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Distribution of Urban Walking Trips and the Effects of Restricting Free Pedestrian Movement on Walking Distance

ALEJANDRO TIRACHINI, INSTITUTE OF TRANSPORT AND LOGISTICS STUDIES (ITLS), THE UNIVERSITY OF SYDNEY, ALEJANDRO.TIRACHINI@SYDNEY.EDU.AU

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Alejandro Tirachini
Institute of Transport and Logistics Studies (ITLS)
The University of Sydney
NSW 2006 Australia
Tel: +61 2 9351 0169
Fax: +61 2 9351 0088
alejandro.tirachini@sydney.edu.au

ABSTRACT

When traffic becomes intense in an urban area and wider spaces are provided to ease the movement of motorized vehicles, a set of external impacts take place, such as social severance, delays and excessive walking distances for pedestrians, increased risk of accidents, noise and so on. These factors affect the environment, the people living nearby, and also make pedestrians and cyclists more vulnerable against motorized vehicles. This paper presents an analytic framework to measure the spatial segregation caused by reducing or forbidding the free movement of pedestrians, due to the existence of a highway or other type of transport facility with barriers that prevent pedestrians from crossing. Probabilities of walking and expected walking distances are calculated under two different road configurations–free and limited pedestrian mobility. The model is applied in Santiago, Chile, on a road where a normal avenue was replaced by a highway segregated with barriers, only with pedestrian overpasses in specific locations to allow crossing. Results show that the latter situation decreases the probability of walking to places where the walking distance is increased, worsening car dependency even for short trips. The greatest inconvenience is for people living directly adjacent to the highway, whose walking distance to cross the road is tripled on average.

Keywords: Transport externalities, segregation, barrier effect, mobility, pedestrians

1. INTRODUCTION

Walking is healthy, free, enjoyable and has no noticeable external costs, typical of motorised transport such as congestion, air pollution, noise, energy consumption and so on. The layout of cities, neighbourhoods and suburbs influences the greater or lesser predisposition to walk; a quiet, safe and comfortable environment for walking is reflected in communities with a major social cohesion, economic development, accessibility to services and work places, and reinforces equity as one of the objectives of the transport system. Nevertheless, walking, cycling and other non-motorised means of transport often play a secondary role in the investment decision process, even considered less attractive or contrary to an image of progress and modernity (Peng, 2005), and have been undervalued in the social assessment of transport projects (Litman, 2003). Thus, it is common that in many cities, transport authorities are inclined to encourage the construction of traffic facilities and roads for motorised transport, oftentimes making the movement of pedestrians and cyclists more difficult. On the contrary, investing in projects that encourage the use of non-motorised modes has benefits that largely exceed the costs. For instance, Sælensminde (2004) analyses investments in walking and cycling track networks in three cities in Norway, estimating that the benefits of such facilities are between 3 and 14 times the cost, becoming more beneficial for society than any other intervention on the transport system.

Narrow streets and/or roads with little traffic are essential for a pedestrian-friendly neighbourhood, where residents and visitors are able to walk easily. On the other hand, wide avenues, highways or severely congested streets may result in a problem for pedestrians if crossing them is difficult, slow or dangerous, inhibiting the disposition to walk and becoming a barrier that separates the city and threatens against social integration and cohesion, a phenomenon referred to as *barrier effect*, *barrier cost* and *severance* (Russell and Hine, 1996; TRB, 2001; Litman, 2003; Handy, 2003; Bradbury *et al.,* 2007 among others). Community severance as a transport externality has three dimensions (DfT, 2005a): *Physical barriers*, as in the introduction of new road infrastructure that produces excessive walking times and distances, or the existence of pedestrian crossings which are inaccessible for people with limited physical mobility; *psychological barriers* such as traffic noise and fear of accidents due to insufficient facilities for pedestrians; and *social impacts*, like the disruption of a quiet lifestyle and social interaction between neighbours. These barriers (physical or sensory), besides affecting negatively the quality of life in the basic necessity that is walking, have impacts on the local economy, as a result of the loss of accessibility to places typical of a human-scale city, such as local shops and markets, usually reached by walking. The pedestrian access to work places, hospitals, schools, bus stops and public transport stations is also worsened. These effects accumulate and persist over time and affect some social groups to a greater degree, as the most affected are those without access to a car, children, seniors and handicapped persons (DfT, 2005a).

