Understanding Capacity Drop for designing pedestrian environments

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Abstract

This paper focuses on pedestrian behaviour along unidirectional corridors and at bottlenecks. This issue is important in any pedestrian environment where there is a change in size which might give rise to a change in capacity. Examples include emergency exits, railway stations and pedestrian footways in the street environment.

To understand this phenomenon, we need to assess the capacity of a bottleneck, whether or not, in oversaturated conditions, a capacity drop occurs and which variables affect it. We therefore planned some experiments to evaluate the effects on capacity drop of: the density at the bottleneck entrance, the pedestrians' desired speed and the pedestrian motivation in passing through the bottleneck.

Knowing the actual value for capacity and capacity drop is essential for understanding pedestrian route choice behaviour and for planning the usage of a given environment. For instance, in the case of evacuation from a building, escape routes should be planned taking into account the actual corridor capacity and the capacity drop phenomenon: moreover, depending on the entity of capacity drop, the opportunity to give different starting evacuation times in different parts of the building, in such a way to reduce the merging flows, and therefore the upstream density, could be assessed.

Knowing at a microscopic level the mechanism that leads to the capacity drop would help in improving the environment design.

Interesting results from the experiments reported in this paper pertain to the use of space upstream of the bottleneck in the case of congestion. Some empirical studies have been carried out by the Dresden University of Technology for a corridor with bottlenecks to compare the effect of pedestrian counter flows and unidirectional flows and by Delft University of Technology to assess the capacity of the bottleneck. However, none of these empirical studies provides any data about the capacity drop so it is difficult to convert these results into applications in the real world.

The research presented in this paper aims to provide a step forward from that research by introducing a more sophisticated understanding of the capacity drop phenomenon for the benefit of designers of street environments to help them construct a more pedestrian-friendly environment.

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This paper focuses on pedestrian behaviour along unidirectional corridors and at bottlenecks. Experiments in a laboratory and observations in the real field have been carried out for understanding pedestrian behaviour. From the data collected two phenomena have been underlined: the capacity drop and an interesting relationship between average inflow and outflow. These phenomena, which will be described in the paper, arise a lot of questions which answers should be basic inputs in pedestrian environment design.

Understanding pedestrian behaviour at bottlenecks is important in any pedestrian environment where there is a change in size which might give rise to a change in capacity. Examples include emergency exits, railway stations and pedestrian footways in the street environment.

Some empirical studies have been carried out by the Dresden University of Technology [HBJ05] for a corridor with bottlenecks to compare the effect of pedestrian counter flows and unidirectional flows and by Delft University of Technology [Hoo04], [DaH02], [HoD05] to assess the capacity of the bottleneck. However, none of these empirical studies provides any data about the phenomena this paper is focused on.

Capacity drop

Capacity drop is a phenomenon which is a characteristic of particulate flows at and around a bottleneck. A gradual increase in the inflow is accommodated by an equal increase in the outflow until a certain point where there is a sudden change and the outflow falls dramatically and remains at the new lower level until the inflow falls below this level, when the outflow is determined by the inflow again rather than by the capacity of the infrastructure.

Pedestrian behaviour at the underground station was recorded by Fotakopoulos by a video camera: pedestrians, having arrived in trains, walked along a wide corridor towards the station exit, going up through the escalator. The escalator acted as a bottleneck as the previous corridor was larger. Figure 1 shows four photographs of the scenario, taken in sequence at 0 seconds, 30 seconds, 50 seconds and 45 seconds respectively.

Figure 1a The inflow commences ... *Source: Fotakopoulos (2005)*

Figure 1b ... the flow increases towards the maximum inflow… *Source: Fotakopoulos (2005)*

Figure 1c … the capacity drop occurs (notice the density of pedestrians on the escalator, compared to that in Figure 2b). *Source: Fotakopoulos (2005)*

Figure 1d The point of maximum accumulation of pedestrians. *Source: Fotakopoulos (2005)*

The camera was located at the top of the escalator. Figure 2 shows an example of the capacity drop at this location: it shows the inflow and outflow of pedestrians at the entrance to an escalator. The outflow increases as the inflow increases until it reaches the point at which the catastrophic fall in outflow occurs, some 15 seconds after the peak inflow. The outflow then increases to a level about 20% less than its maximum, where it remains constant until the flow falls because of the reduction in inflow.

