Human Behaviour in Fire, Proceedings 6th Int Symp 2015, Interscience Communications Ltd, London, ISBN 978-0-9933933-0-3, pp 131-142, Sept 2015

The Impact of Security Bollards on Evacuation Flow

E.R. Galea, D. Cooney, G.G. Sharp, S. Gwynne[1]
Fire Safety Engineering Group, University of Greenwich, UK
Formerly at UoG, now at National Research Council, Canada[1]

ABSTRACT

Individual bollard and bollard arrays (BA) have become a common design of Vehicle Security Barriers surrounding crowded spaces, in particular busy rail and underground stations, airports and many key commercial and public buildings. While guidance on the general installation of BA is available this earlier advice did not take into consideration the potential impact a BA may have on pedestrian flow during emergency evacuation. To address this issue, FSEG in collaboration with the CPNI and DfT investigated the potential impact that security bollards may have on evacuation flows through a series of full-scale experiments. In total 50 trials were conducted over three days on two weekends in March 2013. The experiment for each unique trial set up 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. The trials were designed to capture the conditions produced as the population left a simulated station exit: 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? And how does the BA impact flow passing through the BA? A key finding from these trials is that if the BA stand-off distance is greater than 3m there is not expected to be any adverse impact on exit flow due to the presence of the BA. However, it is essential that the BA is sufficiently wide so that it does not restrict the natural diffusion of the crowd as it exits.

INTRODUCTION

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 (see Figure 1). These bollards form part of the security infrastructure and are primarily intended as part of the Hostile Vehicle Mitigation strategy. Within the UK, the Centre for the Protection of National Infrastructure (CPNI) is the government organisation, reporting to the Home Office, that advices on security issues related to national infrastructure.

CPNI, together with the UK Department for Transport (DfT) has produced guidance on the positioning of bollard arrays (BA) around busy buildings, but this advice does not currently include their impact on evacuation flow[1]. This is an important issue since the initial evacuation safety analysis used in the design and certification of these structures did not take into consideration that a ring of security bollards would be placed outside the exits. To address this issue, the Fire Safety Engineering Group (FSEG) of the University of Greenwich in collaboration with the CPNI and DfT investigated the potential impact that security bollards may have on evacuation flows through a series of full-scale experiments[2,3]. The broad aim of these experiments was to identify and quantify the potential impact that Hostile Vehicle Mitigation bollards may have upon pedestrian movement during evacuation from structures such as rail stations, underground stations and airport terminals. In particular, the project was concerned with determining whether typical BA configurations could adversely impact exit flows during an emergency evacuation, and if so, to what extent. In this paper we present the results from the first series of experiments that consider the impact of the BA with large stand-off distances on exit flow.

Human Behaviour in Fire, Proceedings 6th Int Symp 2015, Interscience Communications Ltd, London, ISBN 978-0-9933933-0-3, pp 131-142, Sept 2015

	
BA around a station	BA around an airport

Figure 1: Bollard Arrays surrounding transportation terminals.

THE EXPERIMENTS

The experiments were specifically designed to investigate the impact of several key BA parameters on the exit flow. The experiments were conducted in two trial campaigns, the first in 2013[2] and the second in 2014[3]. Within the first trial campaign the following parameters were investigated: population density, BA position (large stand-off distances), a single bollard placed in the centre of the exit and the presence of a cross-flow[2]. Within the second trial campaign the following parameters were investigated: exit width, BA position (small stand-off distances) and the presence of participants carrying luggage[3]. Here we focus on the results from the first trial campaign relating to large stand-off distances.

The first trial campaign examined two separate components of crowd interaction with BAs:

(a) Exit flow trials – assuming that participants are moving from an exit point to the BA, see Figure 2a.
(b) BA flow trials – assuming that participants are already located around the BA, see Figure 2b.

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 trials examined specific initial 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 during egress from the target buildings at peak periods. It is assumed that below a crowd density of 3 p/m^2 the population would have sufficient space available during their movement and therefore the BA would have a reduced impact.

