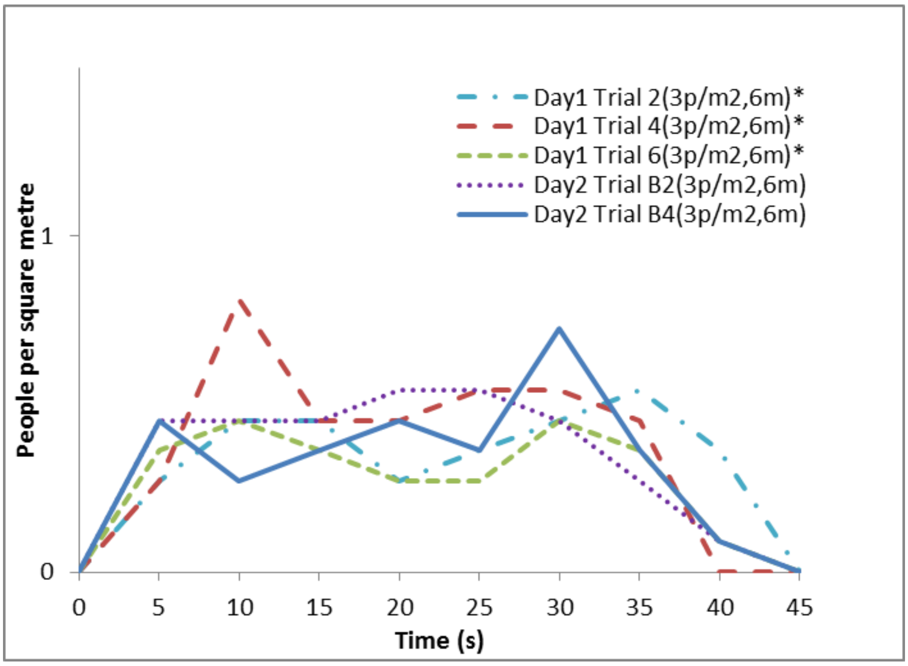


Figure 137: TS1 – BA density measured in 5 sec intervals for the five 6m BA 3 p/m^2 trials

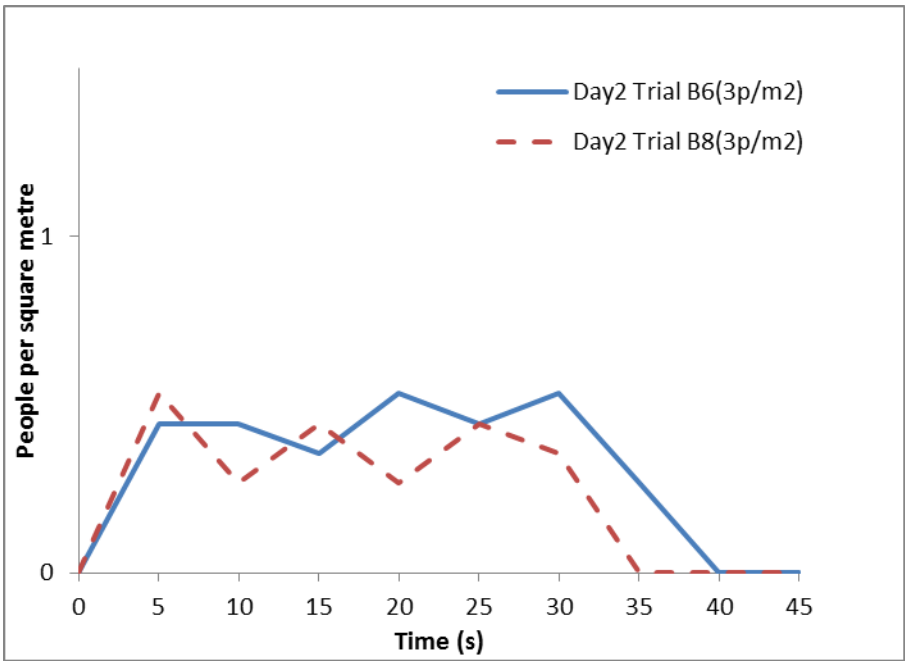


Figure 138: TS1 – BA density measured in 5 sec intervals for the two 3m NoBA 3 p/m^2 trials

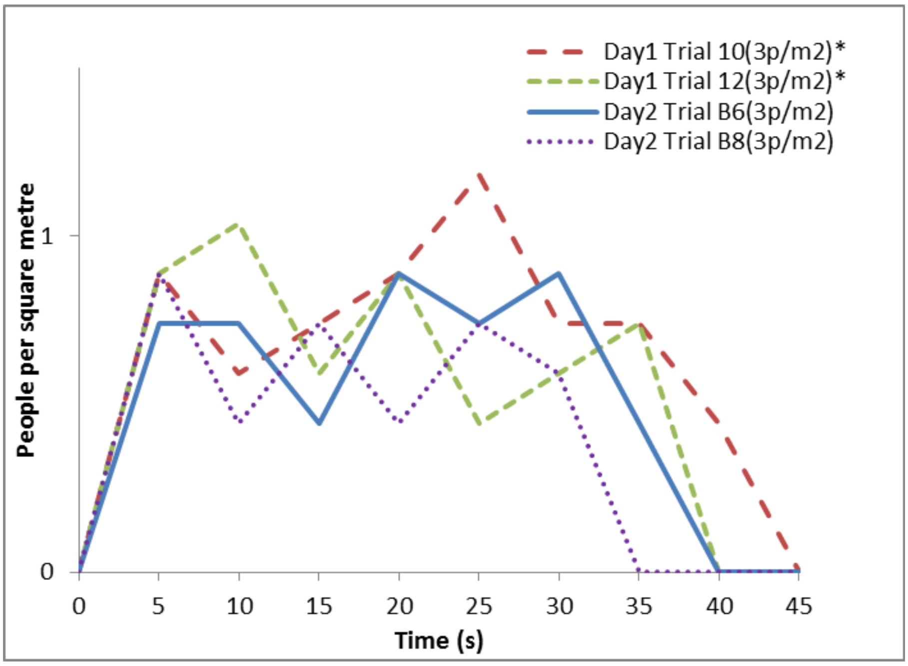


Figure 139: TS1 – BA density region B measured in 5 sec intervals for the four 3m NoBA 3 p/m^2 trials

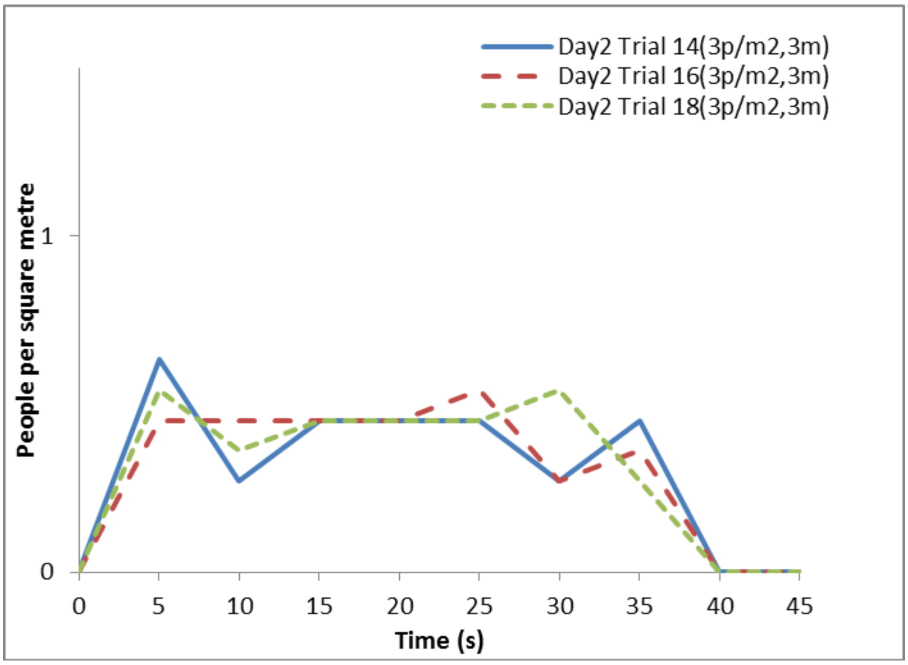


Figure 140: TS1 – BA density measured in 5 sec intervals for the three 3m BA 3 p/m^2 trials

17.3 TS2: 4p/m²

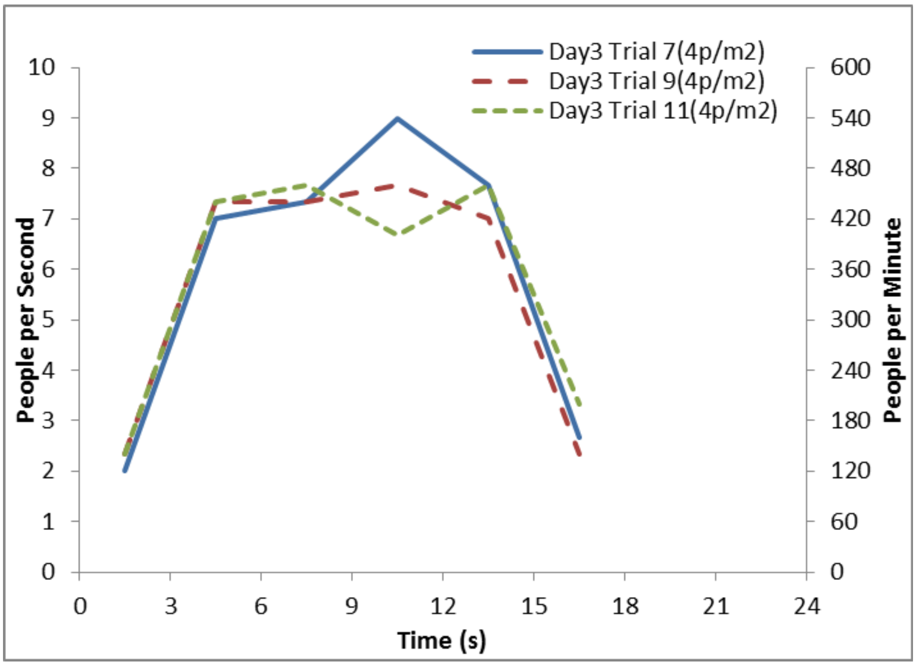


Figure 141: TS2 – BA flow rate measured in 3 sec intervals for the three NoBA 4 p/m^2 trials

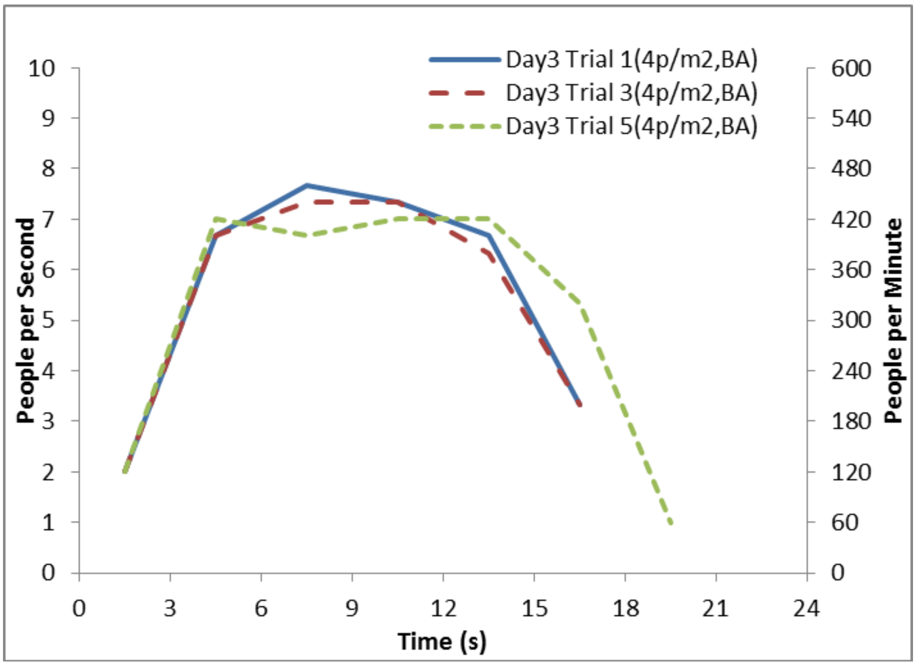


Figure 142: TS2 – BA flow rate measured in 3 sec intervals for the three BA 4 p/m^2 trials

