Journal of Transport & Health 27 (2022) 101522

Contents lists available at ScienceDirect

Journal of Transport & Health

journal homepage: www.elsevier.com/locate/jth

Road traffic reduces pedestrian accessibility – Quantifying the size and distribution of barrier effects in an African city

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ARTICLE INFO

Keywords:
Roads
Pedestrians
Walking
Barrier effect
Community severance
Equity
Developing countries
Mobility
Accessibility
Urban transport
Africa

ABSTRACT

Background and objective: Motorised traffic is growing rapidly in many African cities, creating barriers to the movement of pedestrians. This paper analyses the barrier effect of roads in Praia, the capital of Cabo Verde. We measured the barrier effect to potential trips to homes of other people and to food shops and analysed the distribution of the effect across areas and social groups. The paper contributes to the literature by: 1) quantifying the barrier effect of roads for the first time in an African city; 2) mapping the effect at the city level, and 3) developing indicators that account for land use (i.e. what is on the other side of the road).

Methods: We used spatial analysis to estimate, for each building in the city, two indicators: the proportions of the areas of other buildings and of food shops within 600m that are located across main roads. We then analysed the distribution of those indicators using maps, descriptive statistics, cumulative frequencies, bivariate associations, and regression models.

Results: In some areas, roads are estimated to curtail more than 70% of the walking accessibility potential of residents. The effect is higher in older informal settlements than in formally planned areas or newer informal settlements, and it disproportionately affects individuals aged 65+. The effect is lower for households with very high and very low socio-economic status than for those with high, medium, or low status. The indicators are robust to changes in the assumptions (e.g. type of roads included, maximum walking distance, attractiveness of destinations) and provide extra information, compared with simpler indicators (e.g. distance to roads or length of roads within a certain distance).

1. Introduction

The number of motorised vehicles (private cars, motorcycles, and paratransit) is growing rapidly in many African cities, and so is the provision to accommodate those vehicles, i.e. new, wider, and better roads. However, this has been to the detriment of walking and other non-motorised means of transport. Crossing roads has become dangerous and unpleasant due to the high traffic volumes or speeds, and to the lack of suitable pedestrian crossing facilities.

This problem is known as the barrier effect of roads, or community severance. The barrier effect is both a transport and a health issue (Anciaes et al. 2016). It is caused by transport infrastructure (and poor pedestrian infrastructure), but through its effects on suppressed walking trips, it can affect access to goods and services, physical activity, independent mobility, social inclusion, social

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https://doi.org/10.1016/j.jth.2022.101522
Received 9 September 2021; Received in revised form 22 September 2022; Accepted 17 October 2022
Available online 2 November 2022
2214-1405/

interaction, and ultimately, physical and mental health. While neglected for a long time, this problem is gathering more attention from researchers and planners, resulting in more evidence on its negative effects and more methods to measure its incidence.

Most research in this field has used European or North American case studies. However, the barrier effect of roads is now a pressing problem in many African cities, where, despite the growth in motorised traffic, walking is still the dominant mode, especially for groups most at risk of social exclusion (the poor, especially women and older people). To address this problem, this paper analyses the barrier effect of roads in a small but growing African city: Praia, the capital of Cabo Verde islands. We quantify and map the barrier effect of roads on two types of walking accessibility: to social networks (homes of others) and amenities (food shops). We also analyse the spatial and social distribution of the effect.

2. The barrier effect of roads

2.1. Concepts, evidence, methods

The barrier effect of roads is caused by two aspects: road design (i.e. number of lanes, physical barriers, median strips, crossing facilities) and motorised traffic (i.e. traffic volume, proportion of heavy vehicles, speed, drivers' compliance with regulations). It either leads to detours to walking trips (if pedestrians respond to the barrier by walking further to cross in safe locations) or to higher collision risk (if they cross in convenient, but unsafe, locations). To avoid these two scenarios, pedestrians may choose not to walk, and either use motorised modes or forego the trip altogether (Hine 1996; Mindell et al. 2017; Anciaes et al. 2019).

Living near busy roads is associated with smaller local social networks, as motorised traffic discourages people from making connections with their neighbours (especially those on the other side of the road, but also those on the same side) (Appleyard and Lintell 1972). There is also recent evidence on the negative impacts of the barrier effect on health and subjective wellbeing. Higgsmith et al. (2022) found a dose-response association between the perceived barrier effect of roads and self-rated health: the higher the barrier effect, the higher the probability of reporting poor health. Anciaes et al. (2019) showed that perceptions of high traffic volume and speed were linked to lower subjective wellbeing among people living near major roads, through the intermediate impacts on less pleasant and less frequent walking trips. Foley et al. (2017) found lower subjective wellbeing among people living near a motorway, although the link with walking was not specified.

There were also recent developments in methods. Mindell et al. (2017) developed a suite of tools to study the barrier effects of roads, including spatial analysis, street audits, participatory mapping, surveys, and stated preference methods. Anciaes and Jones (2020) integrated stated and revealed preference methods to derive an indicator of the barrier effect that considers the characteristics of road design, motorised traffic, and crossing facilities. The indicator was also linked with monetary values, which can be included in cost-benefit analyses. Van Eldijk et al. (2020) quantified the reduction of accessibility caused by barriers and Filomena et al. (2020) simulated how pedestrians react to the presence of those barriers. Lara and Da Silva (2019) analysed equity issues related to barriers caused to railways. The study of Anciaes (2011) is the only one to our knowledge that mapped the barrier effect of roads at the city level, but considered only 'absolute' barriers, i.e. infrastructure such as railways and motorways that cannot be used by pedestrians and have physical barriers preventing pedestrians from crossing outside designated crossing facilities.

Apart from the contributions linked to the urban African context (see Section 2.2.), the present study contributes to the literature on the barrier effect by mapping the barrier effect at the city level, extending the methods of Anciaes (2011) by considering 'crossable' roads (i.e. roads without physical barriers). In addition, we estimate indicators of the barrier effect that account for land use, i.e. what is on the other side of the road (homes of other people and food shops). Most previous studies assumed a general need to cross, or focused on perceptions about the road as a barrier in general (not as a barrier preventing access to specific destinations). We chose these two destinations because they are within a reasonable walking distance for most households in our case study city, and because they cover potential barriers effects of roads on local social networks (homes of others) and on access to basic goods (food shops).

2.2. The barrier effect of urban roads in Africa

African cities are diverse, in geographic conditions, size, and spatial and social structure. However, the barrier effect of roads assumes similar characteristics in many cities, due to similarities in colonial history, current population and income growth, income and gender inequality, insufficient public transport, and reliance on walking. The study of Ndiaye (2018) is the only one dealing specifically with the barrier effect of roads in an African city, describing the effect of a new 4-lane motorway crossing through a dense low-income area in Dakar, Senegal.

An obvious cause of the barrier effect on African roads is high traffic volumes, although data is scarce. Because roads are often congested, the role of traffic speed is sometimes neglected. However, high speeds are a problem. For example, Damsere-Derry et al. (2008) found that speed limits were violated by 90–98% of vehicles in urban roads in Ghana (depending on road type).