The trials were conducted over three days over two weekends (16, 17 and 23 March 2013). A total of 50 trials were conducted involving 458 volunteers.

- Day 1: 12 exit flow trials conducted, involving 149 volunteers
- Day 2: 20 exit flow trials conducted, 170 volunteers
- Day 3: 18 bollard flow trials conducted, 139 volunteers.

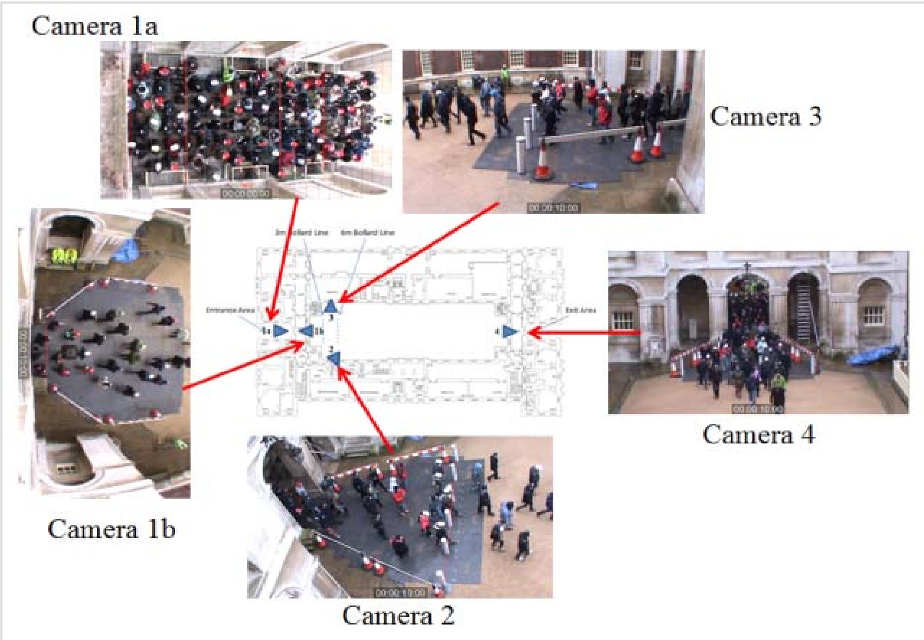
Participants were recruited from the public to match a demographic representative of the target populations. Each participant was compensated £45 for one day involvement. Of the 630 participants invited to take part in the trials, 458 participants actually attended the trials. The actual number of

Human Behaviour in Fire, Proceedings 6th Int Symp 2015, Interscience Communications Ltd, London, ISBN 978-0-9933933-0-3,
pp 131-142, Sept 2015

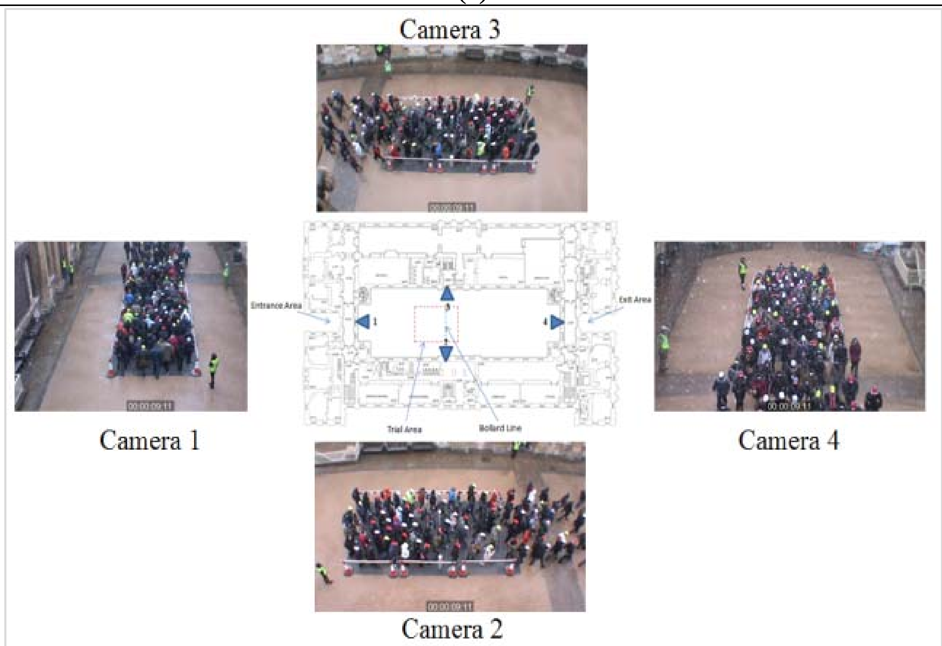
attendees for each of the days is shown in Table 1. On Day 1 approximately 25% of the registered volunteers failed to attend. However, during the trials, only two volunteers withdrew from the trials after only participating for about an hour on Day 1.