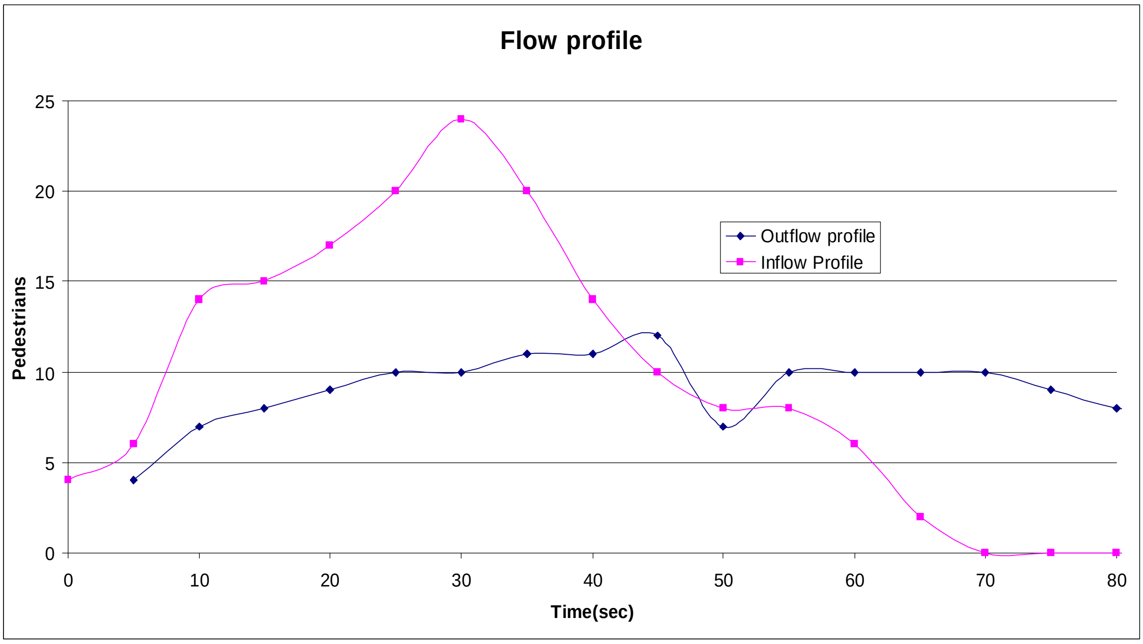

Figure 2 Pedestrian inflow and outflow patterns observed at a width restriction in a London underground station where capacity drop occurs during a period of decrease in inflow. (flow expressed in pedestrians per 5 second period) [Fot05]

Figure 3 shows another example from the London Underground station: the difference between the situations represented in Figure 2 and Figure 3 is that in the former case one train had arrived whereas in the latter case two trains were involved. The graph shows that the capacity drop is similar in size and extent to that shown in Figure 2, and that the maximum outflow and the steady state outflow after the fall are the same. In this case the inflow continues to increase while the capacity drop occurs, showing that the capacity drop and the subsequent steady state outflow are, in combination, the real determinant of the system's ability to handle a given volume of pedestrians.