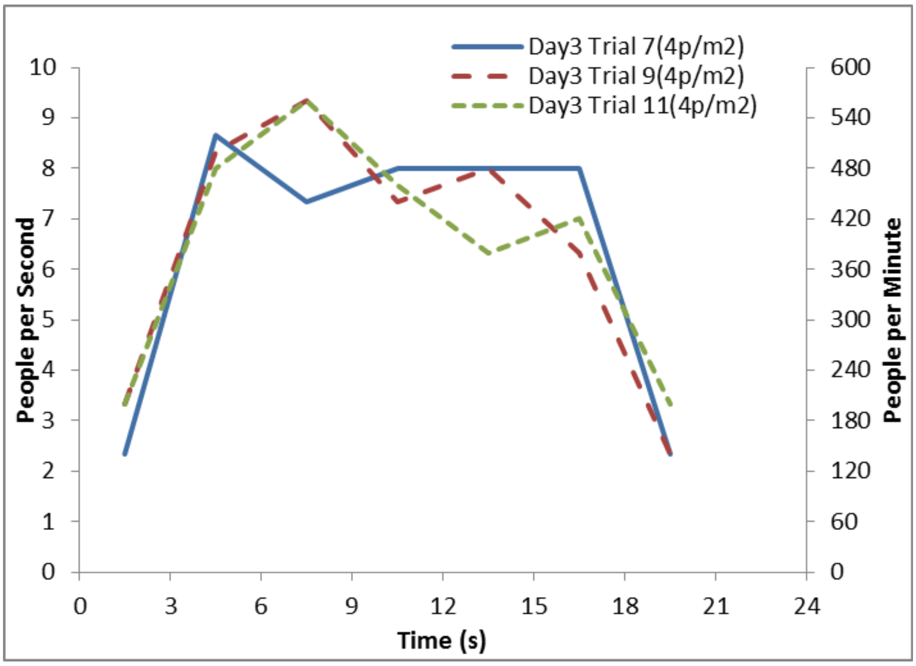


Figure 143: TS2 – Endline flow rate measured in 3 sec intervals for the three NoBA 4 p/m^2 trials

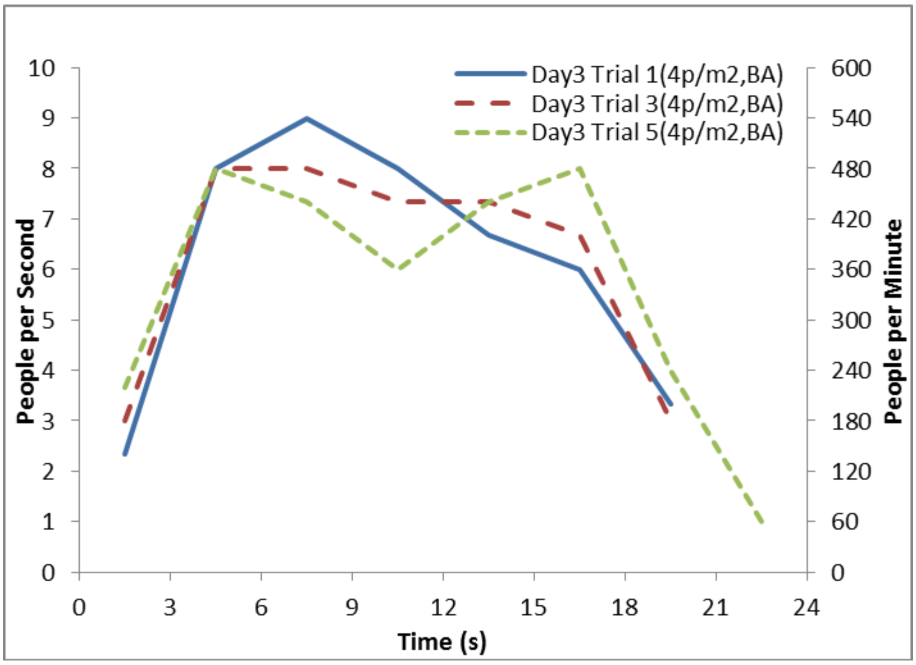


Figure 144: TS2 – Endline flow rate measured in 3 sec intervals for the three BA 4 p/m^2 trials

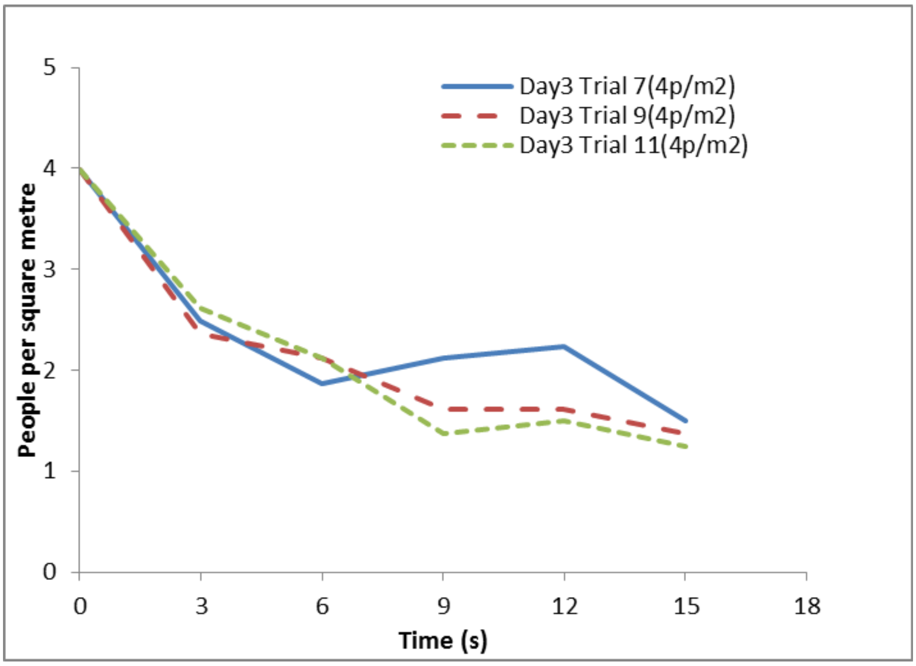


Figure 145: TS2 – BA density measured in 3 sec intervals for the three NoBA 4 p/m^2 trials

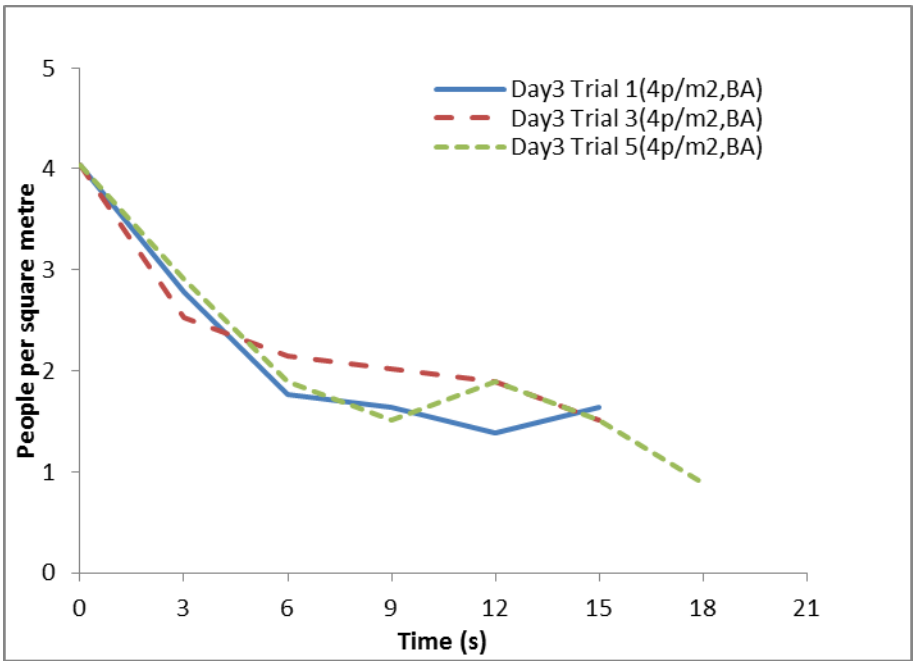


Figure 146: TS2 – BA density measured in 3 sec intervals for the three BA 4 p/m^2 trials

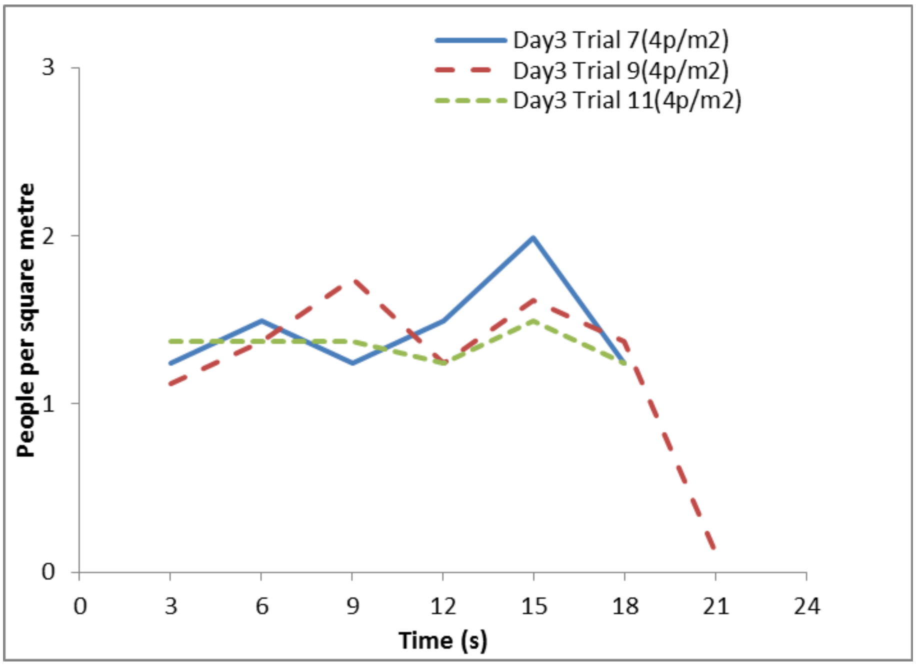


Figure 147: TS2 – Endline density measured in 3 sec intervals for the three NoBA 4 p/m^2 trials

