The impact of integrated street design on flow-density curves: An empirical analysis for motorised and pedestrian traffic

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SHORT SUMMARY

Urban street design has been influenced by a shift in thinking in recent years, which advocates for more equal treatment of all road users. This has effected a move away from the traditional concept of segregation between motorised traffic and pedestrians, and towards greater integration of the two. In practice, the new approach usually manifests itself in more pedestrian-friendly layouts with wider footways, fewer protective guardrails and lower (or even no) kerbs. Following-on from previous research on the topic, this study concentrates on the impact of such designs on the fundamental relationships between flow, density and speed for both motorised traffic and pedestrians, offering empirical evidence. Video footage from London's South Kensington site during periods before and after its conversion from a conventional layout to a more integrated pedestrian-oriented design is used to extract relevant measurements and derive and compare flow-density curves. The findings indicate stabler and more relaxed driving and walking behaviour post-redevelopment, which are in addition to effects arising from changes in the demand and supply. This suggests that both types of road users stand to benefit from integrated street design elements.

Keywords: urban streets; integrated street design; fundamental diagram; flow-density curves; motorised traffic; pedestrians

1 INTRODUCTION

The safe and efficient interaction of pedestrians and motorised traffic has been central to streetscape design ever since the advent of motorised vehicles. With pedestrian injuries and fatalities soaring in the 1950s and 1960s, the "quick-fix" resolution that was adopted and continued to be routinely implemented until relatively recently was that of segregation through pedestrian guardrails and grade separation [1]. In the last few decades, however, streetscape design has gradually moved away from segregation and more towards integration: as opposed to the previous "keep out" principle, pedestrians are now included in the design and are invited to share the space, ultimately asserting the role of streets as places rather than arteries. Prominent integration examples include the "Manual for Streets" approach in the UK [2-3] and the "Complete Streets" initiative in the USA [4] (Figure 1).

Source: Michael Barera, Wikimedia Commons

FIGURE 1: Examples of integrated street design: a "shared space" street in Brighton, UK (left); pedestrian and bicycle paths in Houston, TX, USA (right)

Previous research has uncovered a range of findings relating to this new design approach. Rightful concerns have been expressed in terms of the potential hindrance (and corresponding exclusion) of disabled road users, in particular in streetscapes featuring a more extreme manifestation of the approach (the so-called "shared space") that comprises little to no street furniture and, often, no kerbs [5-7]. On the other hand, several positive effects have been reported, including greater pedestrian confidence [8], improved aesthetics [9], better accessibility [10], and also better safety due to a reduction in the severity of traffic conflicts [11-12]. There has also been some evidence of better quality of service, with not only considerable gains for pedestrians, but also with modest ones for motorised traffic [13].

Nevertheless, one aspect that has received less attention to date is that of the impact of integrated street design on the relationships between speed, flow and density for both motorised vehicle and pedestrian traffic. Some research has approached this aspect analytically by considering scenarios of increased interaction between motorised and non-motorised traffic, and in particular cyclists (e.g. [14]). Due to the absence of appropriate data, however, empirical studies to support the analytical research are lacking. The objective of this study, hence, is to address this gap by performing an empirical derivation and comparison of vehicle and pedestrian flow-density curves for a street site in London's South Kensington area, before and after the implementation of integrated street design features, using data from video recordings.