Table 1: Attendees for each day of the trials.

	Participants attended	Breakdown of attendees by gender and age				
		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



(a)



(b)

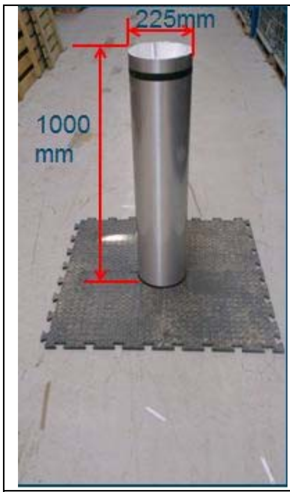
Figure 2: Experimental setup and camera views for exit flow (a) and bollard flow (b) trials.

Human Behaviour in Fire, Proceedings 6th Int Symp 2015, Interscience Communications Ltd, London, ISBN 978-0-9933933-0-3, pp 131-142, Sept 2015

Although different from the number of volunteers originally stating that they would participate, the actual number of attendees was deemed sufficient for the trials to be conducted as planned. A key criteria in this decision was whether sufficient steady-state flow was generated during the trial and whether this then had the potential for feeding back into areas of interest. For instance, whether the length of the participant flow was long enough to be engaged with the BA (up to 6m away) and the exit point simultaneously and for a sufficient period of time in order to make meaningful measurements.

The trials were conducted in physical spaces at the University of Greenwich that were representative of the targeted 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.

The trials were conducted with and without BAs so that the impact of the BA could be assessed. Each bollard had an outer diameter of 0.225m and had a 1m height (see Figure 3a). The spacing between the bollards was the regulated standard of 1.2m (see Figure 3b). For the exit flow trials, each experimental setup was repeated up to five times in order to reduce the impact of random fluctuations in participant performance. The exit flow trials (see figure 2a) involved a 2.4m wide exit with a BA consisting of six bollards, three either side of the exit centre line, positioned at stand-off distances of 3m and 6m and another set of trials consisting of a single bollard placed at a stand-off distance of 0m (typical stand-off distances used in the UK). In this paper we will present the results for 3m and 6m stand-off distances (see Figure 3b). The bollard flow trials (see Figure 2b) involved four bollards with 4.05m between the inner surfaces of the outer bollards, providing 3.6m of effective space through which to move. Each of the bollard flow trials were repeated three times.