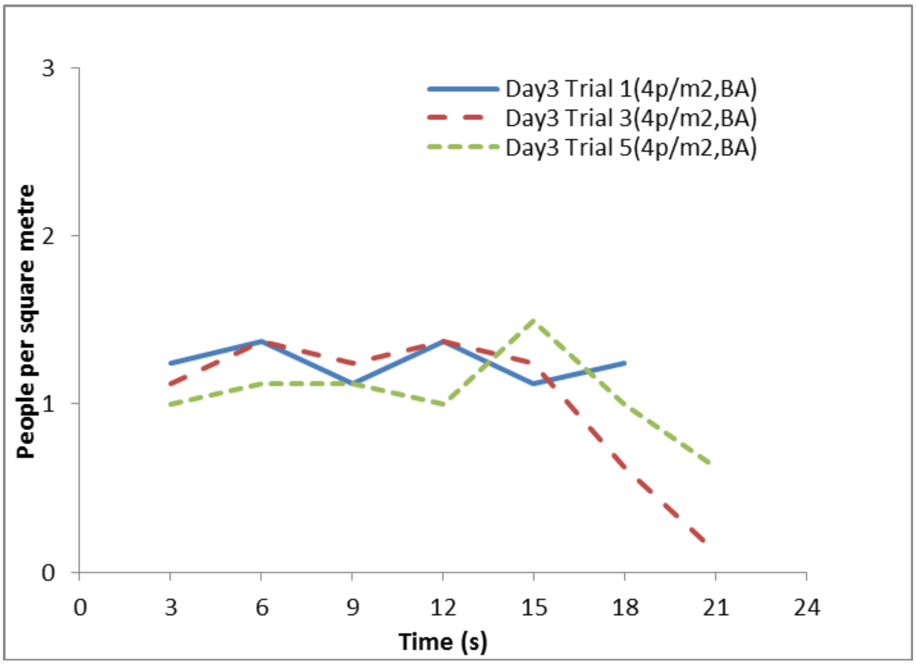


Figure 148: TS2 – Endline density measured in 3 sec intervals for the three BA 4 p/m^2 trials

17.4 TS2: 3p/m²

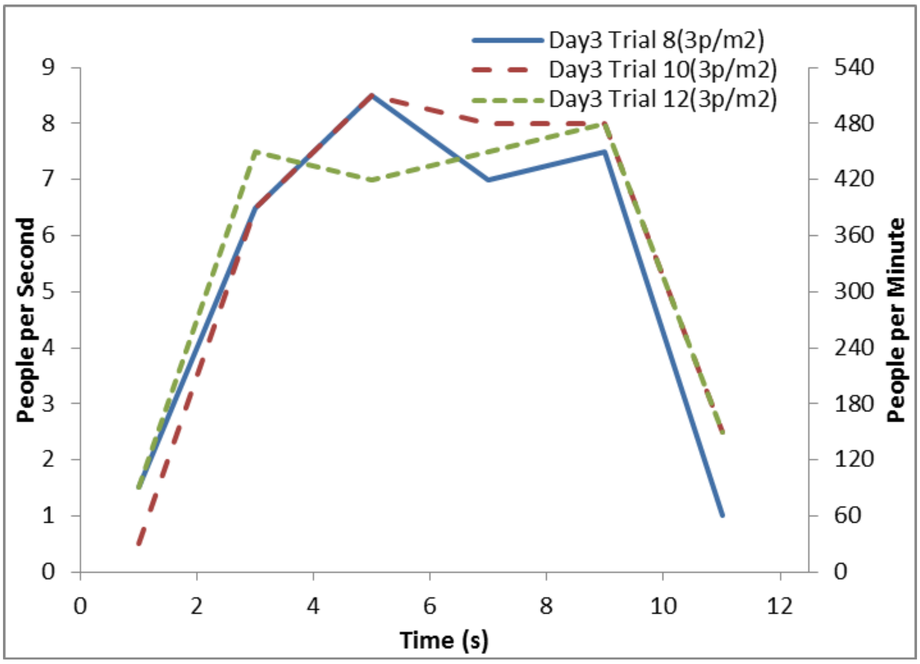


Figure 149: TS2 – BA flow rate measured in 2 sec intervals for the three NoBA 3 p/m^2 trials

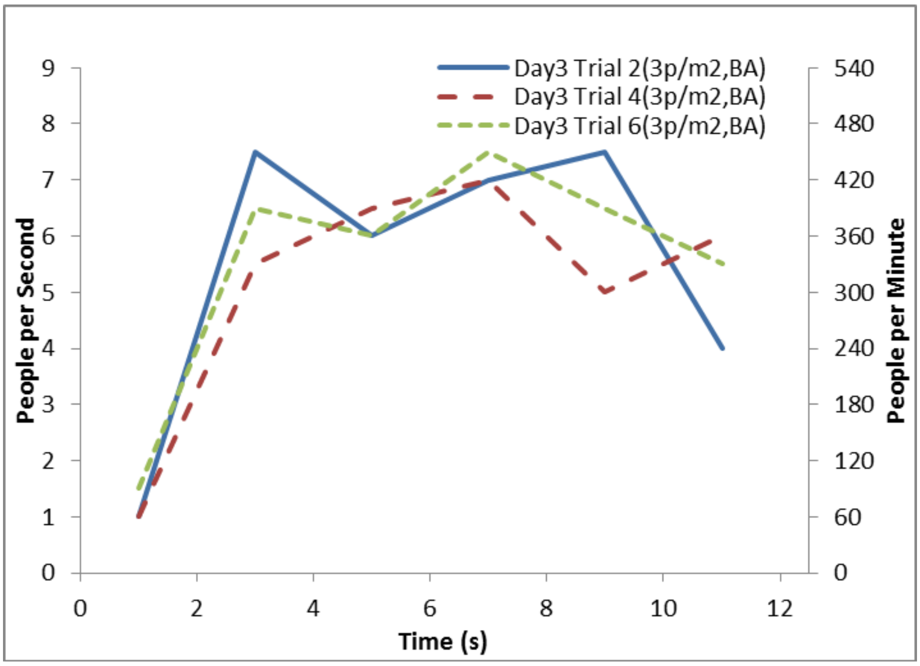


Figure 150: TS2 – BA flow rate measured in 2 sec intervals for the three BA 3 p/m^2 trials

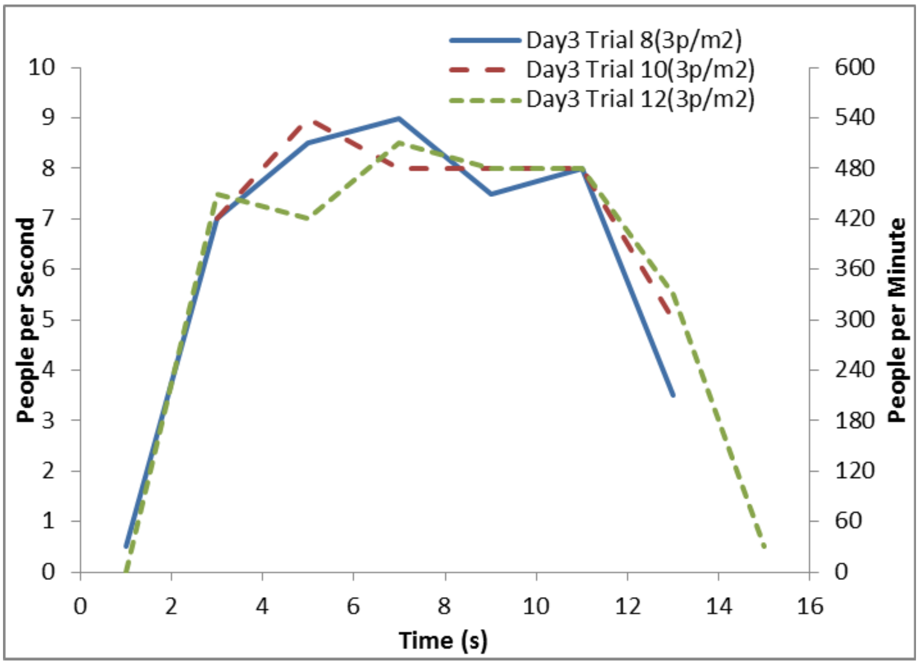


Figure 151: TS2 – Endline flow rate measured in 2 sec intervals for the three NoBA 3 p/m^2 trials

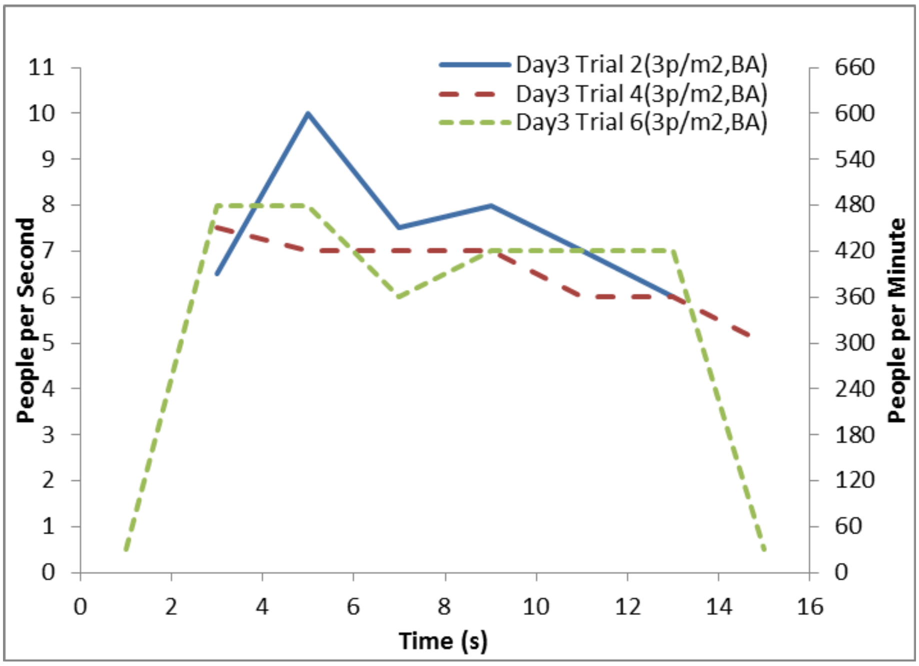


Figure 152: TS2 – Endline flow rate measured in 2 sec intervals for the three BA 3 p/m^2 trials

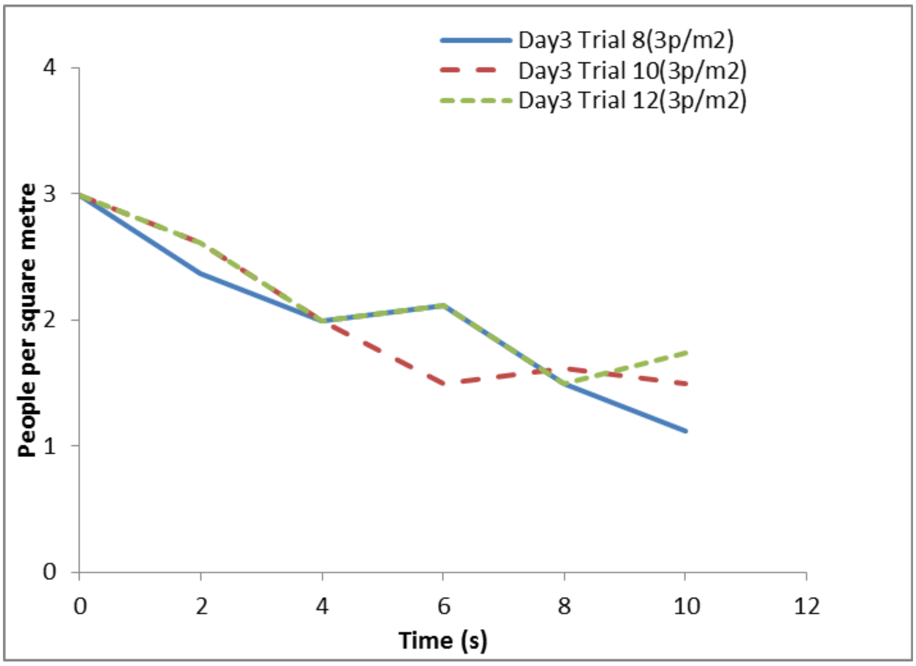


Figure 153: TS2 – BA density measured in 2 sec intervals for the three NoBA 3 p/m^2 trials