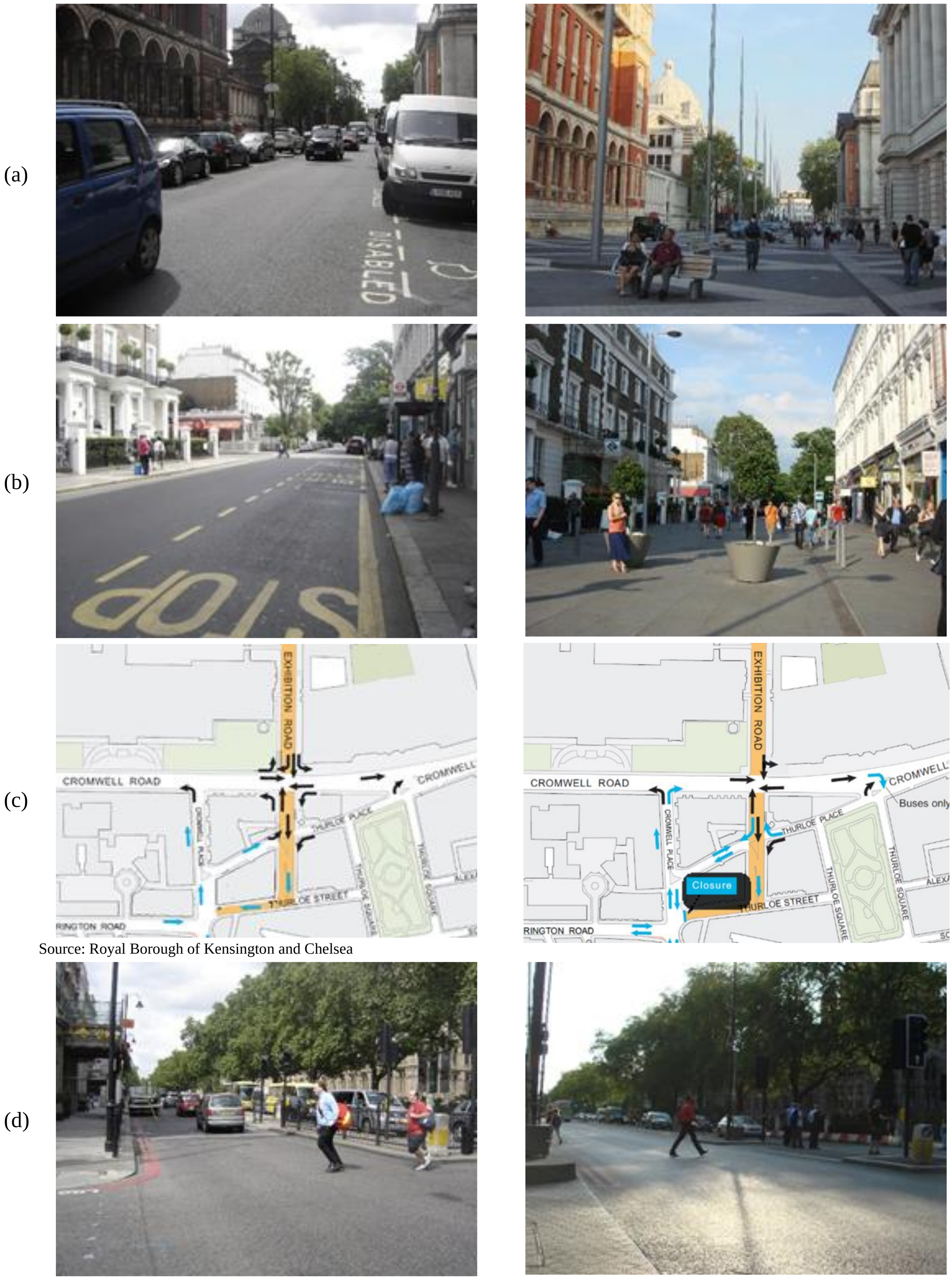
2 METHODOLOGY

Study site

A well-known cultural quarter, South Kensington is home to multiple museums, cultural venues and academic institutions. The area is centred on the 800 m long Exhibition Road – a street frequented by large numbers of regular and occasional visitors, whose previous conventional 24-m wide dual carriageway layout was often dominated by crowded footpaths and traffic congestion. This prompted the local authorities in 2008 to commission a scheme, which implemented a more pedestrian-friendly streetscape with integrated street design features (Figure 2).