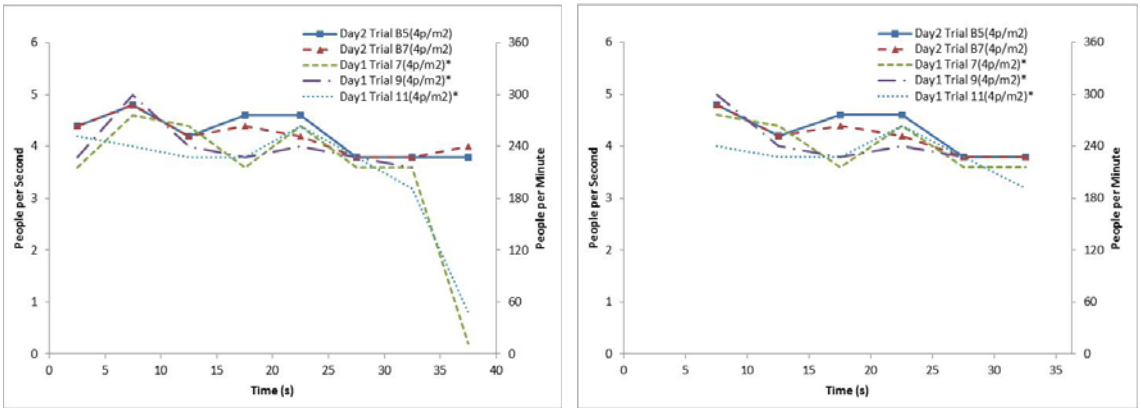
(a)

(b)

Figure 3: Typical bollard (a) and 6m BA stand-off distance set-up (b)

For both sets of trials, the movement and behaviour of the participants were recorded using a series of video cameras positioned at key locations. Video analysis provide measurements of exit flows, BA-line flows, initial crowd densities, crowd densities at the BA-line and BA gap usage. The video analysis package Adobe Premiere Pro was used to analyse the video footage. One of the key measurements used in this analysis is the exit flow. To measure the exit flow, a red line was superimposed on the video footage at ground level and along the start line (exit). The number of people that passed the superimposed red line within each 5 sec period was counted using only the view from the birds eye view camera - Camera 2b in Figure 2a. 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. This provided a measure of the exit flow in 5 sec periods (see Figure 4a).

This data was then filtered to remove the flow during the ramp-up period, where participants have started from a standing start and the ramp-down period, where there is a small number of tail end participants (see Figure 4b). Thus the exit flows considered are over the near steady-state conditions and as such provide a more reliable measure of peak exit performance.



(a) (b)

Figure 4: Exit flow measured in 5 sec intervals for the five no BA 4 p/m^2 trials, over the entire time period (a) and over the steady-state peak period (b).

Using this approach the average exit flow during the peak period could be determined in 5 sec intervals as well as an overall average flow over the peak period. Both these parameters can be used to characterise the exit performance with and without BA to identify the impact of the BA on exit performance. A similar approach was adopted for the Bollard flow trials, only this time the flow at the BA is determined. For these trials both the flow and the unit flow at the BA is required to interpret the results. Finally, over the days of the trials, it was noted that the weather conditions were considered cold, with an average high of 9^{o}C with occasional light snow.

RESULTS AND DISCUSSION

The results from the first trial campaign[2] suggest that with an initial population density of 3p/m^2, the impact of the BA on the evacuation exit flow was less significant than that for the flow with an initial population density of 4p/m^2. Hence the results presented here are based on the trials with the higher population density. It was apparent from the results (see for example Figure 4) that there was a small degree of spread in the results between the trials. To reduce this variability, the outlier trials that produced the slowest and fastest average flow rates during the peak period were removed from the analysis, producing a more uniform and consistent set of results.

BA Stand-off Distance of 6m

The average exit flow (measured in people per minute – ppm) for the 6m BA stand-off distance and the no BA (NoBA) are presented in Tables 2 and 3 respectively. The tables show the average flow produced at the exit within each 5 s interval of the peak flow period for each of the 6m bollard trials and the no bollard trials. The data has then been used to calculate the overall average flow in ppm. The NoBA case produced an average flow of 247.1 ppm (with a standard deviation of 5.0 ppm and a range of -2.1% to +2.0%), while the 6m BA case produced an average flow of 248.7 ppm (with a standard deviation of 5.8 ppm and a range of -2.7% to +1.3%). The 6m BA trials produced exit flows that were on average 1.6 ppm or 0.6% greater than the equivalent NoBA case.