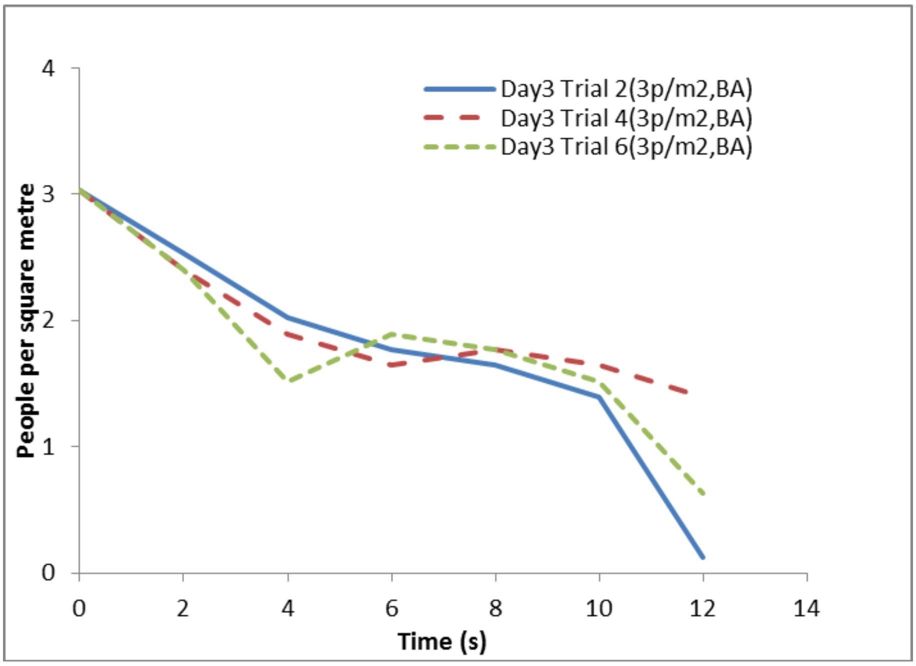


Figure 154: TS2 – BA density measured in 2 sec intervals for the three BA 3 p/m^2 trials

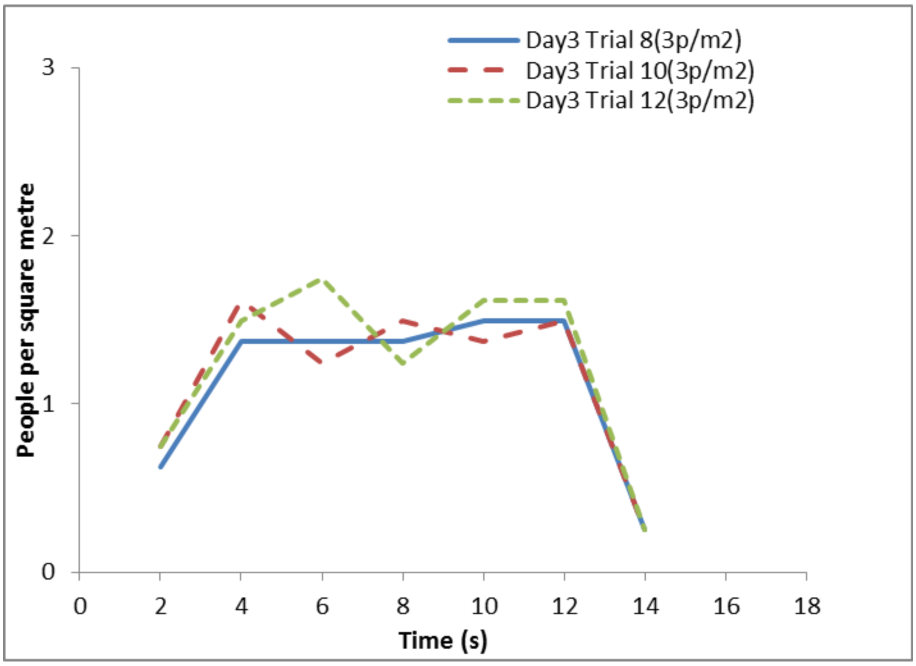


Figure 155: TS2 – Endline density measured in 2 sec intervals for the three NoBA 3 p/m^2 trials

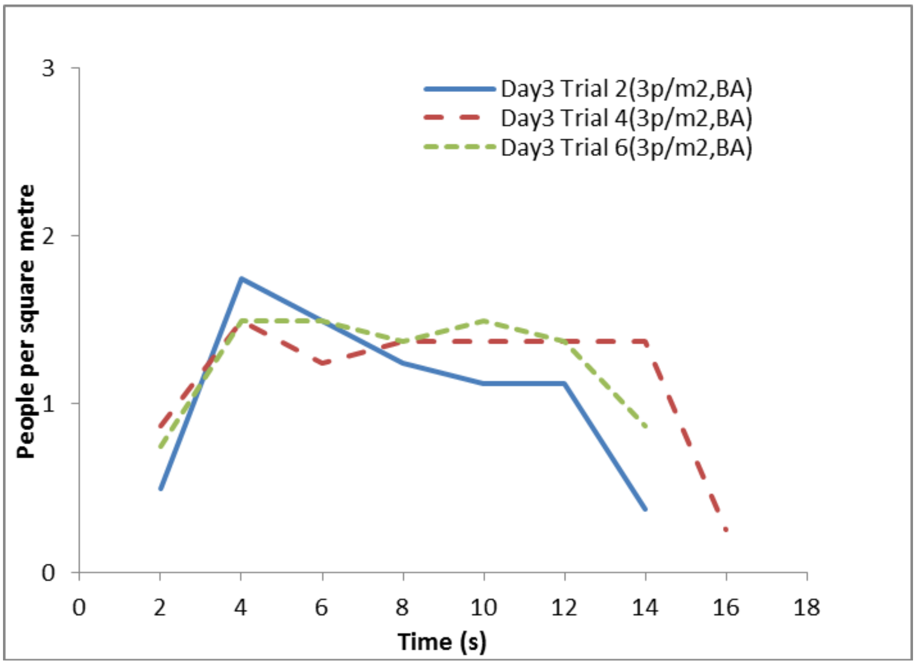


Figure 156: TS2 – Endline density measured in 2 sec intervals for the three BA 3 p/m^2 trials

17.5 TS2 with CW: 4p/m²

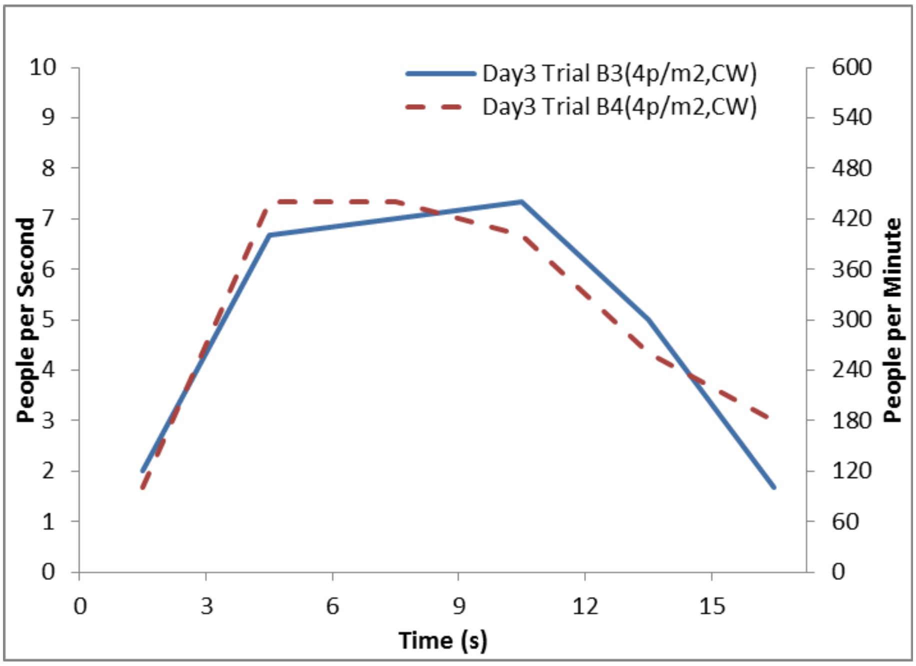


Figure 157: TS2 with CW – BA flow rate measured in 3 sec intervals for the two NoBA 4 p/m^2 trials

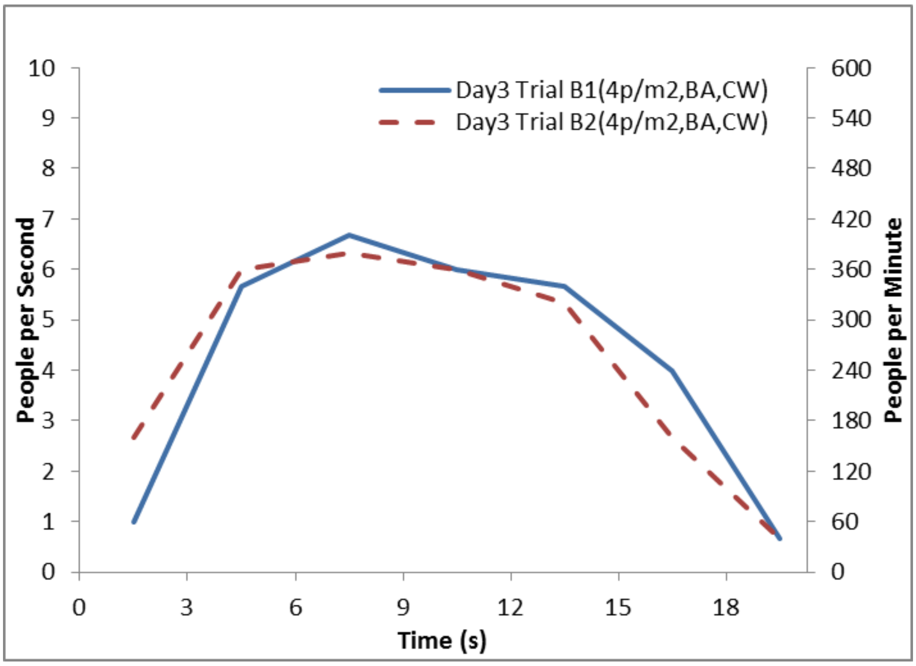


Figure 158: TS2 with CW – BA flow rate measured in 3 sec intervals for the two BA 4 p/m^2 trials