The project ran from mid-2008 to late 2011 and comprised the following streetscape treatments:

1. <u>Re-allocation of street space</u> (Figure 2a): The street's 16-m wide dual carriageway layout with one lane per direction and excess width for parked vehicles has been removed, with traffic having been shifted to the eastern side of the road to occupy an 8-m wide single carriageway. The former western side of the divided roadway now accommodates primarily pedestrians. The space has also seen an end-to-end level surface replace the previous traditional "kerbed" layout.
2. <u>Traffic management changes</u> (Figure 2b and 2c): A one-way system that was in place around the South Kensington Station area (with the southbound traffic led along the southern tip of Exhibition Road and along Thurloe Street and the northbound traffic guided along Thurloe Place) has been replaced by a two-way conversion of Thurloe Place (now accommodating both northbound and southbound traffic) and a conversion of Thurloe Street to access-only. This has been accompanied by a set of turn bans aiming at reducing traffic demand on Exhibition Road by re-directing in onto alternative routes.
3. <u>Re-design of pedestrian crossing facilities</u> (Figure 2d): A staggered north-south pedestrian crossing on the western side of the junction of Exhibition Road with Cromwell Road has been replaced by with a wide 12-m straight-across crossing, allowing pedestrians to cross in a single phase. Pedestrian guardrails have also been removed.



Source: Royal Borough of Kensington and Chelsea

FIGURE 2: Exhibition Road before (left) and after redevelopment (right)

Data collection

Video footage has been collected through high-mast cameras for periods before and after the redevelopment as part of recent studies analysing traffic conflicts, pedestrian and vehicle behaviour and interactions, gap acceptance, and quality of service in the area [8, 11-13, 15]. Here, the footage is used to assess the impact of the new integrated design on the fundamental diagram of motorised and pedestrian traffic. In the before-case, the data come from four of key locations around the site on selected days in August 2008, prior to the start of the redevelopment works (Figure 3, left). For the after-case, the footage comes from the same locations on selected days in October and December 2011, following completion of the scheme (Figure 3, right). Two of the four locations are considered here, and specifically:

- *L1: Exhibition Road* (*Before: Camera A – After: Camera 3*):
  In the original layout, pedestrians were confined in a 4-m wide sidewalk that was often crowded by queuing visitors for the various museums, acting as a barrier to pedestrian movement. At the same time, vehicle traffic was often interrupted by alighting buses in front of the museums. These issues are addressed in the new layout through more pedestrian space and designated bus alighting areas.
- *L4: Thurloe Street* (*Before: Camera F – After: Camera 2*):
  Pedestrians using this location in the original layout were faced with two problems: non-provision of adequate crossing facilities, and insufficient space for pedestrians on the southern footpath. In the new layout, this location has been re-designated as “access-only”.