The exclusion of barrier costs and severance in the social appraisal of transport infrastructure projects results in an overestimation of benefits. However, its inclusion is complicated due to the multiple dimensions affected and the subjective character of some of the effects (for instance, loss of social contact among neighbours), which makes the valuation or measurement of such costs highly complex (Litman, 2003; Handy, 2003; DfT, 2005b). This is the main reason to disregard or barrier effects in transport planning practice (Russell and Hine, 1996). Nevertheless, some countries take into account these variables in the social evaluation of projects, even with quantitative methods as in Sweden and Denmark, that estimate the additional delay and risk for pedestrians to cross a road, using functions based upon variables such as the traffic flow, the speed and the number of heavy goods vehicles (DfT, 2005b). However, as these monetisation approaches are considered as simplifications of a phenomenon much more complex, in general they have been replaced by qualitative analysis, such as the judgment of specialists and experts.

This paper is concerned with physical barriers (e.g. fences) and analyses the impact of preventing pedestrians from crossing a road in any place, forcing them to use only predefined locations (crosswalks in streets or avenues, pedestrian bridges and overpasses on highways and expressways). The extra travel distance imposed by physical barriers can be a significant impediment to walk (Handy, 2003). In this paper, we analytically estimate the decrease in probability of crossing the carriageway by walking, and the expected increase in walking distance. To do so, we apply geometric probability to the analysis of pedestrian movement. In general, geometric probability is defined as the study of the probabilities involved in geometric problems[1]. In urban environments, geometric probability is used to analyse the relations between objects distributed probabilistically over an area, particularly, to estimate travel times and distances given assumptions on the shape of the areas under study (rectangular, triangular, circular, general) and the distribution of objects over the plane. Examples of problems that can be addressed with geometric probability are finding the optimal location of taxi stations given the distribution of pickup calls, the design of a response district for ambulances given the distribution of medical assistance requirements, and several others as shown in Larson and Odoni (1981). Other works estimate average distances between points under different assumptions about the area where the objects are distributed (e.g., Vaughan, 1984; Koshizuka and Kurita, 1991). None of these studies analyses the case of pedestrian movements in a city, which is the object of this paper. A distinguishing feature of trips on foot is that their probability of walking depends on the trip length, which makes standard geometric probability examples found in the literature unsuitable to analyse pedestrian movements.

The rest of the paper is organised as follows. In Section 2 the problem and modelling assumptions are explained, whereas in Sections 3 and 4 probabilities of walking trips and the expected length of these are calculated in a given area, for two different road configurations representing free and limited pedestrian mobility. In Section 5 the model is applied to a road in Santiago, Chile, where an avenue was replaced by a highway segregated with barriers, placing pedestrian overpasses in specific locations to allow crossing. Final comments and conclusions are given in Section 6.

2. EQUIDISTANCE CURVES

The number of walking trips depends on the distance to be walked and quality of the surrounding environment. Relevant factors in making the decision to walk are safety, security and comfort. From the Origin Destination Survey of Santiago (SECTRA, 2001), we find that the distribution of walking trips as a function of the distance s, can be approximated by an exponential random variable (as shown in Figure 1) whose density function is

$$f(s) = \begin{cases} \lambda e^{-\lambda s} & if\ s \geq 0 \\ 0 & if\ s < 0 \end{cases} \tag{1}$$

[1] MathWorld- A Wolfram Web Resource. *http://mathworld.wolfram.com/GeometricProbability.html*

where $1/\lambda$ is the expected value of the random variable s. The value of $1/\lambda$ can be estimated with the method of maximum likelihood, whose result is the average walking distance by travellers in the sample, approximately 700 meters in Santiago.