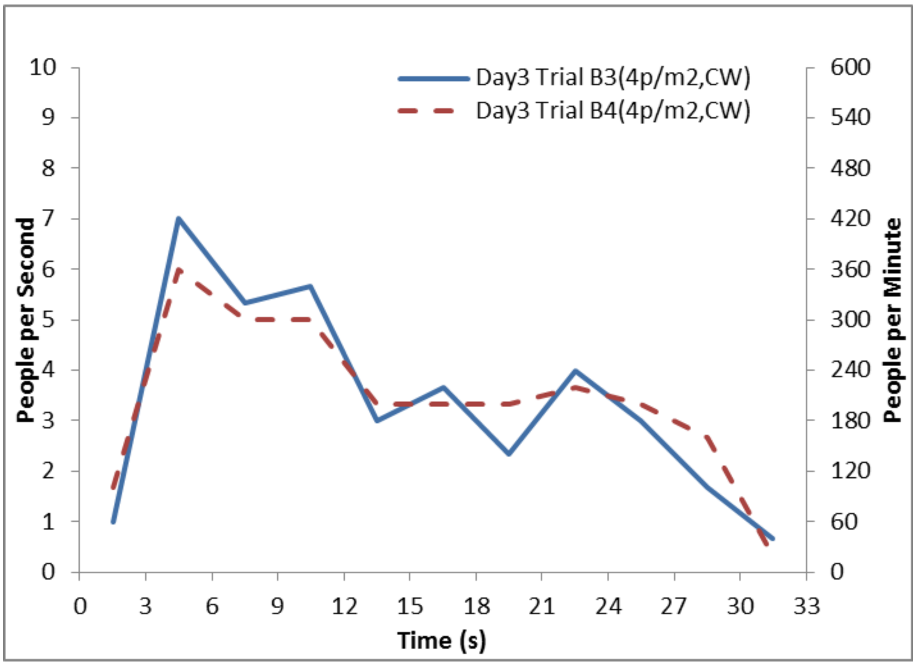


Figure 159: TS2 with CW – Endline flow rate measured in 3 sec intervals for the two NoBA 4 p/m² trials

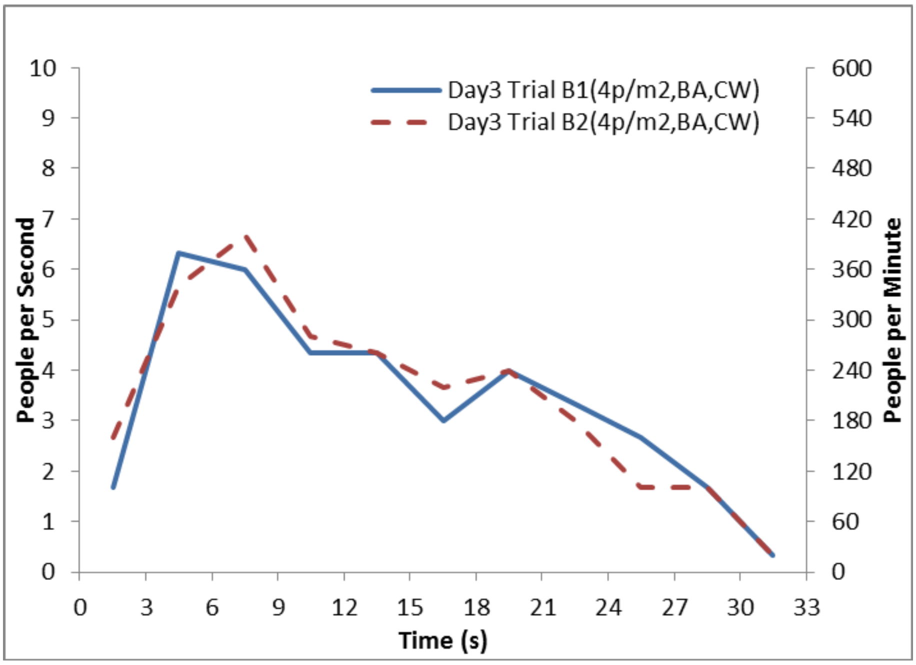


Figure 160: TS2 with CW – Endline flow rate measured in 3 sec intervals for the two BA 4 p/m² trials

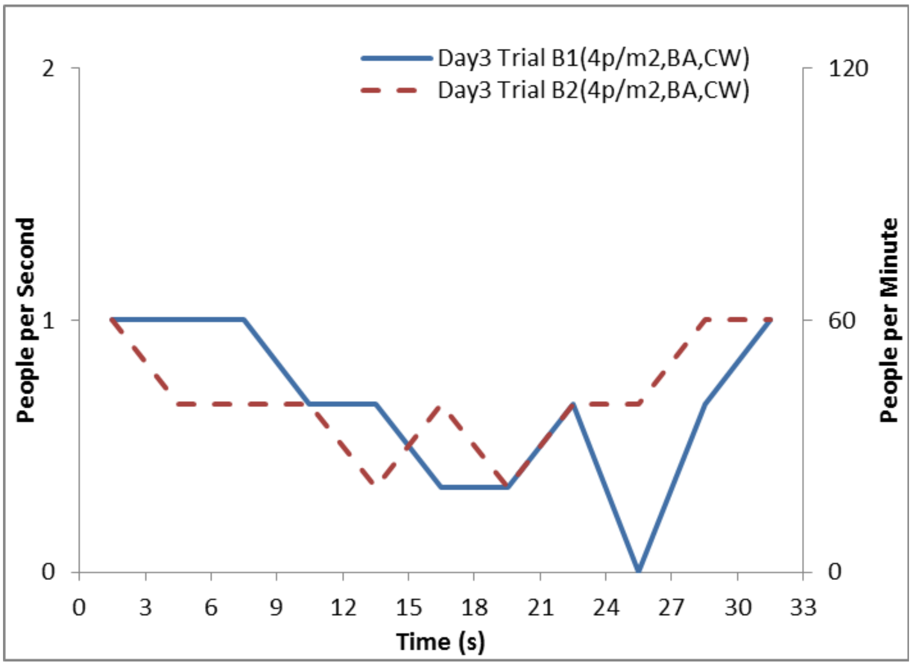


Figure 161: TS2 with CW – Cross Walker Line 1 flow rate measured in 3 sec intervals for the two BA 4 p/m^2 trials

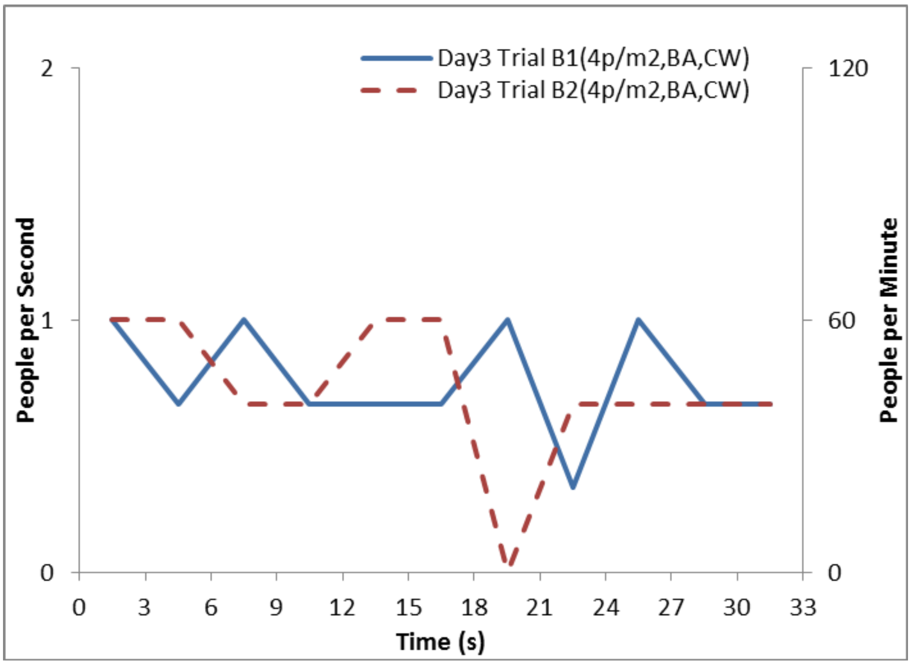


Figure 162: TS2 with CW – Cross Walker Line 2 flow rate measured in 3 sec intervals for the two BA 4 p/m^2 trials

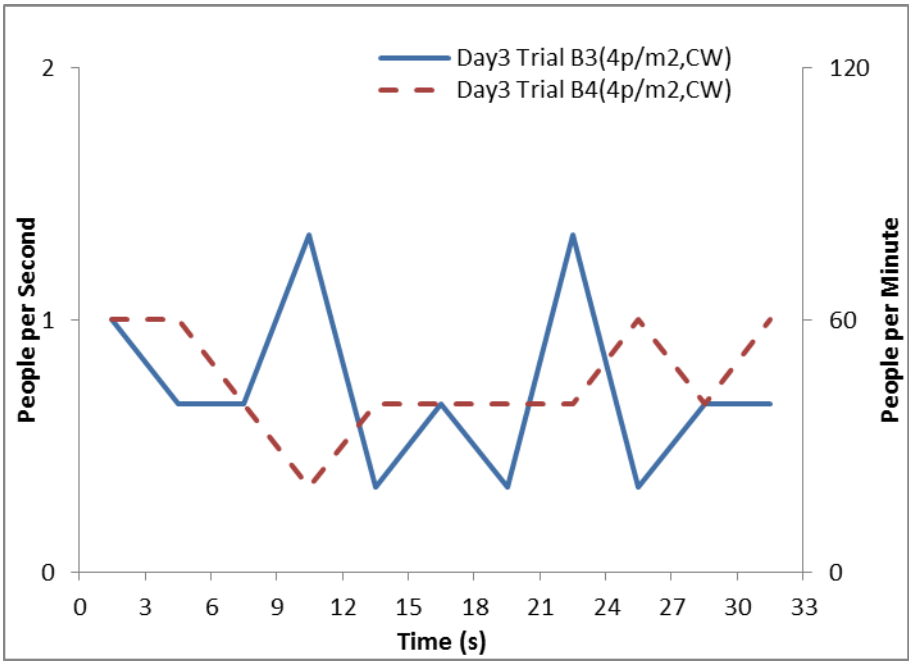


Figure 163: TS2 with CW – Cross Walker Line 1 flow rate measured in 3 sec intervals for the two NoBA 4 p/m^2 trials

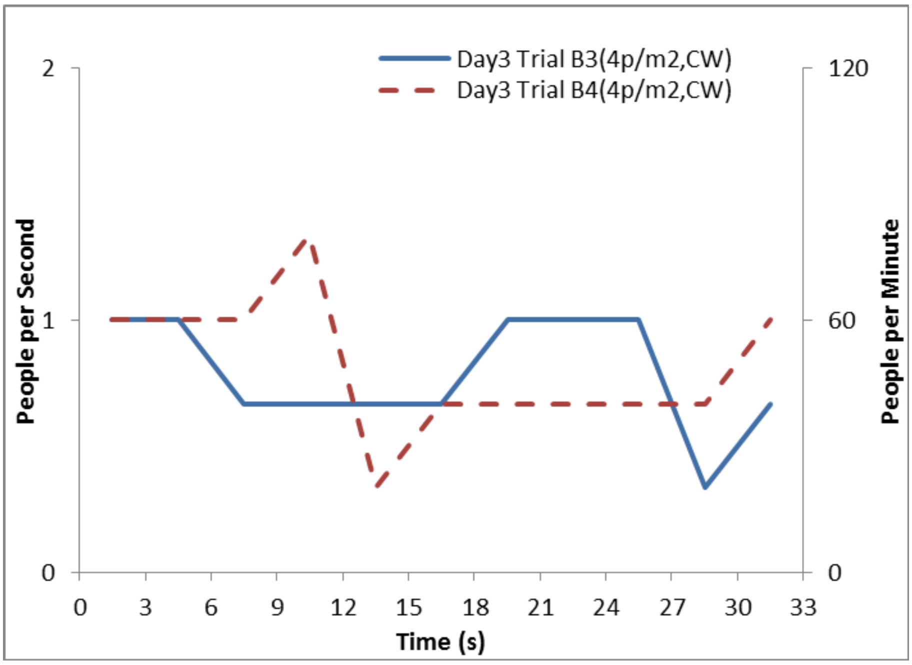


Figure 164: TS2 with CW – Cross Walker Line 2 flow rate measured in 3 sec intervals for the two NoBA 4 p/m^2 trials