Another problem is the insufficient provision of crossing facilities. Roads are often built with few or no crossing facilities (see Maina and Wachira-Towey 2020 about the Thika Superhighway in Nairobi). Where they exist, the facilities are usually of the 'wrong' type, i.e. footbridges, which are intimidating and inconvenient by design and are sometimes taken over by motorcyclists and gangs (Maina and Wachira-Towey 2020). At-grade crossing facilities (marked or signalised) are sparsely spaced and have long red phases for pedestrians (Obeng-Atuah et al. 2017). In contrast, the green phases are too short. In Cape Town, 30% of older pedestrians could not finish crossing within the allocated time (Amosun et al. 2007). Furthermore, many drivers do not comply with the crossing regulations. In the study of Masaoe (2017) in Dar-es-Salaam only 19% of drivers stopped for pedestrians. Many pedestrians also do not comply, as shown in two studies in Cape Town: half of pedestrians never used footbridges to cross a motorway (Sinclair and Zuidgeest 2016) and

80% of pedestrians did not use signalised crossings to cross a busy road - which could because of fear of crime around the crossings (Behrens and Makajuma 2017).

The barrier effect of roads leads to the suppression of some walking trips, replaced or not with trips by motorised modes. For example, Zogo et al. (2017) found that the propensity to walk decreased by more than 30% in places without traffic calming measures in Yaoundé, Cameroon. Malambo et al. (2017) also found an association between perceived traffic risk and reduced walking for leisure in cities in South Africa.

Reduced walking then affects social contacts. After the construction of a motorway in Dakar, the proportion of local residents visiting others dropped from 67% to 7% (Ndiaye 2018). Lack of crossing facilities and perceived risk from traffic have also been associated with reduced physical activity, among the general population (Oyeyemi et al. 2012), the elderly (Oyeyemi et al. 2019), and children (Muthuri et al., 2016), in Nigeria and Kenya.

Despite the growing literature studying transport issues in Africa under the lens of social exclusion, no study to date has analysed the barrier effect of roads as a cause of exclusion. This is a gap, as the problem does not affect all groups equally. Busy roads and poor pedestrian infrastructure affect the independent mobility of both the youngest and oldest groups. Women and the poor are also affected due to their higher reliance on walking. It is possible that the poor are also disproportionately affected due to higher likelihood of living close to busy roads (if the negative environmental effects of these roads are capitalized in land/house prices). However, there is no evidence on these hypotheses.

The methods used in the studies mentioned above include surveys, focus groups, and audits of road and pedestrian infrastructure. We found a single example of a study of stated preferences of pedestrians in an African context (Mofadal et al. 2015, in Sudan). No studies have mapped barrier effects in African cities. In a previous analysis of our case study city (Praia), Anciaes et al. (2017) quantified the length of roads inside each neighbourhood. However, this is an indicator of the overall negative effect of roads (including noise, air pollution, and collision risk), not exclusively of the barrier effect on pedestrians.

The present study covers these gaps, both in terms of supplying evidence (on barrier effects of roads and their equity dimensions) and developing methods (by quantifying the barrier effect of roads for the first time in an African city).

3. Praia

In the African context, Praia is a small city. However, it is growing fast: 24,000 inhabitants in 1960, 132,000 in 2010, and 188,000 in 2023 (projection) (CMP 2016a, p.51, 58). The area of the city has expanded accordingly. Most of the growth was due to the emergence of informal settlements, which in 2016 represented 55% of the city's built up area and 75% of the buildings[1] (Fig. 1). Praia has the highest income in Cabo Verde (which is classified by the World Bank as a lower middle-income country). However, income inequality is high, with a Gini index of 52%, and 15% of the city's population living in poverty (CMP 2016a, p.74).

Car ownership is small (19% of households have a car) but the number of vehicles on the road has been increasing 8.8% per year (CMP 2016a, p.282). Public transport is insufficient: bus routes link distant neighbourhoods with the city centre along main roads, but do not link the neighbourhoods on opposite sides of those roads. Informal public transport is illegal for intra-urban trips (but common). Cycling is almost inexistent, and impractical for inter-neighbourhood movement in a city made up of hills. In many places, walking is the only option for households with no access to a private vehicle.

Fig. 1 shows the city's built-up area and Levels 1 and 2 of the official road hierarchy. The city has expanded in all directions, along Level 1 roads. Level 2 roads exist in some areas only. In other areas there are only (mostly unpaved) Level 3 roads (not shown in the map) or informal footpaths. Arterial roads have been constructed or upgraded recently, including four radial roads. These roads are wide (up to four traffic lanes) and have either high traffic volumes (at peak times) or high speeds (at other times) (Fig. 2, left). Cobblestone roads can also be a barrier when they are in poor condition or flooded. There are few pedestrian crossing facilities. Footbridges are inconvenient and underused (Fig. 2, right). Signalised crossings are a mix: effective in some areas but not in others.

New roads are planned, including an inner ring road. Some of these roads will cut through densely populated informal settlements. Some existing roads will be enlarged, and signalised crossings will be replaced with underpasses. These changes will increase the barrier effect to pedestrians and reduce inter-neighbourhood accessibility. However, at the same time, the reduction of barriers is a policy priority, as mentioned in the municipal master plan (CMP 2016b, p.27). It is therefore useful to have an assessment of where the existing barriers are currently more impactful to pedestrian accessibility, and how the impact is distributed across social groups. That is the objective of this paper.

4. Data

4.1. Buildings

We estimated indicators of the barrier effect of roads for each building in the city. Spatial data was provided by the municipal government, including the location and ground floor shape of buildings and information on number of floors. The original dataset contained 66,795 buildings. After removing duplicate shapes and buildings with ground floor areas less than 10 m^2 (not likely to be residential), the dataset contained 38,910 buildings for further analysis. We then calculated the gross floor area of each building as the

[1] Calculated from spatial data on buildings (provided by the municipal government) and type of zones (geo-coded from image in CMP 2016a, p.215). The calculation excludes isolated buildings.

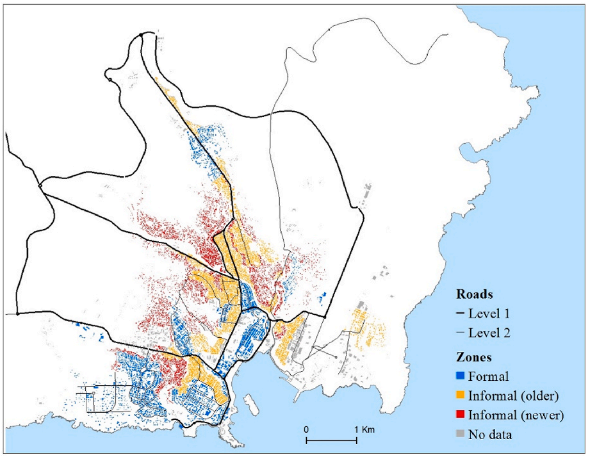

Fig. 1. Praia-context, urban area, major roads, formal/informal zones.

Fig. 2. Aspects of the barrier effect of roads in Praia.

product of ground floor area and number of floors.