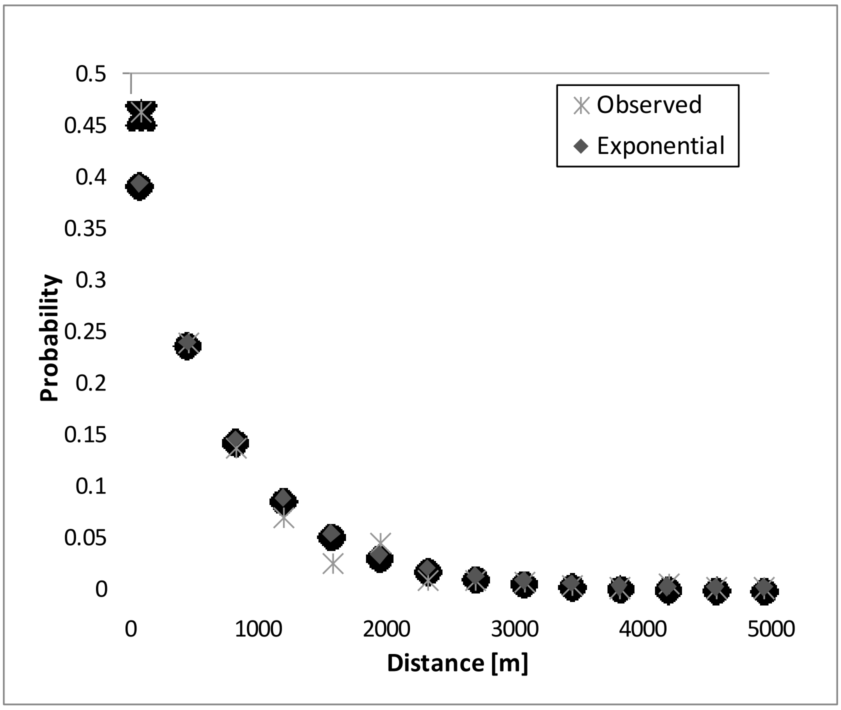


Figure 1: Observed and predicted probabilities (exponential random variable) for walking trips as functions of distance.

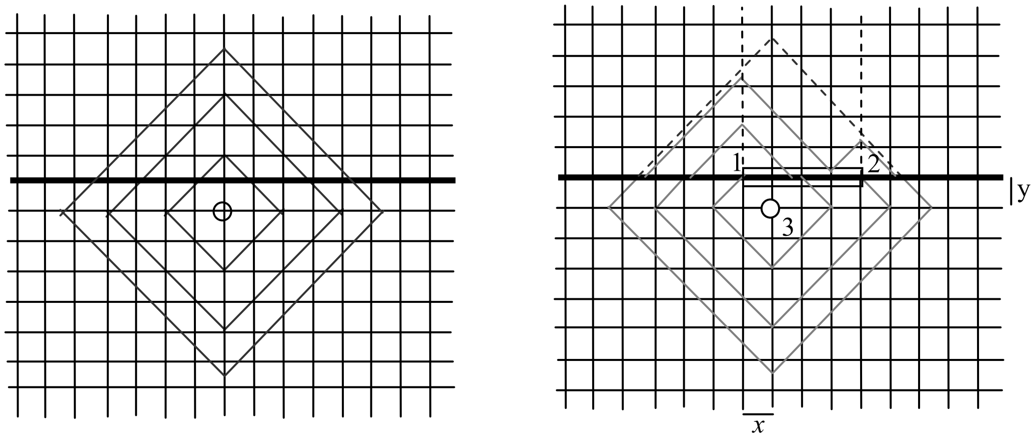
In the following, two road configurations are analysed:

a) Roads in which the pedestrian crossing may be done at any point, because of the absence of regulated pedestrian crossings or existence of a scarce traffic flow. Examples of these roads are local streets, quiet avenues and walking streets. In the following, this type of road will be generically called *streets*.
b) Expressways in which there are physical barriers, like fences or walls, which segregate the carriageway from the environment to isolate the traffic and prevent pedestrian crossing, which is possible only in pedestrian bridges and overpasses (Figure 7). This type of road will be generically called *highways*.

The urban area to be analysed is assumed flat and composed by parallel and perpendicular streets (chess board shape), thus the distance on the plane between two points of coordinates (x_1, y_1) and (x_2, y_2) is

$$d = |x_2 - x_1| + |y_2 - y_1| \qquad (2)$$

The *equidistance curve* will be the set of destination points that a person can visit walking a distance d from a fixed origin, which is a square of diagonal $2d$ (Figure 2.a), with d as in Equation (2).