Human Behaviour in Fire, Proceedings 6th Int Symp 2015, Interscience Communications Ltd, London, ISBN 978-0-9933933-0-3, pp 131-142, Sept 2015

Table 2: Peak flow per 5 s time interval for trials with 6m BA.

Trial	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

Table 3: Peak flow per 5 s time interval for trials with NoBA.

Trial	Peak 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

The quantitative and qualitative similarity between the average peak exit flows produced by the two conditions is more apparent when examining Figure 5. This difference in exit flow is small and as shown in Figure 5, 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 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. Figure 6 shows the average and range of the average peak flow produced over the three NoBA and 6m BA trials with the slowest and fastest trials having been removed. The difference between the averages is less than the spread in the trial results for each case. Furthermore, it is apparent that the range in average exit flow for the two sets of trial conditions is identical.

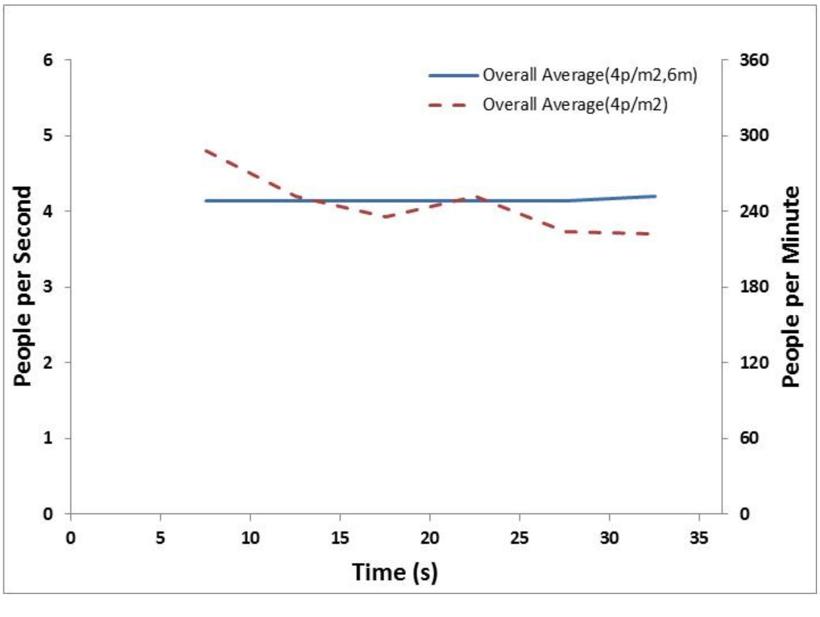


Figure 5: Average exit peak flow measured in 5 s intervals for both the 6m BA and NoBA trials.

Human Behaviour in Fire, Proceedings 6th Int Symp 2015, Interscience Communications Ltd, London, ISBN 978-0-9933933-0-3, pp 131-142, Sept 2015

Key Finding 1 – The trials with the 6m BA present produced average flows 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 that would be produced if a BA was located 6m from the exit compared to the case in which there was no BA present.**

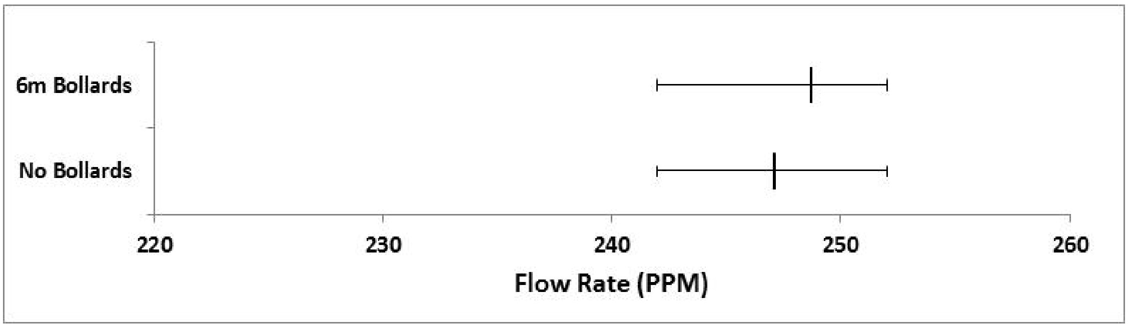


Figure 6: Average and range of peak exit flow for the 6m BA and NoBA 4 p/m^2 trials.