4.2. Food shops

Three types of food shops were considered: markets, supermarkets, and minimarkets. The total number of shops was identified in the Municipal Master Plan (CMP 2016a, p.378): 8 markets and 68 supermarkets and minimarkets. These numbers were disaggregated in the Master Plan by five regions, but the exact location of the shops was not available. We manually mapped in a GIS (geographic information system) the location of all shops, using information from various sources:

- The 8 markets were located based on the authors' knowledge of the city.
- The minimarkets and supermarkets were initially located using information from a list of all private companies in the city in 2011, provided to the authors by the National Institute of Statistics. The list contained the addresses of all minimarkets. Where the address was complete, we geo-coded minimarkets manually, referring to street maps in Open Street Map and Google Maps (two web map platforms). The address of 12 minimarkets was incomplete (it consisted only of the neighbourhood name). In addition, for supermarket chains with several branches, the list included only one record, with the address of the company headquarters.
- The location of 20 supermarket branches and 4 of the 12 minimarkets with incomplete address could be identified in either Open Street Map or Google Maps.
- The map of the located shops was finally compared with the maps in the study of Nascimento (2003), which contained all shops in 2003. This allowed us to locate the 8 minimarkets that remained unlocated. We acknowledge that some of these 8 minimarkets may not be correctly located, due to changes occurring since 2003. However, they are located in the correct neighbourhood, as given by the list of private companies mentioned above.

4.3. Roads

Spatial data on roads was provided to the authors by the municipal government. The dataset includes only formal roads and streets (as defined by the government), not informal footpaths between buildings and across open spaces. We removed roads outside the urban area and split the remaining roads at junctions. We then identified the roads classified as Levels 1 and 2 in the official road classification, using information from a map included in the municipal master plan. The map was only available as an image file (CMP 2016c), which we geo-coded manually. Level 1 includes 131 road segments, with a mean length of 198m. Level 2 includes 425 segments, with a mean length of 88m. We identified the number of lanes of all road segments by overlaying the roads dataset with an orthophoto, provided by the municipal government, and manually counting number of lanes. The existence and size of a median strip (classified as narrow or wide) was also identified. Reliable information on traffic volumes, speeds, and crossing facilities was not available in the dataset and could not be obtained elsewhere. Open Street Map included the location of some crossing facilities, but only in some parts of the city.

4.4. Demographics

There is little demographic data available to researchers at a small level of aggregation (e.g. census units). We found two solutions to this problem. The first solution was to use data at the building level:

- Ground floor area (not multiplied by number of floors). This is a possible proxy for the socio-economic status of the residents, as dwelling size is probably related to household income (we are not able to confirm this hypothesis due to lack of data). Furthermore, in Praia, there are few dwellings sharing the same floor of the same building.
- Type of zone where the building is located. This was identified from a map in the municipal master plan classifying zones into: formal, "consolidated informal" (henceforth: "older informal"), informal (henceforth: "newer informal"), and isolated buildings. Formal areas are those that have been urbanised under the remit of official land use plans and regulations. Informal areas (also known in the planning literature as informal settlements) are those originally settled by residents outside the remit of plans and regulations and have little or no infrastructure. Over the years, informal areas in Praia have received some infrastructure. These are classified as "older informal areas". Isolated buildings are those that are not part of a neighbourhood (as defined in the master plan). The map with these four types of zones was available as an image file (CMP 2016a, p.215). We manually geo-coded the image and then assigned a type of zone to each building.

The second solution to the lack of detailed demographic data was to use data at the neighbourhood level. There are 53 urban neighbourhoods in the city, as defined by the municipal government. These exclude neighbourhoods inside the city's administrative borders but classified as rural. Urban neighbourhoods have an average of 843 buildings and 2741 residents. Socio-economic data (from the 2010 population census) was provided to the authors by the National Institute of Statistics. We used data on: 1) age groups (<15, 15–64, or 65+); 2) sex of household head; and 3) level of material comfort of the household (very high, high, medium, low, or very low). Levels of material comfort (henceforth: "comfort levels") are a composite indicator of ten variables: people per bedroom; access to electricity, piped water, and toilet; use of gas for cooking; and ownership of fridge, car, TV, radio, and CD/DVD player (INE and, 2010; Ch.VII). We did not use data on income, as it was missing for 63% of the households. Other proxies for income were not used because they were correlated with comfort levels. For example, the illiteracy rate had a correlation of −0.83 and 0.71 with the proportion of high/very high and low/very low comfort levels, respectively. Likewise, the proportion of households with no car had a correlation of −0.95 and 0.78 with the proportion of high/very high and low/very low comfort levels, respectively.

5. Methods

5.1. Barrier effect of a road segment

We assigned a barrier effect to each road segment (i.e. the 131 Level 1 and 425 Level 2 road segments), using the scale developed by Anciaes and Jones (2020). This scale is based on pedestrian preferences. The minimum value is zero, representing indifference between crossing the road segment in question and crossing the road in a place where the road goes through a tunnel and pedestrians can cross unimpeded at surface level. The maximum value is 100, representing indifference between crossing the road segment in question and not making the trip (foregoing the utility of accessing destinations across the road). The barrier effect of a road segment depends on number of lanes, presence and size of a median strip, traffic volumes, and traffic speed. In our case study, we have no information on traffic volumes and speeds, so we took the average of the indicators for medium and high traffic levels and 30-40mph (in road segments with 3 lanes in each direction) and 20-30mph (in other road segments). As such, using the Anciaes and Jones (2020) scale, the indicator in our case study can assume values from 28 (1 lane, wide median) to 93 (3 lanes, no median).

5.2. Barrier effect of trips to other people's homes and food shops

We then identified, for each building, the set of other buildings within 600m, recording which of those other buildings are food shops. Several studies have estimated the statistical distribution of walking distances, and the respective means or medians, in various cities. However, the results vary widely. In addition, most studies estimated distances for trips to work or to public transport nodes, not for trips to other people's homes or shops. In this study, we used a distance of 600m. In Section 7, we report the results of a sensitivity analysis, using alternative distances (400m and 800m).

We found that 7.8% of buildings did not have any shop within 600m. In these cases, we have extended the maximum distance to 1600m. This walking distance is plausible in areas with low density of shops - often the case in African cities. For example, the results of

De Lange and Vorster (1989) and Pienaar (1994) (cited in Behrens 2005) in three South African cities found a walking distances of 1600m for shopping trips.

We used straight-line distance because there are many informal footpaths in all parts of the city, allowing for almost straight routes for short trips. As noted previously, these paths were not included in the available roads dataset. Geo-coding them from orthophotos would be too time-consuming for little additional precision, compared with using straight-line distances. However, we adjusted distances by using information on slopes, applying Tobler's hiking function (*speed=6*exp(-3.5*|0.05+slope|)*) (Tobler 1993). Spatial data on slopes was provided by the municipal government.