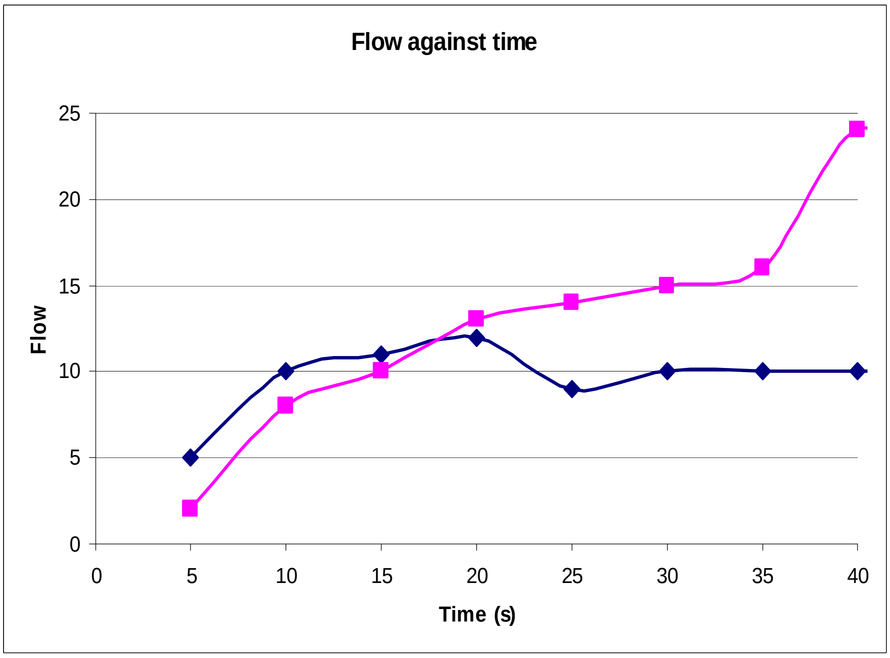

Figure 3 Pedestrian inflow and outflow patterns at a London Underground station when capacity drop occurs during a period of increasing inflow (flow expressed in pedestrians per 5 second period) [Fot05].

This phenomenon is not unique to pedestrian flows – it arises in any system where a flow encounters a restriction in the capacity of the channel. It is particularly noticeable in flows of particles, but it also occurs in fluids and gases.

The phenomenon of *capacity drop* also occurs in over-saturated conditions in the case of vehicular flows. In the case of vehicles, at a certain point the flow through a section breaks down, then it increases a bit in time (without reaching the previous higher value) and it keeps this value for the following period. Figure 4 shows some empirical data showing this behaviour on a freeway section.