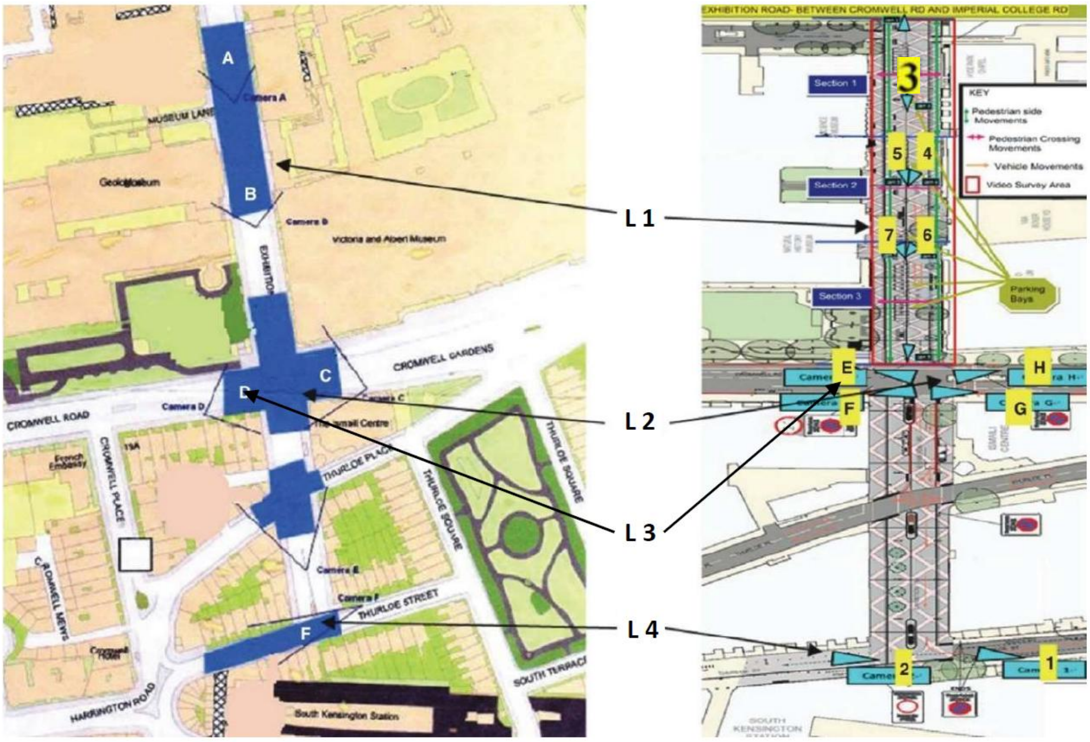


FIGURE 3: Camera locations at the Exhibition Road site in the before- (left) and after-monitoring (right)

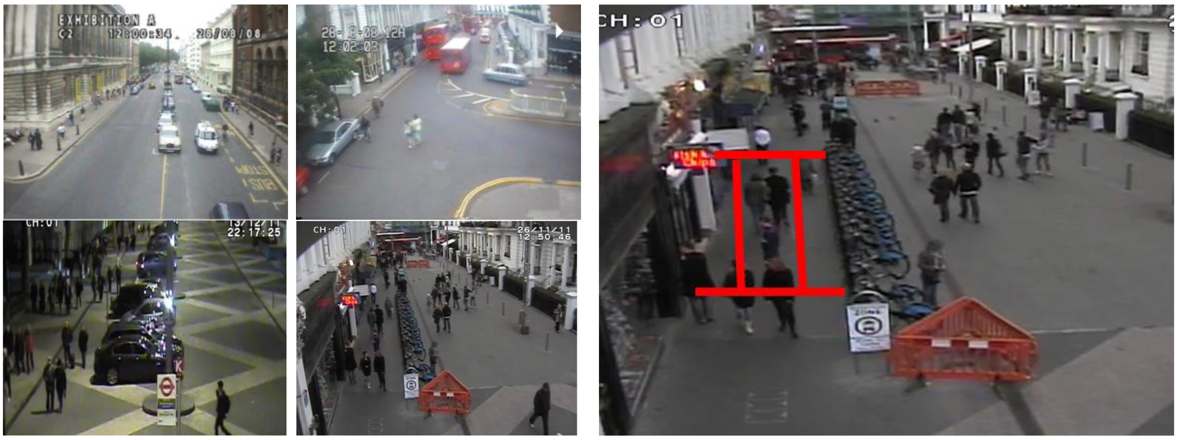
Data extraction

Measurements of relevant traffic variables are extracted from the footage through manual processing, using a 5-min aggregation interval. For each interval, the following are calculated:

- *Average vehicle traffic flow* by defining a fixed 40-m long section on the carriageway (where relevant) and counting the number of vehicles entering it and exiting from it;
- *Average vehicle traffic speed* by measuring the time taken for each vehicle to travel through the fixed section, dividing the distance by it to obtain point speeds, and then calculating the average (space-mean) speed as the harmonic mean of the point speeds;
- *Average traffic density* by applying traffic flow continuity and dividing the average flow by the (space-mean) speed;

- *Average pedestrian flow* by defining 1-m wide by 3-m long sections ("bottlenecks") in the footage at various locations and counting the number of pedestrians walking through them, as per the method documented in [16];
- *Average pedestrian density* by counting the number of pedestrians in the various "bottlenecks" at various fixed time points, as per the approach described in [17]; and
- *Average (space-mean) pedestrian speed* by applying traffic flow continuity and dividing the average flow by the density.