We then identified the road segments crossed by the lines from each building to other buildings within 600m. The combined barrier effect $b_{i,j}$ caused by the set of road segments r crossing the line from building i to building j is defined as the sum of the barrier effect caused by each individual road segment $b_{i,j,r}$. The barrier effect is capped at 100.

$$b_{i,j} = \begin{cases} \sum_r b_{i,j,r} \ if \ \sum_r b_{i,j,r} \leq 100 \\ 100, if \ \sum_r b_{i,j,r} > 100 \end{cases}$$

For a given building i, the indicator of the barrier effect BE_i for trips to other people's homes is then the sum of the barrier effect $b_{i,j}$ of trips to each building j within 600m, weighted by the gross floor area A_j of those buildings.

$$BE_i = \frac{\sum_j A_j b_{i,j}}{\sum_j A_j}$$

As an example, let us consider a building with two other buildings within 600m, with the same gross floor area. Accessing Building 1 does not involve crossing a road (i.e. $b_{i,1} = 0$). Accessing Building 2 involves crossing a road with 3 lanes and no median (i.e. $b_{i,2} = 93$, according to the Anciaes and Jones (2020) scale). The barrier effect for that building is then $BE_i=(0+93)/2=46.5$. The interpretation of this value is that roads are estimated to curtail 46.5% of the walking accessibility potential of the building considered, or alternatively, 46.5% of the potential for social interaction for the residents in the building.

The indicator of the barrier effect for trips to food shops was defined in a similar way. The difference is that in the formulas above, instead of all buildings within 600m, we considered only buildings within 600m that are food shops. The indicator represents the proportion of the potential walking accessibility to shops (or alternatively, the proportion of shopping opportunities) that is restricted by roads.

The two indicators assume that the attractiveness of a destination (home of other people or food shop), within the set of destinations within 600m (or 1600m, when no food shop exists within 600m), is directly proportional to the area of the destination. An alternative would be to assume that the attractiveness is inversely proportional to distance. In Section 7, we report the results of a sensitivity analysis using this alternative assumption.

5.3. Distribution of the barrier effect

The analysis of the distribution of the two indicators of the barrier effect was conducted separately at two levels: building and neighbourhood. The analysis at the building level produced four types of outputs:

- Maps of the indicators
- Statistics of the distribution of the indicators, overall and by type of zone (formal, older informal, newer informal, and isolated).
- The cumulative distribution of the indicators by type of zone. The Kolmogorov-Smirnov test was used to compare the distributions of all pairs of zones.
- Regression models of the indicators.

The models used a fractional regression specification, with a logit link (Papke and Wooldridge 1996), as the indicators are bounded within the 0–100 interval (representing 0–100% of the accessibility potential of each building). The model restricts the predictions to be within that interval. The indicators were first transformed to percentages. Two models were then estimated for each indicator. The first model included spatial variables: distance to the city centre (identified as the main market), location in the coastal strip (between the sea and a Level 1 road running along the coast - see Fig. 1) and number of buildings within 600m (an indicator of density). The second model included variables that are indicators of socio-economic status: building floor area and dummy variables for the type of zone. The two types of variables (spatial and socio-economic) were not included in the same model due to high correlations among them. In both models, quadratic specifications were tested for all continuous variables.

The analysis at the neighbourhood level considered the following demographic variables (as absolute numbers or proportions): households with very low, low, high, and very high comfort levels, households by sex of the household head, and population by age group (less than 15, 15–64, and 65). The analysis produced three types of outputs:

- Means of the indicators at building level, weighted by demographic variables (as absolute numbers).

- The cumulative distribution of the indicators, split by demographic variables (as absolute numbers). The distribution was estimated assuming a similar demographic profile for all households and individuals living in a neighbourhood (due to the lack of data at a smaller level of aggregation).
- Bivariate relationships between mean barrier effects and each of the demographic variables (as proportions), identifying the type of association (linear, exponential, logarithmic, power, or second order polynomial) that have the best fit. Multivariate rRegression models were not estimated because of the small sample and the strong correlations among the demographic variables.

5.4. Sensitivity analysis

As noted, the specification of the indicators of barrier effect relied on assumptions that may affect the results. We tested the effect of changing some of these assumptions.

- Alternative 1: Considering only Level 1 roads, rather than Levels 1 and 2.
- Alternatives 2 and 3: Assuming a maximum distance of 400m or 800m, rather than 600m.
- Alternative 4: Weighting barrier effects by the inverse of distance to the destination building, rather than by the area of this building. This assumes that the attractiveness of the destination decreases with distance, instead of increasing with area.

We also tested the effect of using simpler indicators that do not account for the characteristics of roads (number of lanes and median strip) or land use (i.e. the set of destinations across the road). These indicators are expressed in different scales and cannot be compared directly with the main indicators developed in the paper. However, we can assess how each indicator varies by type of zone or demographic variables, and compare that variation with the variation when using the main indicators. The alternative indicators are:

- Alternative 5: Distance to nearest Level 1 road
- Alternative 6: Distance to nearest Level 1 or 2 road
- Alternative 7: Length of Level 1 roads within 600m
- Alternative 8: Length of Levels 1 and 2 roads within 600m

6. Results

6.1. Characteristics of buildings and neighbourhoods

Table 1 show the characteristics of buildings. On average, isolated buildings have the largest floor area, followed by buildings in

Table 1
Building characteristics.

	City		Neighbourhoods (means)		Zones (means)			
	Mean	SD	Minimum	Maximim	Formal	Informal (older)	Informal (newer)	Isolated
Type of area (% buildings)	–	–	–	–	20%	37%	38%	6%
Building floor area (m^2)	134	237	36	537	201	127	90	227
Density (general indicators)								
Population/km^2	3472	–	8	21928	–	–	–	–
Buildings/km^2	943	–	0.5	5400	1384	4430	2944	74
Building floor area (% of total area)	13%	–	0.003%	66%	28%	56%	26%	2%
Density(other buildings within 600m)								
Number of buildings	3012	1413	7	4957	2457	3443	3131	1452
Area (1000m^2)	856	438	1.3	1452	967	982	733	506
Density (food shops within 600m)								
Number	6.7	5.6	1.2	18.2	6.4[a]	7.4	6.5 [a]	5.1
Area (1000m^2)	3.0	3.0	0.1	9.7	3.2 [a]	3.2[a]	2.6	3.4
Distance to nearest road (metres)								
Level 1	334	265	42	1963	369	248	388	404
Level 2	301	389	35	2538	239	222	363	596
Level 1 or 2	143	126	35	625	93 [a]	93[a]	210	197
Metres of road within 600m								
Level 1	1217	826	0	2558	1051	1557	1029	867
Level 2	3113	1534	16	5686	3687	3616	2447	2348
Level 1 or 2	4116	2810	0	8326	5716	4478	3077	3213

Notes: Population not available by zone. SD: Standard deviation, Min.: Minimum, Max: maximum. Values for neighbouhoods and zones are the mean values for the buildings they contain.

[a] Pairs of zones with means not significantly different at the 5% level. These pairs were identified from regressions with the zones as explanatory variables, followed by pairwise comparisons of marginal linear predictions.

formal, older informal, and newer informal zones. Older informal zones have the highest number of buildings per km^2, proportion of buildings in the total area of the zone, number and area of other buildings within 600m, and number of food shops within 600m. Buildings in older informal zones also tend to be nearer to Level 1 and Level 2 roads and have longer lengths of Level 1 roads within 600m. There is a wide variation across neighbourhoods as shown by the range of values assumed by all variables.