A similar analysis was undertaken to determine the resulting peak flows at the position of the BA for the NoBA and the 6m BA trials. The average peak unit flows are presented in Table 4. Table 4 shows that the 6m BA case produced flows 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 of 246.2 ppm (with a standard deviation of 6.9 ppm and a range of -3.2% to +1.7%) while the 6m BA case produced an average flow of 246.4 ppm (with a standard deviation of 6.7 ppm and a range of -1.9% to +3.1%). The average flows at the position of the BA are almost identical, suggesting that overall, the presence of the BA resulted in little difference in the flow produced at the BA.

Table 4: Flows at the position of the BA for the 6m BA trials and the NoBA trials.

Scenario	Flow (ppm) at BA
NoBA (3 runs)	246.2 [238.3 – 250.3]
6m BA (3 runs)	246.4 [241.7 – 254.0]

Key Finding 2: There is no appreciable difference in the flows at the bollard line produced during the NoBA and 6m BA trials, with the latter producing 0.1% higher flows. **The results suggest that there is no appreciable difference in the average flow 6m from the exit that would be produced if a BA was located at this position compared to the case in which there was no BA present.**

BA Stand-off Distance of 3m

The average exit flow (measured in people per minute – ppm) for the 3m BA stand-off distance are presented in Table 5. The results show that the 3m BA trials produced exit flows that were on average 1.6 ppm or 0.6% lower than the equivalent NoBA case (see Table 3). The 3m BA case produced an average flow of 245.5ppm (with a standard deviation of 12.6 ppm and a range of -3.6% to +5.9%).

The quantitative and qualitative similarity between the average exit flow rates produced by the two conditions is more apparent when examining Figure 7. The progression of the flows appears approximately at the same level throughout, adopting the same downward trend as time advanced.

It is noted that the difference in average exit flows 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.

Table 5: Peak flow per 5 s time interval for trials with the 3m BA.