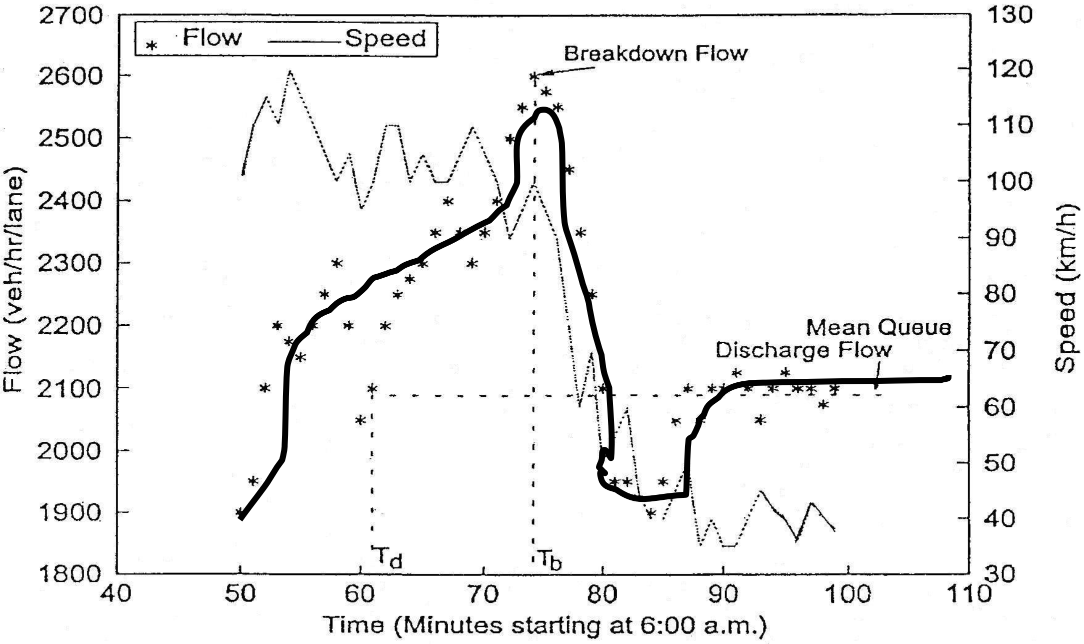

Figure 4 Time Trends for Speed and Flow (Typical Morning Rush) at a freeway section [FHA03]

It is interesting to note that in the case of vehicles, the capacity is assumed to be the maximum flow able to pass a road section. This is due to the fact that control means are used to avoid unstable traffic conditions and capacity drop. For instance on freeways, ramp metering is used to control the flow on the entry ramps: it allows traffic to enter the freeway at a rate dependent on the conditions of the freeway traffic. Motorists are often delayed at the meter, but freeway speeds and overall travel times are improved. In the case of pedestrians, it is more difficult to control the inflow and thus to avoid the capacity drop occurrence. Because of that, in the case of pedestrian infrastructure, it seems more correct to call capacity the steady state outflow which takes after the fall. Therefore, instead of capacity drop, we should speak of an *outflow peak* before the capacity.

As can be seen from Figure 2, the capacity of this infrastructure is some 20% of the maximum possible throughput. It should also be noted that the actual drop falls approximately 25% below the capacity before rising to the steady state.

The reduction in the maximum outflow is particularly important for pedestrians because their ability to cope with a situation in which the flow of pedestrians is very close to the capacity of the infrastructure depends on the relationship between the number of pedestrians present and the capacity of that infrastructure. If the infrastructure cannot deliver sufficient capacity, there will be a queue, leading to overcrowding and possibly panic.

Such reductions in the maximum outflow are severe restrictions on the ability of the infrastructure to cope with the demand and this could be extremely important in situations such as the evacuation of a building, where the resulting queue/crowd could leave some people inside for some time: with reference to figure 2, notice that the outflow only starts to decrease below the capacity level as the inflow falls to zero, meaning that there is in fact quite a crowd waiting to pass through the restriction even 40 seconds after the inflow reached its maximum.

Average inflow-outflow relationships

We collected data also in the PAMELA laboratory, organising ad hoc experiments in a controlled environment. The layouts of the experiments in the laboratory are shown in the following figure:

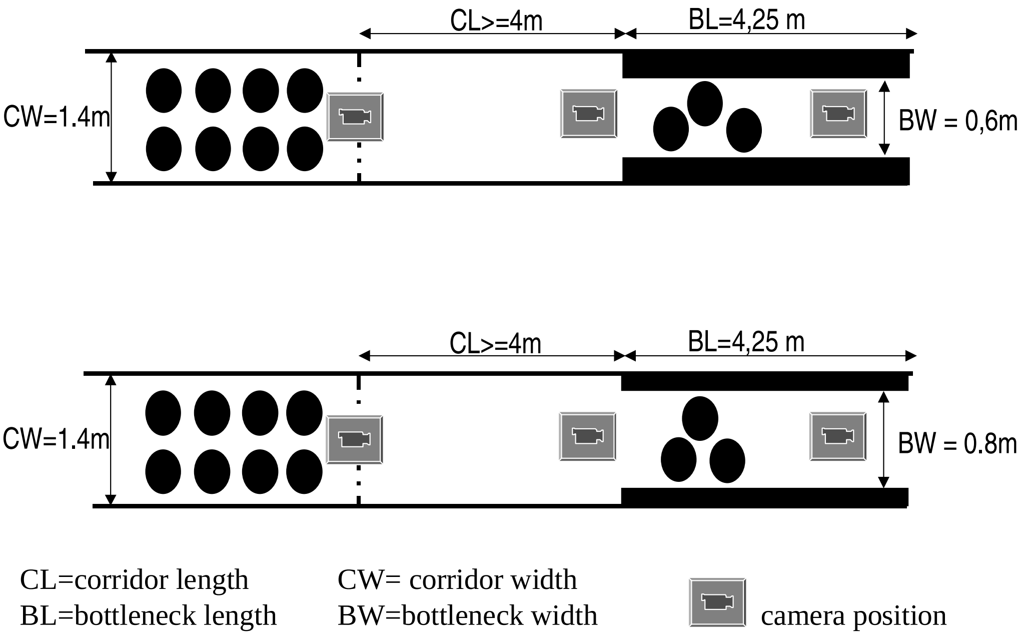

Figure 5 Experimental layouts

We set a corridor with a fixed width of 140 cm followed by a restriction which forms a bottleneck. The bottleneck width was first 60 cm and then 80 cm. 14 pedestrians were asked to walk through the end of the bottleneck, starting from the dotted line shown in the figure, and therefore to turn and to come back to the starting line. We repeated the experiments several times: asking the pedestrians to walk at different speeds (their normal speed and then to walk quickly) and the density of the platoon (by walking at a comfortable distance from each other and then as close as possible to each other) and changing the position of the students within the platoon at the starting line (the quickest person as the platoon leader and at the rear of the platoon).

The results of the experiments are summarised in the following diagrams. All the data from the same experiment run are reported in the same colour. For each experiment run we have reported the average flow at the bottleneck entrance, the average flow through the bottleneck and the average flow at the bottleneck exit.

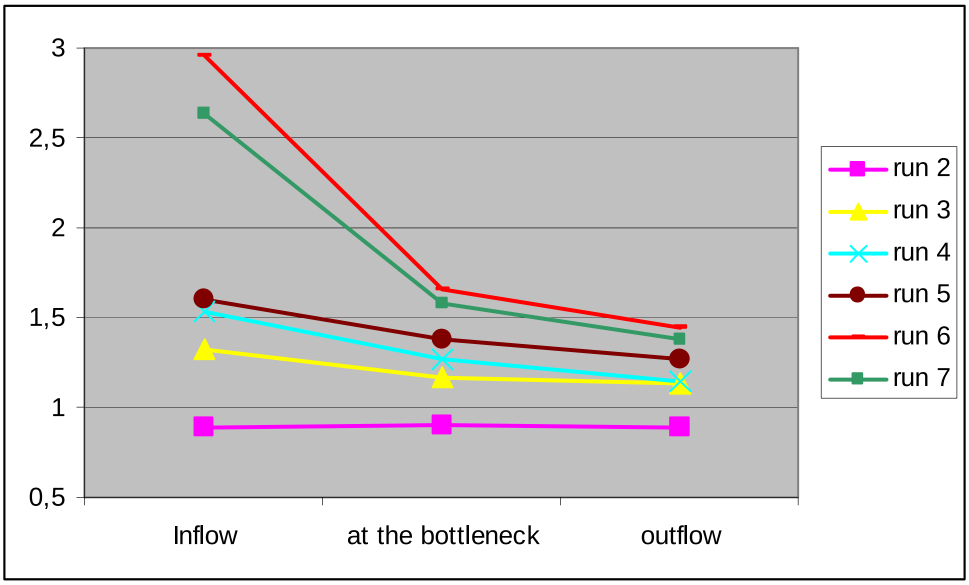

Figure 6 Inflows and outflows (ped/sec), initial experiment: Bottleneck width: 60 cm