Table 2 shows the characteristics of the neighbourhoods. There are more households with comfort levels below medium (40%) than above medium (25%). Around half (48%) of household heads are women. Only 4% of population is aged 65+. Again, there is a wide variation across neighbourhoods. There are strong correlations between the proportions of the various comfort levels and age groups.

6.2. Analysis at building level

Fig. 3 show the spatial distribution of the two indicators of barrier effect. The geographic centre of the city has the highest indicators of barriers to other people's homes, in some cases rising above 70. These are areas near several Level 1 roads, or even surrounded by those roads on all sides. They are mostly in older informal zones but also in some formal (and high-income) zones in the city's business centre. High values also occur in the south, in a small (and high-income) neighbourhood between the sea and the Level 1 road that runs along the coast. There are some asymmetries in values across the two sides of the same roads, for example, the Level 1 roads towards the West and the North. This is explained by different building densities: low-density areas that have high-density areas across the road have higher indicators of barrier effect than high-density areas that have low-density areas across the road.

The geographic centre and the southernmost neighbourhood also have the highest indicators of barriers to food shops, with more buildings with indicators above 70%, compared with the indicator of barrier effect to other people's homes. There are also more asymmetries across the two sides of the same road. This is explained by patterns in the location of shops: areas with no shops on their side of the road but with shops on the other side have higher indicators of barrier effect. Some areas that had low indicators of barriers to other people's homes have high indicators of barriers to food shops. This includes a neighbourhood in the South East and some isolated areas in other locations. This is because these areas have no shops, so trips to shops imply walking longer distances, increasing the probability of having to cross roads.

Table 3 shows statistics of the two indicators of the barrier effect. The two indicators have a correlation of 0.69. The mean values of the barrier effect to other people's homes and food shops are 23 and 25, respectively, but vary by neighbourhood, from 0 to 81 and 85, respectively. Only 2% of buildings have zero barrier effect to other people's homes. 13% have zero barrier effect to food shops. The proportion of buildings with indicators above 75% is small. The mean barrier effect to trips to other people's homes is highest in older informal zones (28), followed by formal and isolated zones (22) and newer informal zones (18). The mean barrier effect to food shops is highest in isolated buildings (30), followed by older informal zones (26), formal zones (24) and newer informal zones (22).

Fig. 4 shows the cumulative distribution of the two indicators, by type of zone. All pairs of distributions are statistically different, as shown by the Kolmogorov-Smirnov test ($p < 0.001$). The curve for older informal areas is below the others for values between around 10–35. The curve for isolated buildings is above the others for values up to around 15, but below the others for almost all values above 35, i.e. these buildings tend to have more small values but also more high values than buildings in other zones. The curve for newer informal zones is consistently above the curves for formal and older informal zones, i.e. newer informal zones tend to have smaller barrier effects across the range of all possible values of the indicator.

The cumulative distributions of the indicators of barrier effect to food shops, by type of zone, are less smooth than the ones of the indicator of barrier effect to other people's homes. This is because the calculation is for a smaller set of destinations, which means there are several buildings with the same subset of shops within 600m, accessed by crossing the same roads. As such, these buildings have the same barrier effect. The distributions in formal and new informal areas follow a similar pattern (but still significantly different). Again,

Table 2
Neighbourhood characteristics.

	Weighted mean	SD	Minimum	Maximum	Correlations			
					% female	%<15	%15-64	%65+
Comfort level (% of households)								
Very high	8%	10%	0%	79%	−0.45***	−0.70***	0.72***	0.28*
High	17%	9%	0%	43%	−0.30**	−0.78***	0.65***	0.53***
Medium	35%	7%	0%	46%	0.27*	−0.19	0.06	−0.26*
Low	32%	13%	0%	68%	0.37**	0.87***	−0.78***	−0.52***
Very Low	8%	5%	0%	75%	0.08	0.71***	−0.59***	−0.48***
High or very high	25%	17%	0%	94%	−0.42***	−0.81***	0.76***	0.44***
Low or very low	40%	17%	0%	100%	0.30**	0.88***	−0.78***	−0.54***
Household head (% of households)								
Female	48%	5%	15%	74%	–	0.23	−0.35**	0.05
Age (% of population)								
<15	31%	4%	11%	44%	–	–	–	–
15-64	65%	3%	56%	79%	–	–	–	–
65+	4%	2%	0%	17%	–	–	–	–

Notes: Excludes neighbourhoods with less than 10 inhabitants. Means and correlations weights neighbourhoods by number of households. Significance levels of correlations: ***<1%,**<5%,*<10%. SD: Standard deviation.