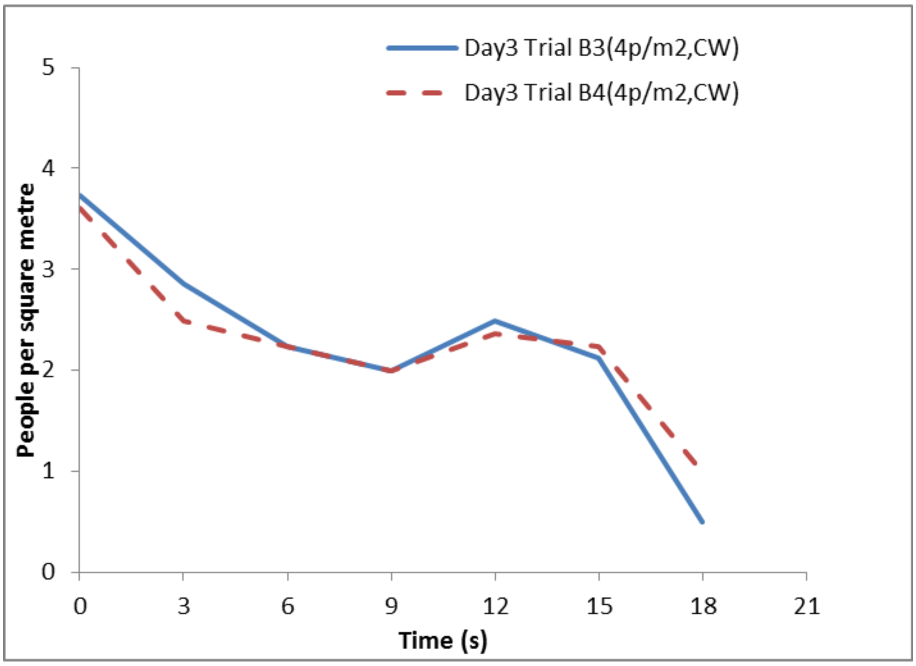


Figure 165: TS2 with CW – BA density measured in 3 sec intervals for the two NoBA 4 p/m^2 trials

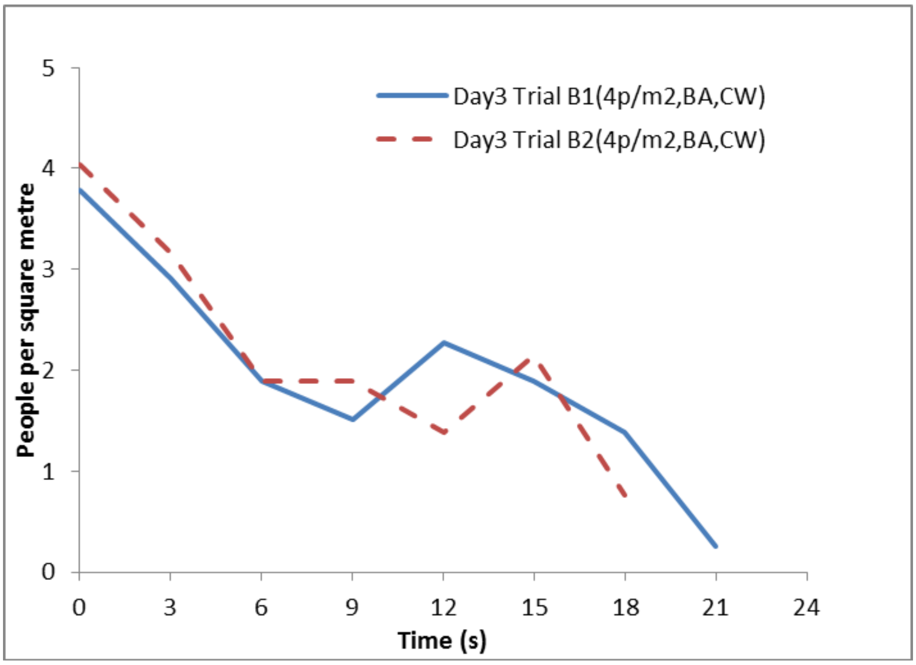


Figure 166: TS2 with CW – BA density measured in 3 sec intervals for the two BA 4 p/m^2 trials

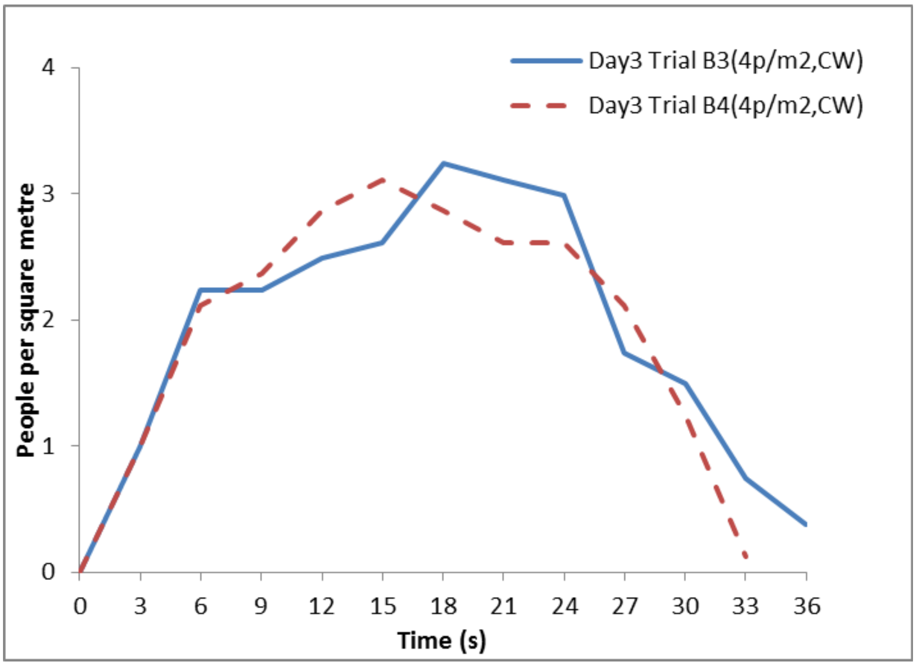


Figure 167: TS2 with CW – Endline density measured in 3 sec intervals for the two NoBA 4 p/m^2 trials

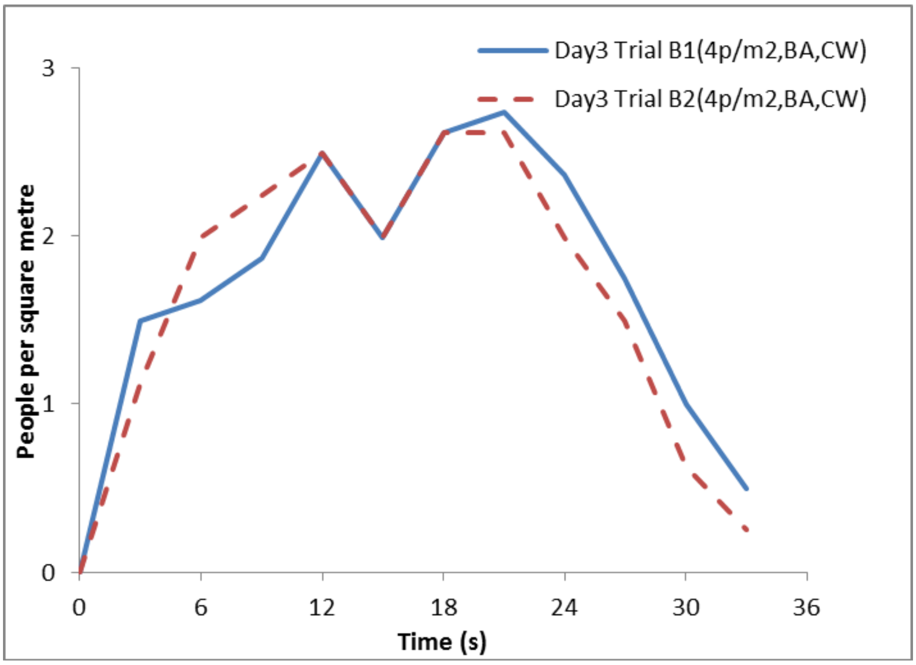


Figure 168: TS2 with CW – Endline density measured in 3 sec intervals for the two BA 4 p/m^2 trials

17.6 TS2 with CW: $3p/m^2$

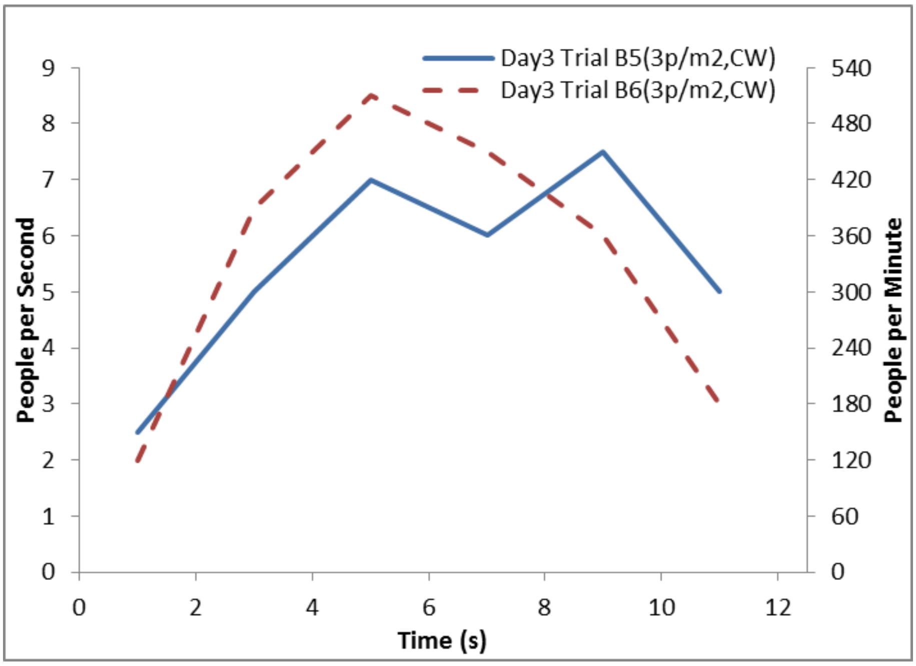


Figure 169: TS2 with CW – BA flow rate measured in 2 sec intervals for the two NoBA 3 p/m^2 trials