	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

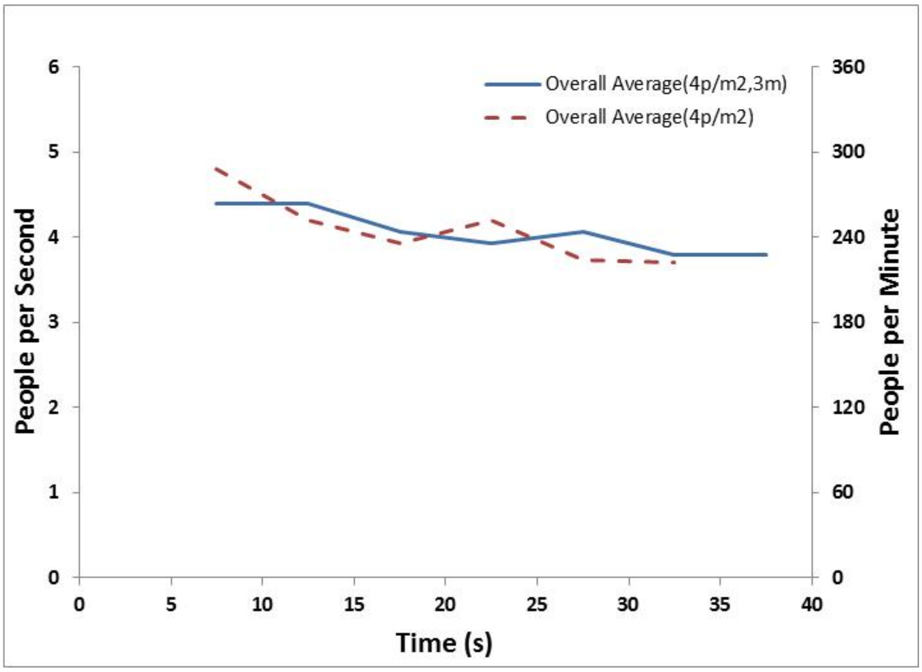


Figure 7: Average exit peak flow measured in 5 s intervals for both the 3m BA and NoBA trials.

Figure 8 shows the results of the average and range of the average peak flows produced over the NoBA and the 3m BA trials. This shows that there was little difference between the average flow 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.

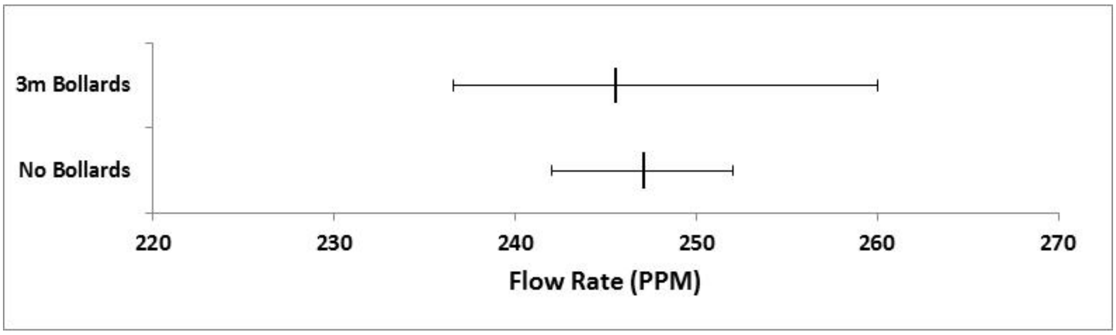


Figure 8: Average and range of peak exit flows for the 3m BA and NoBA trials.

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

A similar analysis was undertaken to determine the resulting peak flows at the position of the BA for the NoBA and the 3m BA trials. The average peak unit flows are presented in Table 6. Table 6 shows that the 3m BA case produced flows that were on average 5.3 ppm 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 of 248.7 ppm (with a standard deviation of 2.31 ppm and a range of -1.1% to +0.5%) while the 3m BA case produced an average flow of 243.4 ppm (with a standard deviation of 10.71 ppm and a range of -3.5% to +4.9%). The average flows at the position of the BA are almost identical, suggesting that overall, the presence of the BA resulted in little difference in the flow produced at the BA.

Table 6: Flows at the position of the BA for the 3m BA trials and the NoBA trials.

Scenario	Flow (ppm) at BA
NoBA 3m line (3 runs)	248.7 [246.0 – 250.0]
3m BA (3 runs)	243.4 [234.9 – 255.4]

Key Finding 4: There is a small difference between the flows produced at the BA line during the NoBA and 3m BA trials, with 3m BA producing 2.1% lower flows. **The results suggest that there is no appreciable difference in the average flow 3m from the exit that would be produced if a BA was located at this position compared to the case in which there was no BA present.**

Exit Unit Flow

The exit unit flow achieved in these trials without BA was 1.71 p/m/s and with BA at 3m stand-off was 1.70 p/m/s. The unit flow rates can be compared with existing flow rates presented in guidance documents[4] and the research literature[5]. It is apparent that the unit flows produced in these trials are greater than the (deliberately conservative) unit flows assumed in regulatory guidance documents – 1.33 p/m/s, but lower than those presented elsewhere in research literature – 2.0 p/m/s. The presence of a BA with a 3m or 6m stand-off distance is therefore not expected to have a significant impact on evacuation exit flows.