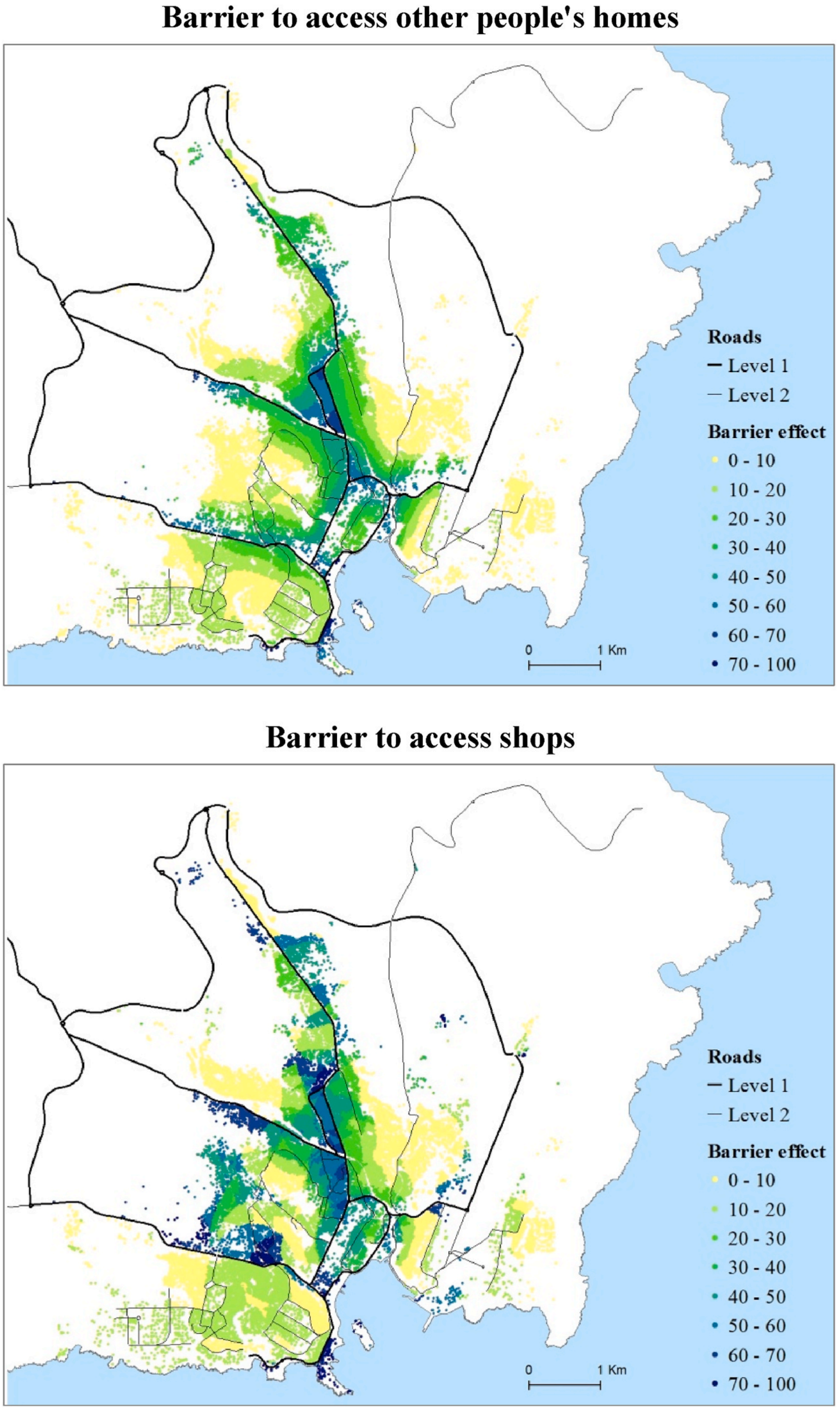

Fig. 3. Spatial distribution of barrier effects.

isolated buildings have more small values and more high values than buildings in other zones. In particular, the curve for isolated buildings is markedly below the other curves, for values above 30.

Table 4 shows the fractional regression models of the two indicators. In the models with spatial variables (Models 1a and 1b), distance to the city centre is significant, with quadratic relationships with the two indicators: distance to centre decreases the barrier effect, but the decrease is progressively smaller. Buildings in the coastal strip tend to have stronger barrier effects. Density (as measured by the number of buildings within 600m) is also related with a stronger barrier effect. This relationship is linear (quadratic terms were insignificant and removed from the final model).

Table 3
Descriptive statistics of barrier effects.

	Barrier to other people's homes	Barrier to food shops
Mean	23	25
Standard deviation	16	21
Coefficient of variation	0.68	0.86
Minimum	0	0
Median	20	15
75% percentile	34	42
90% percentile	45	56
95% percentile	52	65
Maximum	81	85
%0	2%	13%
%>25	42%	40%
%>50	6%	16%
%>75	0.02%	0.62%
Neighbourhood (means)		
Minimum	0	0
Maximum	81	85
Type of area (means)		
Formal	22[a]	24
Informal (older)	28	26
Informal (newer)	18	22
Isolated	22[a]	30
Correlation with barrier to food shops	0.69	–

Notes.
[a] : The means of the barrier effect to other people's homes in formal and isolated buildings are not significantly different at the 5% level.

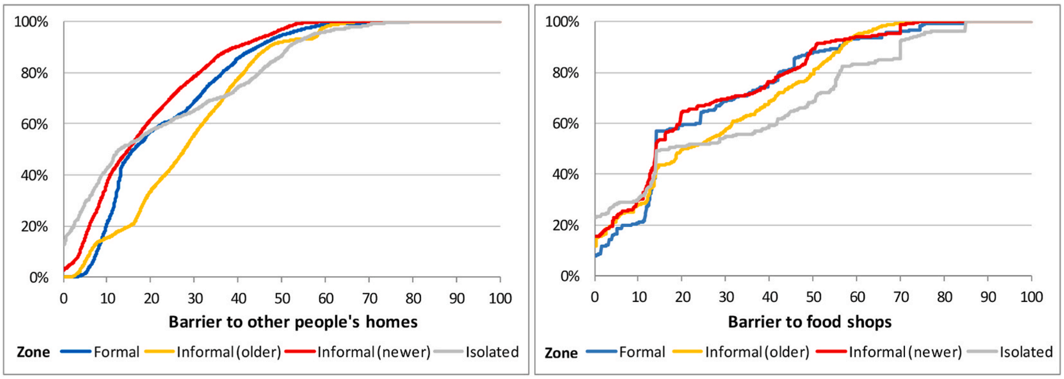

Fig. 4. Cumulative distribution of barrier effects, by zone.

In the models with socio-economic indicators (Models 2a and 2b), building area is a positive predictor of both types of barrier effect. Older informal zones have significantly higher barrier effects and newer informal zones have significantly lower barrier effects, compared with formal zones (the omitted category). The dummy for isolated buildings is not significant at the 10% level in the case of barriers to other people's homes, but significant and positive in the case of barriers to food shops.

6.3. Analysis at neighbourhood level

Table 5 shows the mean barrier effects according to neighbourhood characteristics. The mean of both indicators is lowest for households with very high comfort levels, followed by those with very low comfort levels. The mean is equal for households headed by men and women and higher for individuals aged 65+ than for individuals in other age groups.

Fig. 5 shows the cumulative distribution of the two barrier effect indicators by household comfort level and age. The distributions by sex of household head are not shown, as they are similar for men and women. The curve for households with very high comfort levels is above the others for values above around 15, for both indicators. The curve for individuals aged 65+ is consistently below the curves for individuals aged 15 and 15–64 (which have similar curves). This shows that individuals aged 65+ tend to live in buildings with stronger barrier effects, across the whole range of possible values of the indicator.

Fig. 6 plots some of the relationships between the barrier effects and neighbourhood characteristics. We have aggregated the

Table 4
Fractional regression of barrier effects.

	Barrier to other people's homes				Barrier to food shops			
	Model 1a		Model 2a		Model 1b		Model 2b	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
Distance to centre (km)	−0.91	0.02***	–	–	−0.54	0.02***	–	–
[Distance to centre (km)]^2	0.22	0.005***	–	–	0.14	0.006***	–	–
Coastal strip	2.35	0.06***	–	–	2.85	0.07***	–	–
Number of buildings within 600m (1000s)	0.29	0.004***	–	–	0.23	0.005***	–	–
Building area (1000m^2)	–	–	0.07	0.02***	–	–	0.07	0.02***
Zone								
Informal (older)	–	–	0.30	0.01***	–	–	0.14	0.02***
Informal (newer)	–	–	−0.24	0.01***	–	–	−0.08	0.02***
Isolated	–	–	−0.04	0.03	–	–	0.33	0.03***
Constant	−1.45	0.02***	−1.25	0.01***	−1.44	0.02***	−1.17	0.14***

Note: Omitted category: formal zones.

Table 5
Mean barrier effects, by neighbourhood characteristics.

	Weighted means	
	Barrier to other people's homes	Barrier to food shops
Comfort level		
Very high	20	20
High	24	25
Medium	24	25
Low	23	25
Very Low	21	23
High or very high	23	23
Low or very low	22	24
Household head		
Male	23	24
Female	23	24
Age		
<15	23	24
15-64	23	24
65+	26	27

Notes: Means by comfort level and household head are weighted by the number of households. Means for age groups are weighted by number of individuals.

proportion of households with high, medium, and low comfort levels because the relationships between the barrier effects and the proportions of other two comfort levels ('very high' and 'very low') are similar. Likewise, we show the relationships with the proportion of individuals aged 65+ because the relationships between the barrier effects and the proportions of individuals aged 15–65 and aged below 15 are similar.