Data are extracted for periods both before and after the redevelopment. The exact times of the 5-min intervals have been selected from the footage on various days between 08.00 and 20.00, striving for a good spread of congested and uncongested conditions for both motorised and pedestrian traffic. An example illustration of the data extraction carried out is shown on Figure 4.



(a) (b)

FIGURE 4: (Left) examples of footage used – before (top) and after (bottom) the re-design: (a) Exhibition Road (L1), (b) Thurloe Street (L4); (Right) "bottleneck" method for extracting pedestrian traffic measurements.

Analysis methodology

The analysis proceeds by assimilating the measurements extracted and fitting flow-density curves using Ordinary Least Squares regression. A curve is fit for each of the two locations of South Kensington (L1 and L4), before and after the redevelopment, for motorised traffic and pedestrians (except for the after-case motorised traffic of Thurloe Street (L4), for which no data has been collected, as it has been converted to an access-only street and therefore no longer carries any substantial traffic flows). A total of seven flow-density curves are, hence, fit.

Each curve is fit on the basis of 80-100 data points, whereby each point represents a 5-min interval with a corresponding flow and density value combination. The quadratic form, corresponding broadly to the Greenshields fundamental diagram [18], is selected as the preferred form, as it is found to offer the best fit to the data as a result of trials with other relevant forms, such as linear and triangular.

The flow-density curves are, then, compared to each other, for motorised traffic and pedestrians respectively. Comparisons during the same time period (before or after) between the two locations provide an insight into site-specific differences. More crucially, comparisons at the same location between the different time periods (before and after) enable drawing conclusions as to the potential effects that the implementation of integrated street design features may have had on the relationships of the key phases of traffic behaviour, from free-flow to congestion and, ultimately, to traffic breakdown. Of particular interest, to this end, is the determination of the capacity flow and of the corresponding density value.

3 RESULTS AND DISCUSSION

Motorised traffic

The flow-density curves for motorised traffic for the South Kensington site before and after the redevelopment are shown in Figure 5. The curves confirm the notable reduction of speeds and flows across the site found by previous related studies. The free-flow speed is estimated as 40 km/hr before the redevelopment, dropping to 26 km/hr post-redevelopment, while the capacity flow drops from around 700 veh/hr (with a range of observed values of 600-800 veh/hr) in the before-case to about 520 veh/hr (with a range of 500-550 veh/hr). Student's t-tests at the 5% level confirm these differences as significant.

What is most interesting, however, is that the capacity density remains broadly similar before and after the redevelopment (around 73 veh/km before and 67 veh/km after, both with a range of 60-80 veh/km). This is consistent across the entire range, whereby the same flow values in the after-case are associated with higher density (and, consequently, lower speed) than the before-case, and indicates a potential change in the intrinsic relationships between flow and density (and speed) as a result of the implementation of the integrated street design features, which is beyond the direct effect of merely reducing the demand and the supply (by re-routing flows elsewhere through the turn bans and by removing one lane of traffic in each direction). Furthermore, it is noted that the after-curve exhibits a considerably lesser degree of scattering (as portrayed by a higher coefficient of determination), which implies stabler and less agile driving, in addition to the slower speeds. Both these findings are indicative of more pedestrian-friendly traffic conditions, irrespective of congestion levels, as intended by the redevelopment.

Comparisons cannot be made for the Thurloe Street location (L4) given its conversion to an access-only street. However, it can be observed that the fundamental diagram before redevelopment is broadly similar to the one for Exhibition Road (L1), with similar speeds in the uncongested traffic state and capacity flow and density values of the same order.