(a) Street **(b) Highway**

Figure 2: Equidistance curves

In the presence of *highways*, (2) is not valid for walking trips as the crossing is only allowed in specific pedestrian facilities (points 1 and 2 in Figure 2.b), commonly separated for long distances (e.g., 500 meters). In this case, the *equidistance curve* is deformed for walking to destinations close to the highway (as point 3 in Figure 2.b). All walking trips are affected if crossing a pedestrian bridge, overpass or underpass is required, due to the extra inconvenience imposed on pedestrians of going up and down stairs or ramps (see Figure 7). The major impact is in journeys that depart from a point like 3 in Figure 2.b and have a destination in the area between points 1 and 2, due to the imposition of making the trips either through crossings 1 or 2, increasing the walking distance. This area (between 1 and 2, on the other side of the road from point 3) will be called *vicinity* and this type of trip will be called a *vicinity trip*.

It is also assumed that walking trips are made in every direction with the same probability, that is, a trip of length d can be made to any point of the *equidistance curve* with the same probability. The validity of this assumption depends on the land use in the studied area: if the land use is uniform the assumption is reasonable, but it could be unrealistic if the land use is differentiated, for example with areas mostly commercial, residential, industrial, etc.

3. PROBABILITY OF MAKING VICINITY TRIPS

The average probability of making vicinity trips is calculated for both types of roads. The details in the calculation of formulae (5), (6), (8) and (9) are in the APPENDIX

3.1 *Streets* (pedestrians crossing anywhere)

Let L be the distance between two consecutive crossings, Δ the extra distance with respect to the normal width of the road that pedestrians have to walk due to the use of the crossing (for example, going up and down stairs or ramps), x the east-west (horizontal) distance between the origin of the trip and point 1, y the north-south (vertical) distance from the origin to point 1, s the trip length and M the maximum walking distance acceptable for pedestrians.

Let us consider a walking trip w of length s. For an exponential random variable, the probability P_{s_1,s_2} of s to be between s_1 and s_2 is:

$$P_{s_1,s_2} = P(s_1 \le s \le s_2) = \int_{s_1}^{s_2} \lambda e^{-\lambda s} ds = e^{-\lambda s_1} - e^{-\lambda s_2} \tag{3}$$

In addition, due to the directional equiprobability assumption for walking trips, the probability of making trip w to the vicinity is the quotient between the area enclosed by the equidistance curves s_1 and s_2 in the vicinity, $A^v_{s_1,s_2}$ (area with oblique lines in Figure 3) and the total area enclosed by s_1 and s_2, $A^T_{s_1,s_2}$. Then, the probability $P^v_{s_1,s_2}$ for a trip whose length is between s_1 and s_2 to be made to the vicinity is:

$$P^v_{s_1,s_2} = P_{s_1,s_2} \frac{A^v_{s_1,s_2}}{A^T_{s_1,s_2}} = \left(e^{-\lambda s_1} - e^{-\lambda s_2}\right) \frac{A^v_{s_1,s_2}}{A^T_{s_1,s_2}} \tag{4}$$

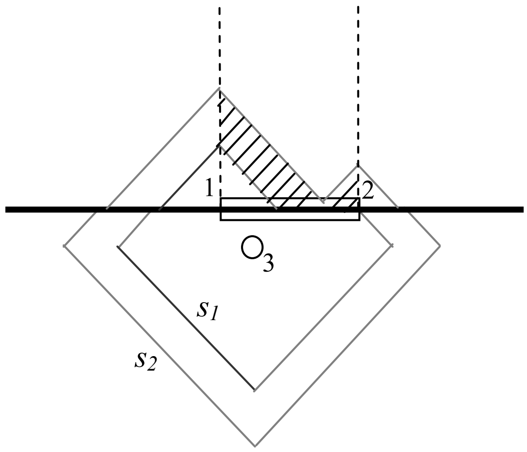


Figure 3: Example of area $A^v_{s_1,s_2}$, *highway* case

With this, the probability $P(x,y)$ of a trip, with the origin (x,y) on the other side of the road, to be made to the vicinity is calculated as[2]:

$$P(x,y) = \begin{cases} P_1(x,y) = A(x,y) + B(x,y) + C(x,y) & \text{if } 0 \le y < M - L + x \\ P_2(x,y) = A(x,y) + B(x,y) & \text{if } M - L + x \le y < M - x \\ P_3(x,y) = A(x,y) & \text{if } M - x \le y < M \end{cases} \tag{5}$$

where

$$\begin{aligned} A(x,y) &= \left(e^{-\lambda y} - e^{-\lambda(x+y)}\right) \frac{x}{2(x+2y)} \\ B(x,y) &= \left(e^{-\lambda(x+y)} - e^{-\lambda(L-x+y)}\right) \frac{L^2 - 4x^2}{4(L+2y)(L-2x)} \\ C(x,y) &= \left(e^{-\lambda(L-x+y)} - e^{-\lambda M}\right) \frac{L}{2(M+L-x+y)} \end{aligned} \tag{6}$$

Therefore, if the same calculation is made $\forall x \in (0, L/2)$ and $\forall y \in (0, M)$, the mean probability P of making vicinity trips is obtained by:

$$P = \frac{1}{M\,L/2} \int_0^{L/2} \left\{ \int_0^{M-L+x} P_1(x,y)dy + \int_{M-L+x}^{M-x} P_2(x,y)dy + \int_{M-x}^{M} P_3(x,y)dy \right\} dx \tag{7}$$

[2] Valid for the case $0 \le x < L/2$. The case $L/2 \le x \le L$ is analogous.

which cannot be solved analytically. In theory, the exponential distribution allows trips to be infinitely long, however, as 99.9% of walking trips in Santiago have a length $s \leq$ 5.000 *m*. (SECTRA, 2001), the maximum walking distance assumed is *M*=5000 *m*. In other words, even though it is possible to have walking trips longer than 5.000 *m*., the frequency is so low that omitting these trips produces negligible errors, but provides an expression for the mean probability of making vicinity trips, as in (7).

3.2 *Highways* (pedestrians crossing through overpasses)

In this case, the probability *R(x,y)* of making vicinity trips is lower due to the contraction of the equidistance curves in the vicinity, as can be seen in Figure 2.b (i.e. at an equal value of the travelled *distance*, the *displacement* is shorter).

$$R(x,y) = \begin{cases} R_1(x,y) = D(x,y) + E(x,y) + F(x,y) & \text{if } 0 \leq y < M - L - \Delta \\ R_2(x,y) = D(x,y) + E(x,y) & \text{if } M - L - \Delta \leq y < M - L - \Delta + x \\ R_3(x,y) = D(x,y) & \text{if } M - L - \Delta + x \leq y < M \end{cases} \quad (8)$$

where

$$\begin{aligned} D(x,y) &= \left[e^{-\lambda(x+y+\Delta)} - e^{-\lambda(L-x+y+\Delta)}\right]\frac{L-2x}{4(L-x+2y+\Delta)} \\ E(x,y) &= \left[e^{-\lambda(L-x+y+\Delta)} - e^{-\lambda(L+y+\Delta)}\right]\frac{L-x}{4L-3x+4y+2\Delta} \\ F(x,y) &= \left[e^{-\lambda(L+y+\Delta)} - e^{-\lambda M}\right]\frac{L}{2M+L+y} \end{aligned} \quad (9)$$

Then, in the same way than in (7), the mean probability *R* is obtained

$$R = \frac{1}{M\,L/2}\int_0^{L/2}\left\{\int_0^{M-\Delta-L} R_1(x,y)dy + \int_{M-\Delta-L}^{M-\Delta-L+x} R_2(x,y)dy + \int_{M-\Delta-L+x}^{M} R_3(x,y)dy\right\}dx \quad (10)$$