The (positive) relationship between the barrier effect to other people's homes and the proportion of individuals aged 65+ (with a power specification) is the strongest ($R^2 = 0.55$). The relationships between the two indicators of barrier effect and the proportions of households with high, medium, or low comfort levels are non-linear: negative for some small values, but positive for higher values. The relationships with the proportion of female household heads are weaker, compared with the relationships with other demographic variables.

7. Sensitivity analysis

Table 6 compares the key results using the main indicators (as shown in the previous sections) and using indicators based on alternative assumptions. The alternatives yield smaller mean values for both indicators, but also increase their variability (as shown by the high coefficient of variation). Most of the patterns found for the main indicators also apply in the three alternatives. However, in Alternative 4 (distance-weighted indicators), older informal zones no longer have markedly higher barrier effects to other people's homes than all other zones. In Alternative 1 (indicators that consider Level 1 roads only), the disadvantage of older individuals disappears (i.e. the indicators are no longer higher than those for other age groups).

Table 7 shows the results for the four alternative indicators. The indicators are less variable than the main ones. In alternatives 6 and 8, the barrier effect to people's homes in formal zones is equal to the effect in older informal zones, and households with very high and high comfort levels have the strongest indicators. In contrast, using the main indicator, the barrier effect in formal areas was

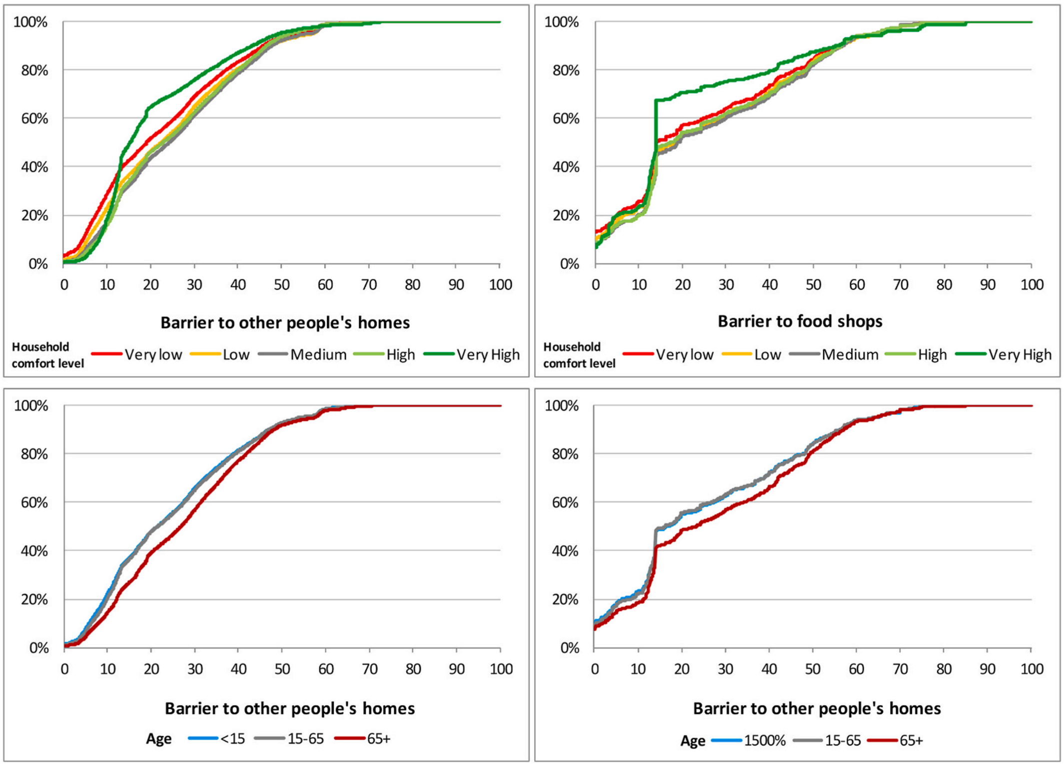

Fig. 5. Cumulative distribution of barrier effects, by neighbourhood characteristics.

smaller than in older informal areas, and households with very high comfort levels have the weakest barriers.

8. Discussion

8.1. Synthesis and interpretation of results

The results showed that roads reduce walking accessibility to social networks (other people's homes) and amenities (food shops) in Praia. The problem affects most of the city, but has a higher incidence in older informal zones, and disproportionately affects older people. Households with very high or very low comfort levels (a composite indicator of socio-economic variables) tend to live in areas with weaker barrier effects, compared with households with high, medium, or low comfort levels.

These patterns are probably due to a mix of historical and economic aspects. Older informal settlements first emerged just outside the city centre and other formal zones, along main roads. Newer informal settlements are emerging in more peripheral areas, farther from those roads. These areas tend to have a poor and young population, with low proportions of people aged over 65. At the same time, households with high income can afford to live in places further away from the main roads, with lower exposure to the negative environmental effects of roads. These hypotheses, to be confirmed in future work, may apply to other cities in developing countries where rapid urban growth has resulted in large areas of informal settlements, built at different times.

The disproportionate effect felt by residents in older informal areas and by older populations is concerning because these two groups tend to be particularly vulnerable to losses of pedestrian mobility. Previous research in African urban contexts showed that many low income households rely on walking for most of their accessibility needs (Olvera et al. 2013; Tembe et al., 2020; Oviedo et al. 2021) and that older people face several problems crossing busy roads (Amosun et al. 2007) and tend to do less physical activity when living in neighbourhoods with those roads (Oyeyemi et al. 2019). The present work suggests that in Praia, these income- and age-based vulnerabilities are compounded by spatial factors, i.e. the patterns of residence of poor and older populations.

8.2. Contribution of this paper and directions for further research

The indicators of barrier effect developed in this paper capture differences between effects in areas near main roads that have many potential trip destinations on the other side and areas near similar roads but where there is no reason to cross the road. For example, sensitivity analysis showed that using simpler indicators (e.g. indicators that consider only distance to roads or length of roads within 600m) yielded indicators that were less variable (as they do not consider the differences mentioned above). Nevertheless, this aspect can still be further developed. Our indicators were based on potential walking trips. However, the need to access destinations on the