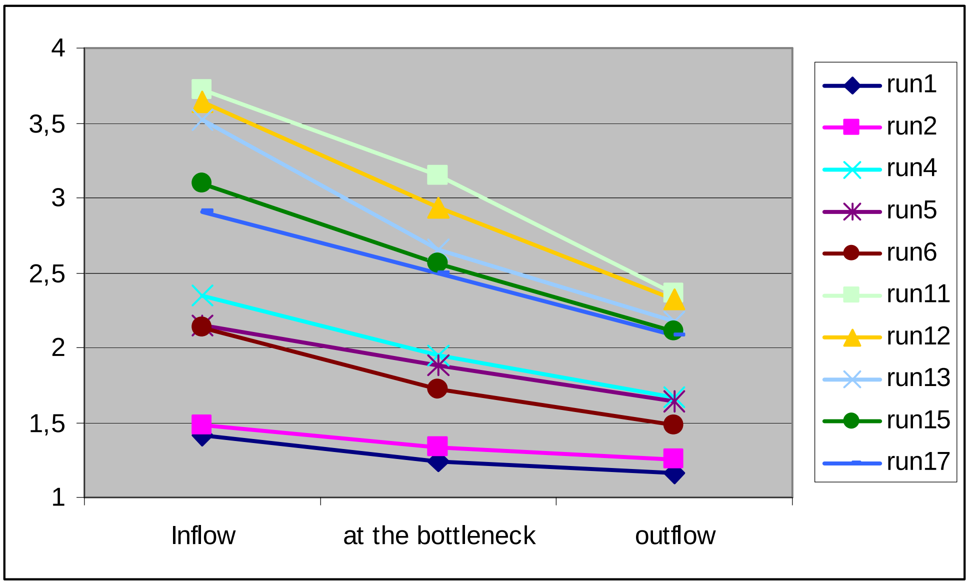

Figure 7 Inflows and outflows (ped/sec), initial experiment: Bottleneck width: 80 cm

We repeated these experiments with a much larger cohort of pedestrians (about 50). The flows obtained in this case are shown in Figures 8 and 9. Again the pedestrians were asked to walk at different speeds, and in some cases ‘spies’ were placed among the pedestrians to force the speed a little. Also, the pedestrians were asked to repeat the walk through the bottleneck, forming a continuous flow over a period of time. As Figures 8 and 9 show, the results show a remarkable consistency in relation to the previous experiments.

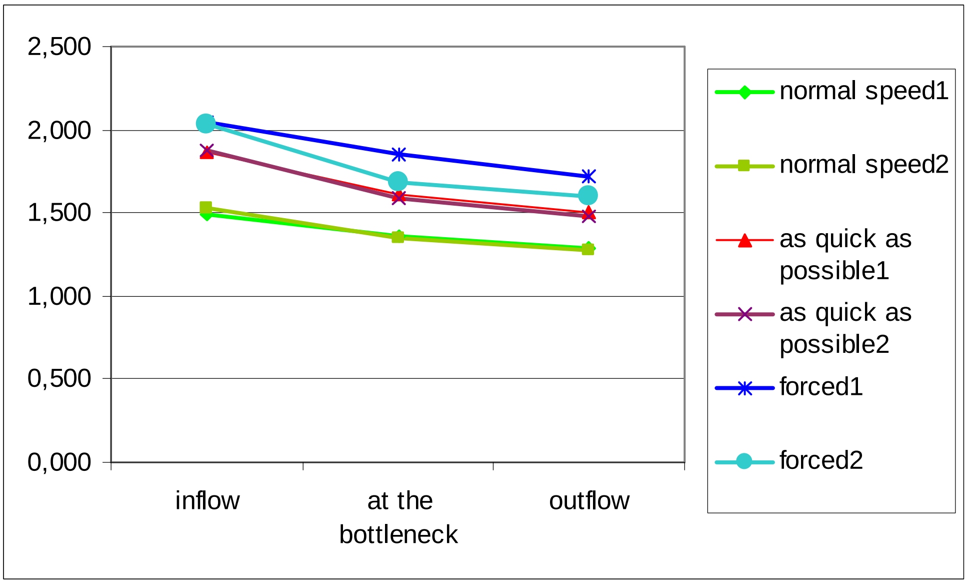

Figure 8 Inflows and outflows (ped/sec) for a bottleneck width 90 cm (from 1.4m)