Flow Diffusion

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). The average gap usage over the entire set of trials (3 trials) was determined using a weighted average (i.e. the number of participants using each gap divided by the total 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. The average gap usage across the trials is presented in Table 7.

It was noted in the exit flow trials that as the participants passed through the confined (2.4m wide) exit they spread out to occupy the available space. This can be seen in Figure 3b and the results presented in Table 6. While the bulk of the participants are focused on using the central gaps (gaps 2, 3 and 4), a few participants are also noted utilising the gaps on the extremities (gaps 1 and 5). The width of the central gap area (as measured from the inner edge of bollard 2 to the inner edge of bollard 4) is 4.05 m. The participants are focused on using the central gap (gap 3) and the gaps either side of the centre (gaps 2 and 4), with very little usage of the gaps at the extremities (i.e., 1 and 5). It is also noted that the gap usage is symmetrical, with one side typically not being favoured over another side. This is because the target for the participants is at the opposite end of the courtyard; i.e., directly ahead of them. Almost 90% of the flow passes through the central three gaps (see Table 6) suggesting that the flow has expanded to cover 4.05 m from its original 2.4 m opening. On passing through the confines of an exit, a high density exit flow tends to spread out (or diffuse) into the available space. The diffusion of the flow into the available space is to allow the population to experience a less dense flow and so be able to attain their desired walking speed.

It is also noted from Table 7 that the use of the central gaps decreases with increased distance from the exit irrespective of whether the BA is absent or present. Thus, the diffusion of the crowd into the available space increases with distance from the exit. Furthermore, with no BA present there is a slight tendency for greater use of the central gaps compared to the case with BA irrespective of stand-off distance. These results suggest that the BA behaves like a divergent lens, encouraging pedestrians to modify their paths and diverge slightly from the central paths.

Table 7: Gap usage.

Stand-Off	Average Central Gap Use (gaps 2-4)	% Gap Use				
		1	**2**	**3**	**4**	**5**
6m BA	87.3	6.7	25.2	36.4	25.7	6.0
3m BA	93.1	3.6	28.7	37.3	27.1	3.2
6m NoBA	88.4	6.5	29.0	32.4	27.0	5.1
3m No BA	97.9	0.9	30.8	40.8	26.3	1.1

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 4.05 m 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 4.05 m 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. If a smaller expanse of BA is available, it is possible that the flow would back up and impinge on the exit flow.

Key Finding 5: When positioning bollards in an array at an exit point, it is important that the BA does not constrain the natural tendency for the crowd to spread out (or diffuse) as this may lead to a reduction in the exit flow. Therefore, to avoid this, the BA width would need to be greater than that of the exit.

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. The results presented and discussed in this paper focused on one of the specific issues addressed by the trials, namely, how does BA stand-off distance impact exit flow. 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. Only the results for the 4 p/m^2 population are presented in this paper as the trends were similar but not as severe for the smaller population density. The main conclusions of this work can be summarised as follows:

- 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 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.

- 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 flows and the BA flows are 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.*

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.

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. Some of these factors have been studied in further trials and will be reported in the literature in the near future. The results of this work are being used to specify additional guidelines for the safe positioning of BA around exits.

ACKNOWLEDGEMENTS

The authors are indebted to the UK CPNI and UK DfT for funding this work and for allowing the results to be reported in these proceedings.

REFERENCES

1. Traffic Advisory Leaflet 2/13, May 2013, Dept for Transport and CPNI.
2. Galea, E.R., Gwynne, S. Cooney, D., Sharp, G.G., Impact of Hostile Vehicle Mitigation Measures (Bollards) on Pedestrian Crowd Movement. FSEG University of Greenwich report for the CPNI and DfT, 22 August 2013.
3. Galea, E.R., Cooney, D., Xie, H., Sharp, G.G., Impact of Hostile Vehicle Mitigation Measures (Bollards) on Pedestrian Crowd Movement - 2. FSEG University of Greenwich report for the CPNI and DfT, 19 Oct 2014.
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.