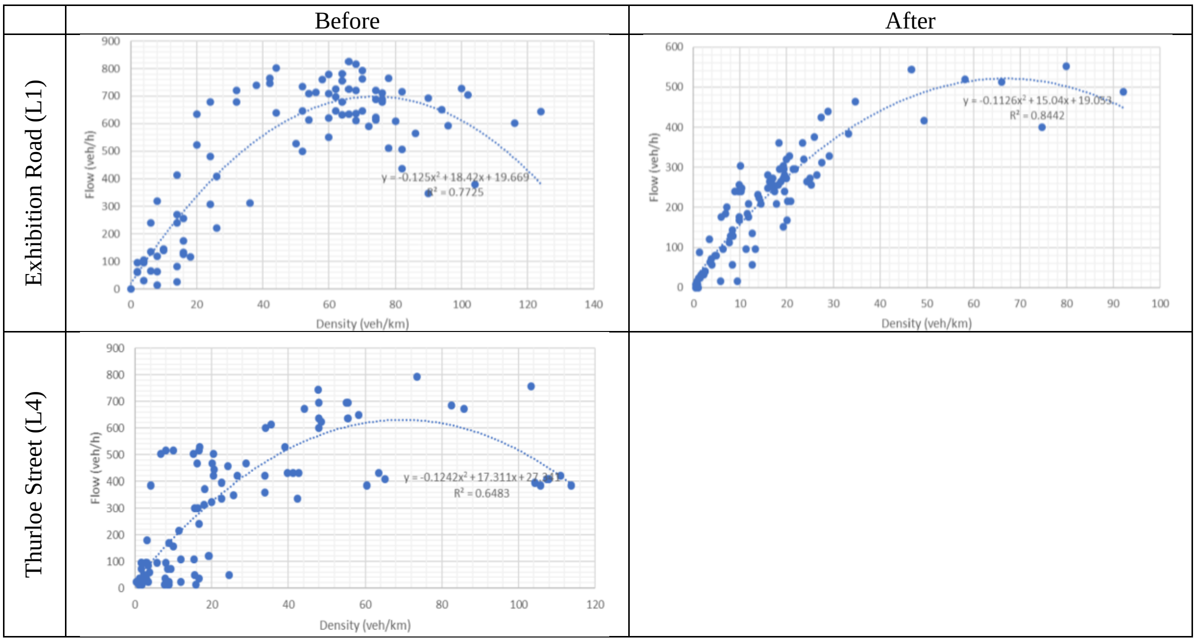


FIGURE 5: Flow-density curves for motorised traffic before and after redevelopment

Pedestrians

Considering the pedestrian flow-density curves (Figure 6), and looking first at Thurloe Street (L4) (i.e. the bottom set of curves), a clear increase in the capacity is noted, and specifically from about 0.12 ped/sec (with a range of observed values of 0.10-0.16 ped/sec) to about 0.19 ped/sec (with a range of 0.16-0.22 ped/sec), which is coupled with a corresponding increase in the capacity density from about 0.05 ped/m^2 (with an observed range of 0.04-0.06 ped/m^2) to around 0.09 ped/m^2 (with a range of 0.07-0.10 ped/m^2). Student's t-tests at the 5% level confirm these differences as significant. While this clearly demonstrates a much wider uncongested regime as a result of the substantial additional space given to pedestrians at that location, however, attention must also be given to the notable drop in pedestrian speeds that is observed in the after-case compared to before, with pedestrian free-flow speeds estimated as 2.1 m/sec before and 1.3 m/sec after the redevelopment. This is, overall, consistent with previous findings that noted more relaxed walking behaviour in the pedestrian-dominated after-design compared to more rushed walking in the car-dominated and pedestrian-unfriendly before-case, and is suggestive of a change in the fundamental relationship between flow, speed and density, effected by the implementation of integrated street design features.

A similar picture emerges from the pedestrian flow-density curves of Exhibition Road (L1) (i.e. the top set of curves on Figure 6), though much less pronounced. Again, an increase in pedestrian capacity is observed, and specifically from about 0.11 ped/sec (with a range of observed values of 0.09-0.12 ped/sec) to about 0.13 ped/sec (with a range of 0.11-0.14 ped/sec), combined with an increase in the capacity density from about 0.045 ped/m^2 (with an observed range of 0.04-0.05 ped/m^2) to about 0.07 ped/m^2 (with an observed range of 0.06-0.07 ped/m^2). While only marginal, these changes are statistically significant at the 5% level. They are also accompanied by very small (statistically insignificant at the 5% level) reductions in the pedestrian free-flow speed. These findings can be attributed to the fact that, unlike Thurloe Street (L4) where motorised traffic access has been restricted, vehicles remain present on Exhibition Road (L1) post-redevelopment, which causes pedestrians to be more aware of their surroundings and, therefore, make only small changes to their walking behaviour.