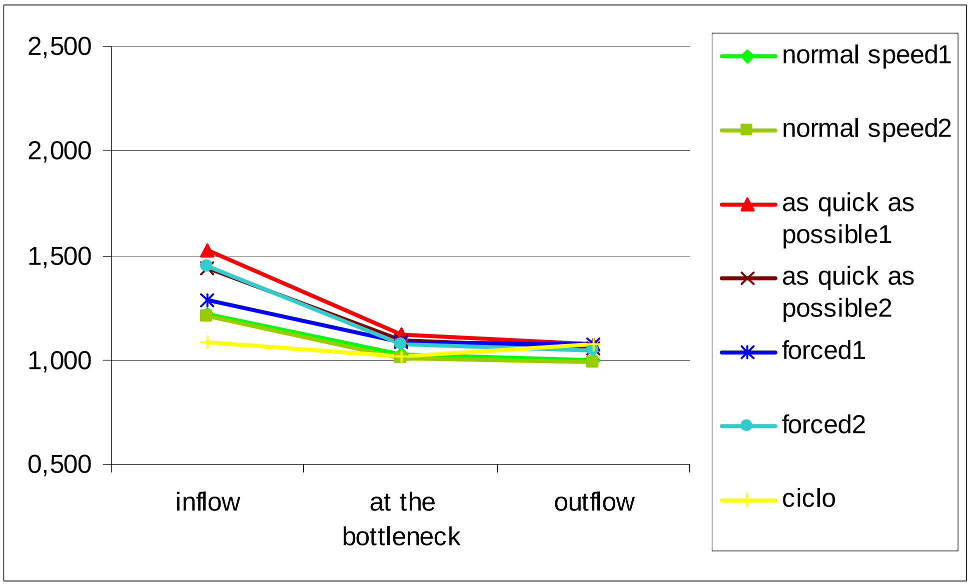

Figure 9 Inflows and outflows (ped/sec) for a b ottleneck width of 60 cm (from 1.4m)

All the data reported in these graphs refer to over-saturated conditions because the outflow is lower than the inflow: congestion occurred and a queue took place at the bottleneck entrance.

Another feature that can be discerned in the graphs is an *average pushing effect* given by a consistent inflow: when the inflow is higher the outflow is higher, even if lower than the related inflow. Thus the nature of the activity at the inflow affects the nature of the outflow, suggesting that the capacity of the bottleneck increases if the speed at the inflow is increased. In Figure 8, which represents a bottleneck width of 90cm, it can be seen that the observed outflows are actually quite elastic – consistently lower than the associated inflow, but not indicating an absolute capacity level. However in Figure 9, although the same reduction in flow is observed, the various runs converge on an outflow of a little over 1 person/second. To see why such a difference is evident, it is necessary to consider two effects. First, as the average human body width is 60 cm (as shown in Figure 10), it seems reasonable that in a bottleneck of 60 cm there is no room for the pedestrians to adjust their behaviour to increase the flow: they have to walk in only one lane.

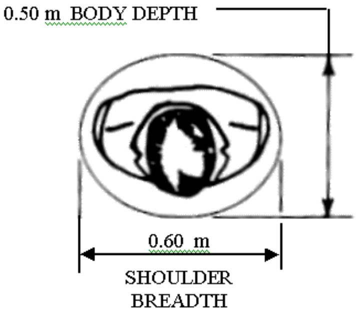

Figure 10 Body ellipse [HCM00]

The second effect is that when the bottleneck is wider there is more space for pedestrians' flexibility: they can rotate themselves at the bottleneck entrance and phenomena like the 'zip effect' (see Figure 11) can take place along the bottleneck. This behaviour confirms what has been found in previous experiments carried out at the Delft University [Hoo04].