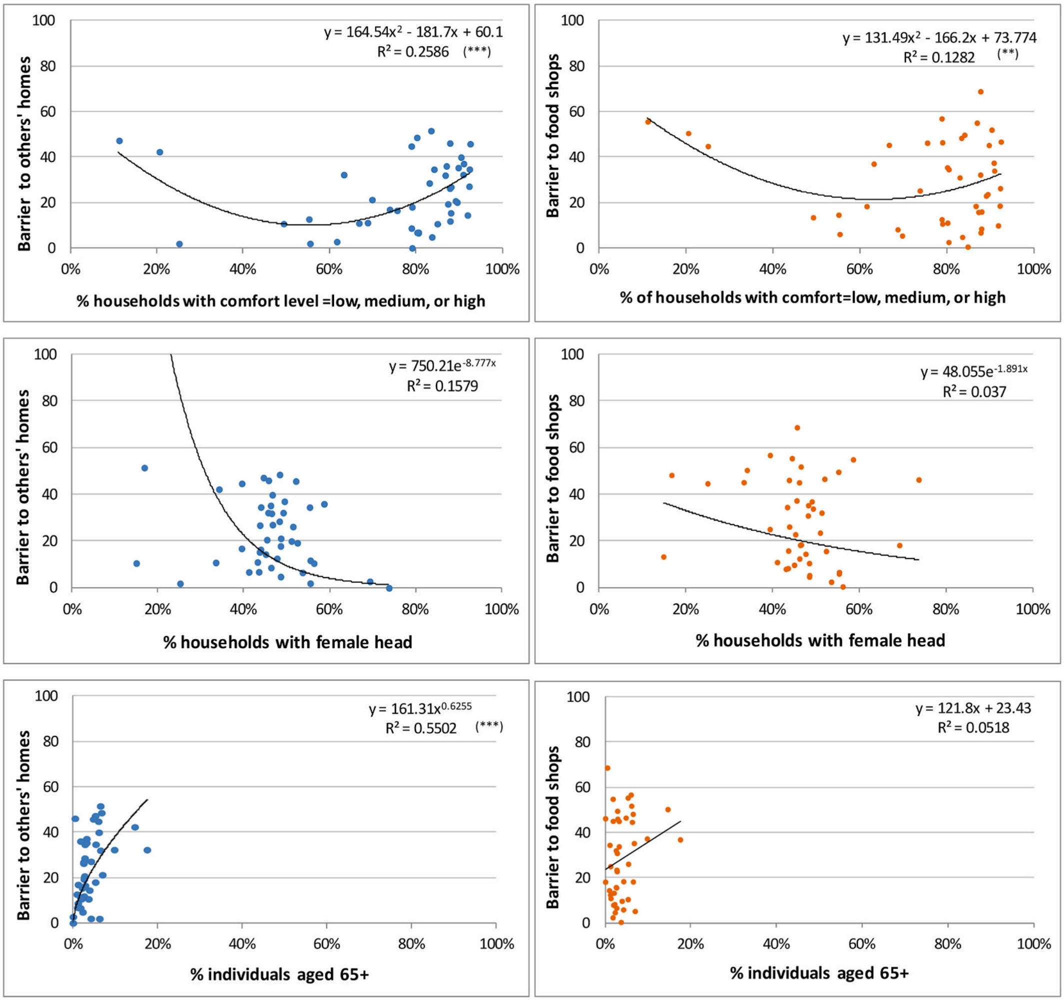

Fig. 6. Bivariate relationships between barrier effects and neighbourhood characteristics.
Notes: (***): All coefficients significant at the 1% level. (**): All coefficients significant at the 5% level. Relationships are unweighted.

other side of roads depends on the characteristics of the population (e.g. the proportions of commuters, single households, or individuals with poor health).

We used several strategies to overcome the lack of data. We manually compiled and inputted in a GIS several variables (e.g. road characteristics, location of food shops) and converted and manually corrected data only available as image files (e.g. road hierarchy, zones with informal settlements). However, we could not account for the characteristics of traffic (e.g. volume, speed) and pedestrian crossing facilities. We used a threshold of 600m as the maximum walking distance. Sensitivity analysis showed that results did not change much for thresholds of 400–800m. Nevertheless, using straight-line distances, even corrected for slopes, is still a limitation, because barriers themselves affect walking routes. For example, in areas where walking trips involve crossing several roads, pedestrians may detour when crossing the first of those roads. Another caveat is the relatively large size of the units of analysis used to estimate patterns in barrier effect across groups. The population living closer to the road may have different characteristics from the population living further away, in the same neighbourhood.

9. Conclusions

Due to the increase of traffic volumes, roads are becoming barriers to pedestrians in many African cities, increasing the risk of social exclusion of women and the poor, and reducing physical activity and independent mobility among children and older people. This paper quantified the barrier effect of roads for the first time in an African city. It also contributed to the literature by mapping the effect at the city level and developing indicators that account for land use (i.e. what is on the other side of the road).

The implication of this study for transport policy in Praia is that the barrier effect is already high in many parts of the city. New road projects will increase the effect, so mitigation measures are needed in road segments crossing through dense neighbourhoods. These measures include low speed limits, traffic calming, and new or improved crossing facilities (accessible to all and safe from traffic and

Table 6
Comparison with indicators using alternative assumptions.

	Barrier to other people's homes					Barrier to food shops				
	Main indicator	*alt1*	*alt2*	*alt3*	*alt4*	Main indicator	*alt1*	*alt2*	*alt3*	*alt3*
		Only Level 1	400m	800m	Distance-weighted		Only Level 1	400m	800m	Distance-weighted
Overall mean	23	12	7	38	14	25	11	7		22
Standard deviation	16	14	7	19	13	21	18	12		19
Coefficient of variation	0.68	1.20	0.96	0.48	0.88	0.86	1.62	1.66		0.86
Type of zone										
Formal	22	7	8	34	17	24	7	9		17
Informal (older)	28	14	10	43	17	26	11	9		23
Informal (newer)	18	11	5	34	10	22	13	5		22
Isolated	22	13	7	35	16	30	14	6		30
Comfort level										
Very high	20	7	7	32	13	20	6	6		17
High	24	10	8	40	15	25	9	8		21
Medium	24	11	8	38	15	25	10	8		22
Low	23	12	7	40	14	25	12	7		22
Very Low	21	11	6	35	12	23	11	6		21
Household head										
Male	23	11	7	38	14	24	10	7		21
Female	23	11	8	37	14	24	10	7		21
Age										
<15	23	11	7	38	14	24	11	7		21
15-64	23	11	7	38	14	24	10	7		21
65+	26	11	8	43	16	27	9	8		23

Table 7
Results using alternative indicators.

	alt5	alt6	alt7	alt8
	Distance to Level 1	Distance to Levels 1 or 2	Length of Level 1 roads within 600m	Length of Levels 1/2 roads within 600m
Overall mean	25	38	50	79
Standard deviation	16	10	33	37
Coefficient of variation	0.66	0.27	0.66	0.47
Type of zone				
Formal	23	42	43	87
Informal (older)	31	42	64	87
Informal (newer)	20	33	42	69
Isolated	24	34	36	61
Comfort level				
Very high	23	41	44	91
High	26	40	53	85
Medium	26	39	54	84
Low	24	38	49	79
Very Low	22	36	44	77
Household head				
Male	25	39	50	83
Female	25	39	51	82
Age				
<15	24	38	49	80
15-64	25	39	50	82
65+	28	40	59	85

crime).

More generally, in Praia and in other African cities, the improvement of roads needs to be accompanied with good provision for pedestrians. This is because as car ownership increases, individuals will tend to walk less and use motorised modes, which then aggravates the barrier effect. In the long term, reducing barriers also requires reducing car traffic volumes, by improving public transport and using land use policies to reduce trip distances. It also requires an understanding of the accessibility needs of vulnerable groups and a shift in current policy and research paradigms: walking conditions need to be treated not merely as a traffic safety issue but more broadly as a health issue.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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