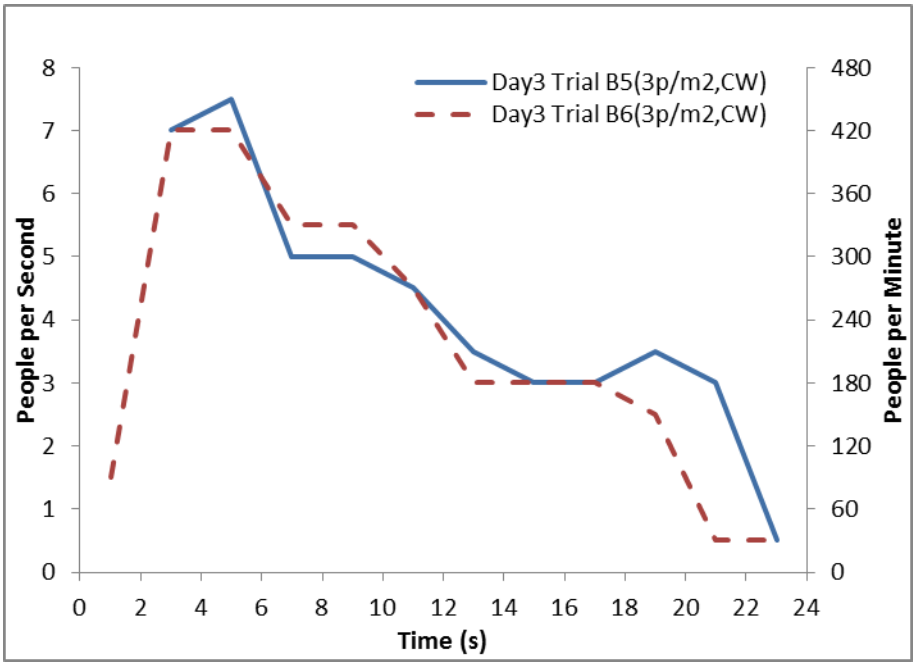


Figure 170: TS2 with CW – Endline flow rate measured in 2 sec intervals for the two NoBA 3 p/m^2 trials

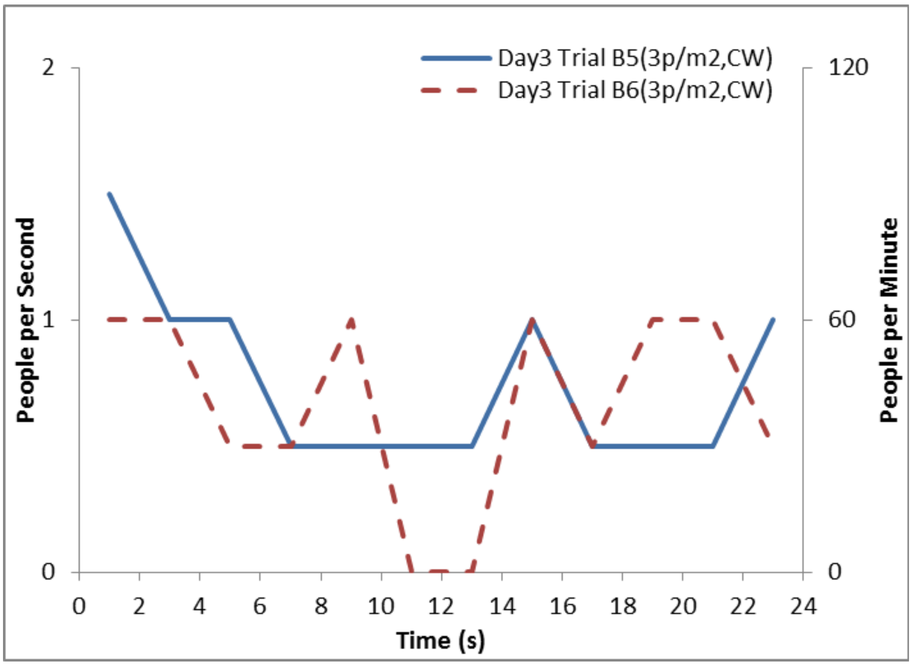


Figure 171: TS2 with CW – Cross Walker Line 1 flow rate measured in 2 sec intervals for the two NoBA 4 p/m^2 trials

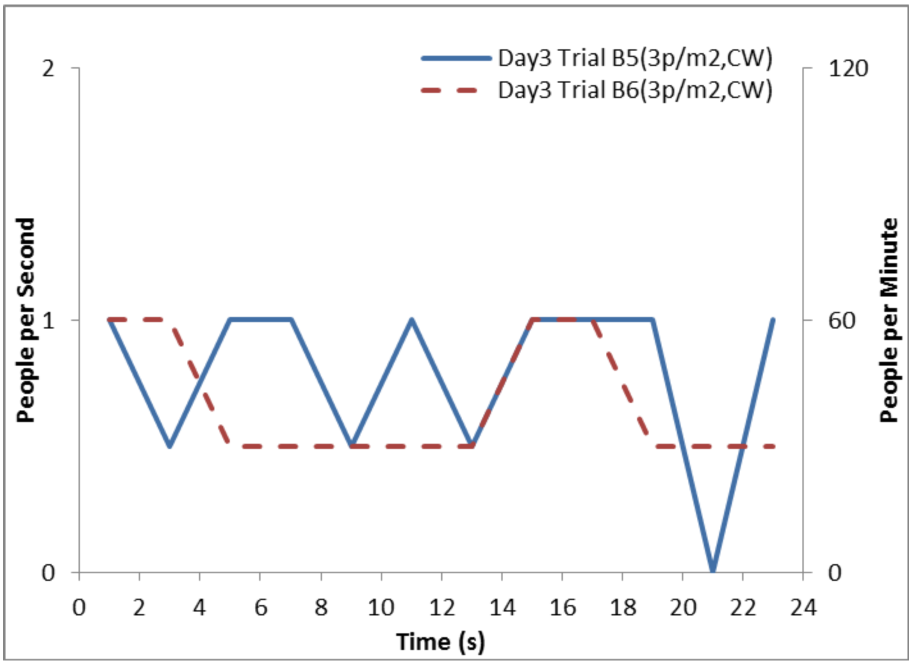


Figure 172: TS2 with CW – Cross Walker Line 2 flow rate measured in 2 sec intervals for the two NoBA 4 p/m^2 trials

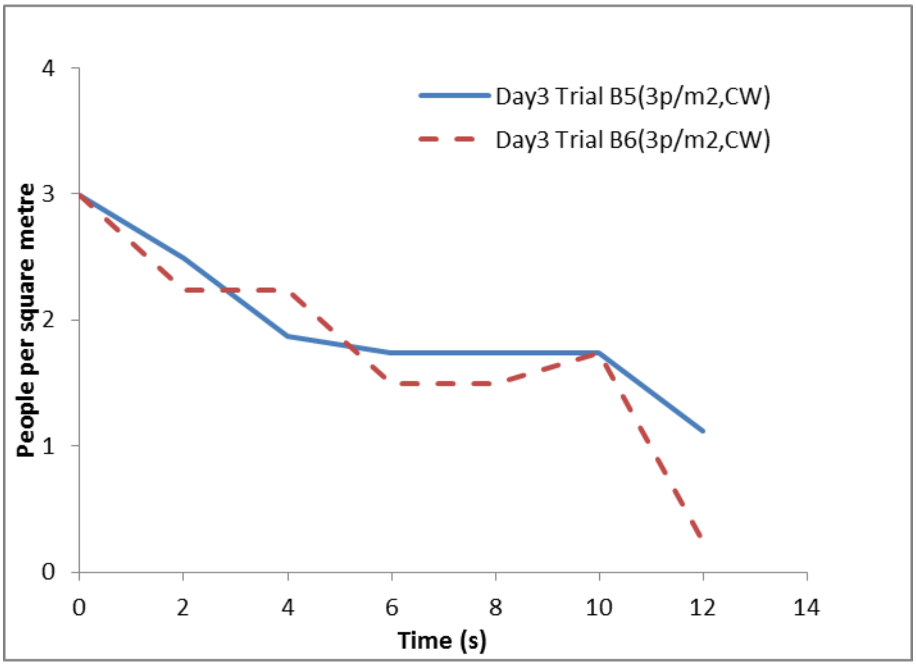


Figure 173: TS2 with CW – BA density measured in 2 sec intervals for the two NoBA 3 p/m^2 trials

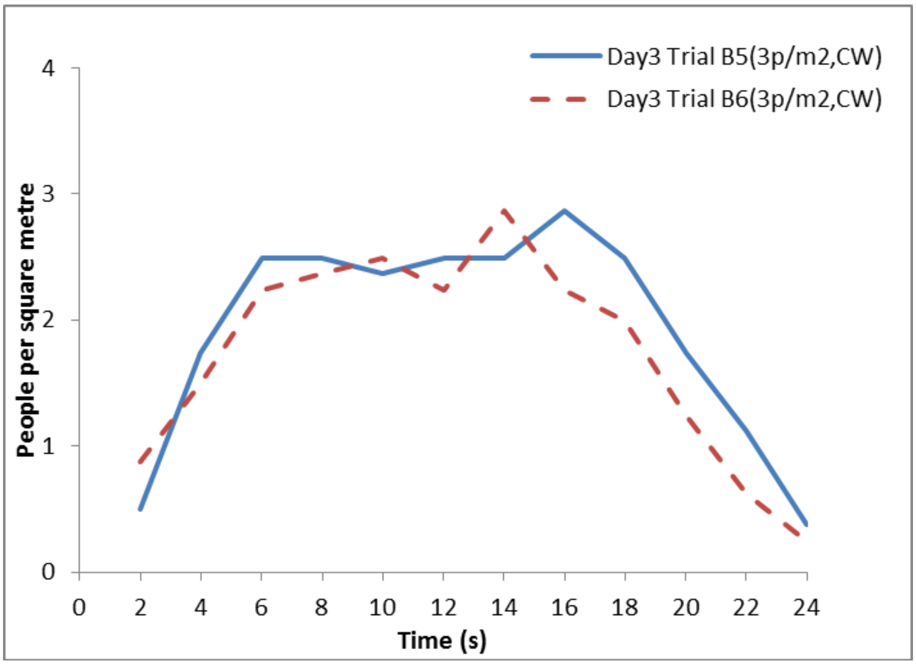


Figure 174: TS2 with CW – Endline density measured in 2 sec intervals for the two NoBA 3 p/m^2 trials

18 ANNEX J: KEY FINDINGS

The key findings from each of the result sections have been compiled into a single overview table (see Table 130). This should enable a simple qualitative comparison to be made between the observations made. These findings are then discussed in more detail in the rest of this section.

Table 130: Overview of key findings.