It is, finally, noteworthy that, just like for motorised traffic, the pedestrian after-curves of both locations exhibit considerably less scattering than the before- ones (as shown by the considerably higher coefficients of determination), thus reinforcing the finding of more relaxed, stabler and less agile walking behaviour in the presence of integrated street design features.

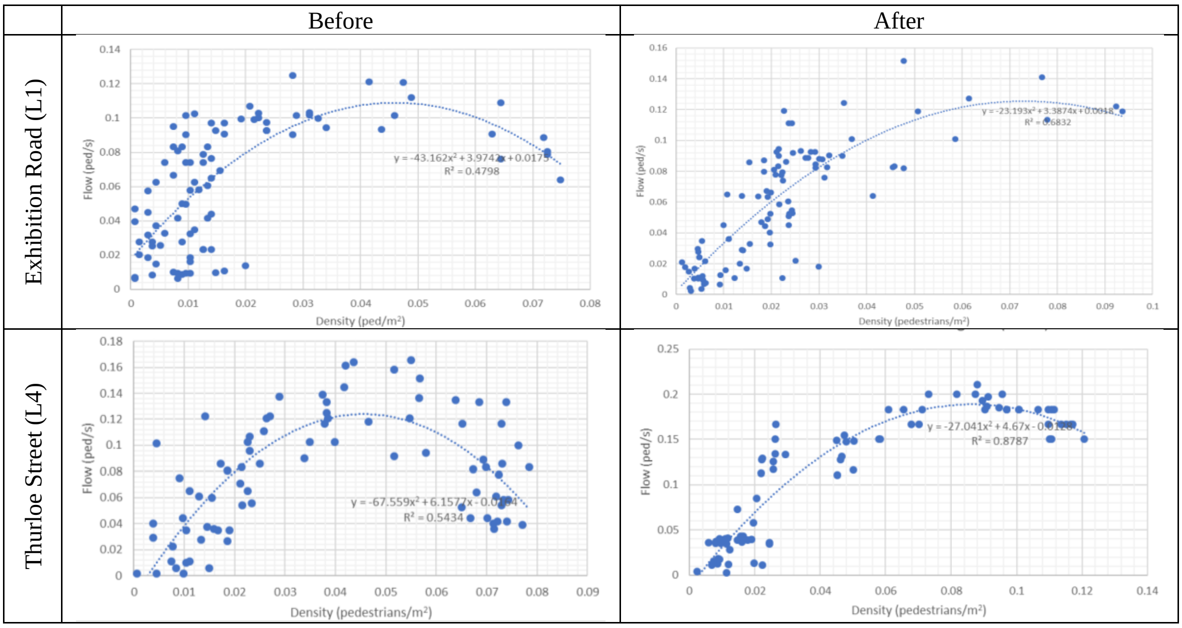


FIGURE 6: Flow-density curves for pedestrians before and after redevelopment

4 CONCLUSION

The present study has provided an initial empirical insight into how the implementation of integrated street design features may impact the inherent relationships between flow, speed and density of both motorised and pedestrian traffic, with findings indicating stabler and more relaxed driving and walking behaviour, irrespective of increases and decreases of demand and supply. However, this is only the beginning of the investigation of this topic, and research in this direction continues. Next steps will concentrate on formalising, validating and extending these findings, through: extraction of more data points with automated means; use of more advanced curve-fitting methods and tools, such as machine learning; systematic investigation of unexplained heterogeneity contained in the residuals of the fitted curves; consideration of capacity-drop and hysteresis phenomena; and analysis of any impacts at the macroscopic level.

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