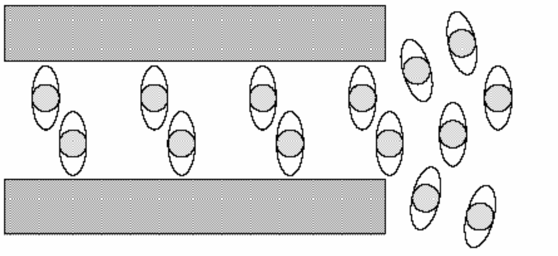

Figure 11 The 'zip effect' where pairs of pedestrians walk slightly offset in relation to each other.

It seems that the pushing effect is related to pedestrian speed at the bottleneck entrance: as far as pedestrians are able to keep a high speed, the pushing effect is strong; as the queue reaches a certain length, pedestrians have to slow down to very low speed and then their pushing effect expires. How exactly this then relates to the capacity effects is a subject for further experiments.

Implications in pedestrian environments design

Knowing the actual value for capacity and capacity drop is essential for understanding pedestrian route choice behaviour and for planning the usage of a given environment. If the design of the environment or control techniques allow to control the pedestrian inflow arriving at a bottleneck, it will be possible to make the bottleneck working at its maximum rate and therefore having the maximum flow throughout the bottleneck; however if it is not possible to control the inflow, the designer have to take into account that the bottleneck will work at its capacity and therefore a lower outflow will be possible.

For instance, in the case of evacuation from a building, many actions could be adopted for reducing the time required for evacuating the building. First, if it is possible to control the inflow by assigning to pedestrians different escape routes or different evacuation starting times in different parts of the building (for instance, by ringing the alarm bells at each floor of the building in a different time), it will be possible to avoid the reductions of the outflow through the bottlenecks in over-saturated conditions. Depending on the capacity drop, the opportunity afforded by these actions could be assessed. If it is not possible to control the inflow and thence to avoid the reductions of the outflow through the bottlenecks in over-saturated conditions, the building design could be modified in order to reduce the time required for evacuating it: for instance, the exit doors could be enlarged or their number increased.

Also the average pushing effect underlined by the experiments has to be taken into account in the design of pedestrian environments. Its impacts concern bottlenecks with widths that allow the zip effect.

Conclusions

This paper has sought to raise some questions about the understanding of pedestrian flow at and around the point of the capacity of the infrastructure.

When a difference between the bottleneck inflow and outflow occurs, it is due to:

- a geometry issue: the bottleneck is narrower than the upstream corridor
- a time effect: the time people require for their reorganization in a lower number of lanes because of the bottleneck.

The experiments presented in this paper are focused on these two contributions. The geometry issue determines the bottleneck capacity while the time required by pedestrians for their reorganisation in a reduced number of lanes and reshaping in terms of the direction of their body ellipse, could influence the capacity drop and therefore the pedestrian delay. If the time required by pedestrians for their reorganisation is longer than the time headway related to the bottleneck capacity, a capacity drop will occur at the bottleneck entrance. It seems that the time required for the pedestrian reorganisation increases with the upstream density and the pedestrian motivation at passing through the bottleneck. This in turn suggests that, at least to some quantifiable extent, such events could be managed by sensible interventions in the infrastructure or, in the case of evacuation, by timed starts to evacuation in different parts of a building in order to achieve the fastest overall exit. Similarly, in the case of pulsed arrivals, such as in a railway or bus station, the capacity needs to be able to take account of the arrivals of trains, the speeds of different passengers when leaving the train and thus their arrival time at the bottleneck.

The research presented in this paper aims to provide a step forward by introducing a more sophisticated understanding of the capacity drop phenomenon in relation to pedestrian use of infrastructure for the benefit of designers of street environments to help them construct a more pedestrian-friendly environment. Using the PAMELA laboratory, we are able to set up a further series of experiments which will enable us to study in even more detail how these effects arise and how they can be managed, for example under different lighting conditions (emergency evacuations rarely happen in good lighting conditions) and with different infrastructure details (e.g. the surface of the floors and walls, location of pillars and so on). Some of these experiments have been conducted and the analysis of the data is underway.

References

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