Scenario	Findings
4_BA_6m_TS1	• The core trials with the 6m bollards present produced average flow rates at the exit that were 0.6% higher than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 6m from the exit compared to the case in which there was no bollard array present.** • Participants disproportionately favoured the central gaps of the 6m BA. In the NoBA trial, participants were more evenly distributed over the three central gaps then in the BA trial; however, there was no appreciable difference in the use of the extreme gaps in either trial. • There is no appreciable difference in the flow rates at the bollard line produced during the NoBA and 6m BA trials at 4p/m^2, with the latter producing 0.1% higher flow rates. The results produced do not demonstrate a clear numerical difference between the conditions examined. **The results suggest that there is no appreciable difference in the average flow rate 6m from the exit that would be produced if a bollard array was located at this position compared to the case in which there was no bollard array present.** • **The densities produced at the bollard array during the 4_BA_6m_TS1 trials and the 4_NoBA_TS1 trials are similar. However, both are lower than the initial population density of 4p/m^2 in the holding area due to the diffusion of the population.**
4_BA_3m_TS1	• There is little difference between the flow rates at the exit produced in the NoBA and 3m BA trials at 4p/m^2, with the 3m bollard trials producing 0.6% lower flow rates. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 3m from the exit compared to the case in which there was no bollard array present.** • At a distance of 3m from the exit, the central gaps were used by a disproportionate number of participants whether or not the BA was present. However, slightly more people tend to use the gaps in the extremity if the BA is present at 3m compared to if the BA was not present. • There is a small difference between the flow rates produced at the BA line during the NoBA and 3m BA trials given that the average 3m BA trial falls below the entire range of the NoBA trials, with 3m BA producing 2.1% lower flow rates. Although suggestive, the results produced do not demonstrate a clear numerical difference

	between the conditions examined. • The densities produced at the bollard array during the 4_BA_3m_TS1 trials were 15.4% greater than during the 4_NoBA_TS1. However, both are lower than the initial population density of 4p/m^2 in the holding area.
4_BA_0m_TS1	• On average the flow rate at the exit with a 0m bollard present was some 1% lower than the case without bollards. This reduction in flow rate is less than the natural variation in the no bollard case but greater than the variation in the 0m bollard case. Therefore it is difficult to determine whether or not the presence of the bollard resulted in an appreciable reduction in flow rate. **However, the reduction in flow rate due to the presence of the bollard was not as great as would be expected due to the reduction in exit width**. The better than expected flow rate with the 0m bollard present is due to a 9% improvement in the unit flow rate for the exit with the bollard present. The reduction in flow rate due to the reduction in exit width was partially compensated by the improvement in unit flow rate. In is not known whether this improvement in exit unit flow rate will also be evident in situations with passengers carrying luggage.
3_BA_6m_TS1	• The core 6m BA trials with an initial population density of 3p/m^2 produced average exit point flow rates 1.1% lower than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 6m from the exit compared to the case in which there was no bollard array present.** • The core 6m BA trials with an initial population density of 3p/m^2 produced average exit point flow rates 1.1% lower than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 6m from the exit compared to the case in which there was no bollard array present.** • The central gap was disproportionately used in the 6m 3p/m^2 trial, as in the 4 p/m^2 trial (see Section 4.2.1.6). The gaps in the extremities were used by more people with the BA present then without the BA. This is different to the 4 p/m^2 trial and suggests that in the lower density case, the participants are more able to spread out and make greater use of the BA. • The presence of the bollard array did not unduly influence the average densities produced across the 6m bollard line, there seems to be a difference in the manner in which these densities were distributed across the BA line. It is not clear whether this difference is due to methodological factors or flow dynamics.
3_BA_3m_TS1	• The core 3m BA trials with an initial population density of 3p/m^2 produced average exit point flow rates 0.8% higher than the NoBA trials. **The results suggest that there is no appreciable difference in the average exit flow rate that would be produced if a bollard array was located 3m from the exit compared to the case in which there was no bollard array present.** • There is little difference between the average flow rates produced at the bollard array for the NoBA and 3m BA trials, with the 3m BA

	trials producing 1.5% higher flow rates. The results suggest that there is not a pronounced difference in the average flow rate at the line of the 3m BA that would be produced if a bollard array was located 3m from the exit compared to the case in which there was no bollard array present. • At a distance of 3m from the exit, the central gap was disproportionately used by the participants in the 3p/m^2 case, similar to that observed in the 4p/m^2 case. More participants made use of the extreme gaps when the BA was at 6m compared to 3m, again similar to the behaviour observed in the 4 p/m^2 case. • The presence of the bollard array did not unduly influence the densities produced at the 3m bollard line; however, as is to be expected, the densities are considerable smaller than the initial 3p/m^2 in the holding area.
3_BA_0m_TS1	• On average the flow rate at the exit with a 0m bollard present was some 0.2% lower than the case without bollards. This reduction in flow rate is smaller than the variation in the 0m bollard and the NoBA cases. **Therefore, it is unlikely that the presence of the bollard resulted in an appreciable reduction in flow rate.** However, the reduction in flow rate due to the presence of the bollard was not as great as would be expected given the reduction in exit width. The better than expected flow rate produced with the 0m bollard present is due to a 10.2% improvement in the unit flow rate for the exit with the bollard present. The reduction in flow rate due to the reduction in exit width was partially compensated by the improvement in unit flow rate. It is unknown whether this improvement in exit unit flow rate will also occur in situations with more passengers carrying luggage.
4_BA_TS2	• The presence of the BA produced a flow rate at the BA location that was on average 8.1% lower than the NoBA trials. This reduction in flow rate is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate. However, the reduction in flow rate due to the presence of the BA was not as great as would be expected due to the reduction in effective width of the path. The better than expected flow rate produced with the BA present is due to a 15% improvement in the unit flow rate for the exit path with the BA present. The reduction in flow rate due to the reduction in path width was partially compensated by the improvement in unit flow rate. It is unknown whether this improvement in unit flow rate will occur in situations with more passengers carrying luggage. • **:** In both the BA and NoBA trials, the average density at the BA line was approximately half the initial packing density; i.e. 2.0 p/m^2 rather than the 4.0 p/m^2. • The BA trials produced Endline flow rates that were 7.5% lower than the equivalent NoBA flow rates. These are comparable with the differences evident at the BA line. The flow rate at the Endline is greater than that at the BA as the population is able to more easily travel at their desired speed due to greater diffusion of the population (leading to a reduction in density) once the BA has been passed. • In the BA and NoBA trials, the average density at the Endline was 1.19 p/m^2 and 1.44 p/m^2, a significant reduction from the initial 4.0 p/m^2. This result is consistent with expectation, where pedestrians are

	assumed to have more opportunity to disperse after crossing the BA line during actual egress from a station. The density at the Endline for the BA case was less than that for the NoBA case due to the reduction in flow rate at the BA line.
4_BA_TS2_CW	**The presence of the cross-flow had a greater impact on the flow rate at the BA line than the presence of the BA itself.** A number of comparisons can be made with the previous results collected to demonstrate the impact of the crosswalk flow. Compared to a flow without a BA or cross-walking flow: • The introduction of the BA reduces the flow rate at the BA line by **8%** • The introduction of the cross-walkers reduces the flow rate at the BA line by **14%** • The introduction of the BA /cross-walkers reduces the flow rate at the BA line by **27%** Thus the cross-walkers have almost twice the impact of the BA on flow rate at the BA line and the combined impact of the BA and cross-walkers has more than three times the impact of the BA on the BA flow rate. Compared to the flow with BA present: • The introduction of the cross-walkers reduces the flow rate at the BA line by **21%** This can then be compared to the flow when the cross-walkers are present: • The introduction of the BA reduced the flow rate at the BA line by **16%** This can be compared to the flow produced with a BA present: • A flow with cross-walkers reduces the flow rate at the BA line by **6%.** The presence of the cross-flow had a significantly greater impact on the flow rate at the end line then the impact of the BA. A number of comparisons can be made with the previous results collected to demonstrate the impact of the crosswalk flow at the Endline. Compared to the Endline flow without a BA or cross-walking flow: • The introduction of the BA reduces the flow rate at the end line by **7%** • The introduction of the cross-walkers reduces the flow rate at the end line by **48%** • The introduction of the BA/cross-walkers reduces the flow rate at the end line by **48%** Thus the cross-walkers have almost seven times the impact of the BA on flow rate at the end line and the combined impact of the BA and cross-walkers is the same as the cross-walkers alone. Compared to the flow at the Endline when the BA was present • The introduction of the cross-walkers reduces the flow rate at the end line by **44%**

	Compared to the flow at the Endline when the cross-walkers are present: • The introduction of the BA reduced the flow rate at the end line by **1%** Compared to a flow at the Endline when the BA is present: • A flow with cross-walkers reduces the flow rate at the end line by **43%**
3_BA_TS2	• For the 3.0 p/m^2 initial crowd density, the presence of the BA produced a flow rate at the BA location that was on average 13.3% lower than the NoBA trials. This reduction in flow rate is larger than the natural variation in results for BA and NoBA cases suggesting that the BA is having an observable and marked negative impact on the BA flow rate. However, the reduction in flow rate due to the presence of the BA was not as great as would be expected due to the reduction in effective width of the exit path. The better than expected flow rate with the BA present is due to an 8.4% improvement in the unit flow rate for the exit path with the BA present. The reduction in flow rate due to the reduction in exit path width was partially compensated by the improvement in unit flow rate. The improvement in unit flow rate offered by the BA is greater the higher the density of the crowd. However, the improvement in unit flow rate may not occur in situations with more epassengers carrying luggage. • In both the BA and NoBA trials, the average density at the BA line was approximately a third less than the initial packing density (i.e. approximately 2.0 p/m^2 rather than the 3.0 p/m^2), although the fall in densities is not as pronounced as in the 4.0 p/m^2 case. This result is consistent with what may happen in actual situations on site where it is reasonable to assume that pedestrians are free to disperse after crossing the BA line. • The BA trials produced Endline flow rates (downstream of the BA) that were 9.3% lower than the equivalent NoBA flow rates. These are comparable with the differences evident at the BA line. The flow rate at the Endline is greater than that at the BA as the population is able to more easily travel at their desired speed due to greater diffusion of the population (leading to a reduction in density) once the BA has been passed. • In the BA and NoBA trials, the average density at the Endline was 1.39 p/m^2 and 1.47 p/m^2, a significant reduction from the initial 3.0 p/m^2. This result is consistent with what may happen in actual situations on site where it is reasonable to assume that pedestrians are free to disperse after crossing the BA line. The density at the Endline for the BA case was less than that for the NoBA case due to the reduction in flow rate at the BA line. These results are consistent

	with those for the 4.0 p/m^2 initial density.
3_BA_TS2_CW	**For the 3.0 p/m^2 population, the presence of the cross-flow had a smaller impact on the flow rate at the BA line then the impact of the BA.** A number of comparisons can be made with the previous results collected to demonstrate the impact of the crosswalk flow. Compared to a flow without a BA or cross-walkers: • The introduction of the BA reduces the flow rate at the BA line by **13%** • The introduction of the cross-walkers reduces the flow rate at the BA line by **10%** This is different to the 4.0 p/m^2 population, in which case the cross-walkers had a more pronounced effect than the BA on flow rates at the BA line. Compared to the flow with BA present: • The introduction of the cross-walkers increases the flow rate at the BA line by **3%.** This result is again different to that observed in the 4.0 p/m^2 population, in which case the introduction of the cross-walkers decreased the flow rate at the BA by 21%. This is likely due to the population being able to compress into a smaller area, with the resultant population density approximating 4p/m2, leading to the tailing off of the flow at the BA. For the 3.0 p/m^2 population, the presence of the cross-flow had a more pronounced impact on the flow rate at the Endline then the impact of the BA. A number of comparisons can be made with the previous results to demonstrate the impact of the cross-walkers on the flow at the Endline. Compared to the Endline flow without a BA or cross-walking flow: • The introduction of the BA reduces the flow rate at the end line by **9%.** • The introduction of the cross-walkers reduces the flow rate at the end line by **47%.** Compared to the flow with BA present: • The introduction of the cross-walkers decreases the flow rate at the Endline by **42%.** This is likely due to the population being able to compress into a smaller area, with the resultant population density approximating 4p/m2, leading to the tailing off of the flow at the BA. These results are broadly similar to the effect that the cross-walkers had on the 4.0 p/m^2 population.