4. EXPECTED LENGTH OF VICINITY TRIPS

Vicinity trips have a minimum length, which is the orthogonal distance from the origin of the trip to the road, in the case of *streets*, and the distance to the closest pedestrian crossing, in the case of *highways*. This minimum distance must be considered in the calculation of the expected length of vicinity trips. The expectation value of a continuous random variable *s*, given that its value is restricted to an interval $a < s < a + b$ ($b > 0$), is calculated as

$$E\left[s \mid a < s < a+b\right] = \frac{1}{F_s(a+b) - F_s(a)}\int_a^{a+b} s\,f(s)ds \quad (11)$$

where $f(s)$ is the probability density function and $F_s(\cdot)$ is the cumulative distribution function. In the case of a exponential variable, $f(s)$ is given by (1) and

$$F_s(a) = \begin{cases} 1 - e^{-\lambda a} & \text{if } a \geq 0 \\ 0 & \text{if } a < 0 \end{cases} \quad (12)$$

Therefore, introducing (1) and (12) into (11),

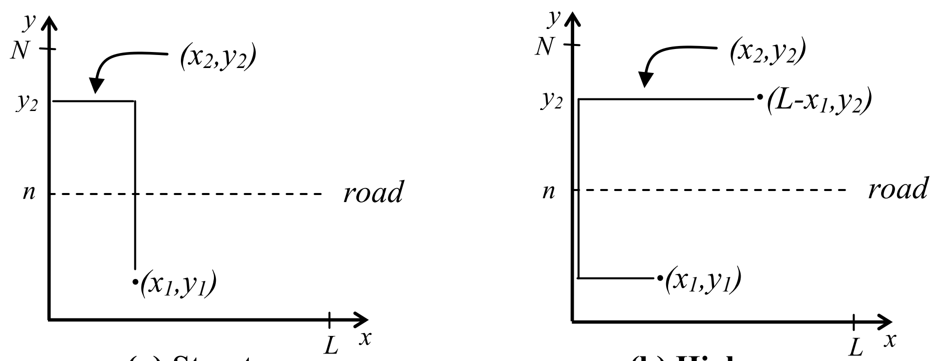
$$E\left[s \middle| a < s < a+b\right] = \frac{1}{e^{-\lambda a} - e^{-\lambda(a+b)}} \int_a^{a+b} s\lambda e^{-\lambda s} ds$$

$$= \frac{1}{\lambda\left(e^{-\lambda a} - e^{-\lambda b}\right)}\left[e^{-\lambda a}(\lambda a+1) - e^{-\lambda(a+b)}(\lambda(a+b)+1)\right]$$

an expression that turns out to be[3]

$$E\left[s \middle| a < s < a+b\right] = a + \frac{1}{\lambda} - \frac{e^{-\lambda b} b}{1 - e^{-\lambda b}} \tag{13}$$

In order to determine the expected length of vicinity trips, for simplicity, the study area is constrained to a rectangular area of sides L and N, where L is the distance between two consecutive pedestrian crossings in the case of *highways* (as shown in Figure 4). A system of orthogonal coordinates is defined, whose origin is at the left bottom corner of the rectangle. The road (street or highway) is in the ordinate $y=n$ and the vertices of the rectangular area are the points $(0,0)$, $(L,0)$, $(0,N)$ and (L,N). Note that n is defined by the relative position of the rectangular area to study, with respect to the road. For example, if $n = N/2$, the road is in the middle of the rectangle.



(a) Street **(b) Highway**

Figure 4: Area for the calculation of the expected length of trips

4.1 *Streets*

For the sake of simplicity, only the expected value of vicinity trips made to the left will be determined (by symmetry, trips to the right will have the same expected length), considering trips with origin in (x_1, y_1) and destination in (x_2, y_2), such that $0 \le x_2 \le x_1$ (trips to the left in Figure 4.a), with y_2 fixed. Using (13), the expectation value of these trips is (replacing x_1 by x)

$$E\left[s \middle| y_2 - y_1 < s < y_2 - y_1 + x\right] = y_2 - y_1 + \frac{1}{\lambda} - \frac{e^{-\lambda x} x}{1 - e^{-\lambda x}} \tag{14}$$

Then, covering all the feasible space, the average value l_1 of the expectation is obtained by[4]

[3] Expression (13) satisfies the following property:

$$E\left[s \middle| a < s < a+b\right] = a + E\left[s \middle| 0 < s < b\right]$$

Result obtained from the "no-memory" property of the exponential distribution:

$$P\left[s > a+b \middle| s > a\right] = P\left[s > b\right] \; \forall a,b > 0$$

$$l_1 = \frac{1}{Ln(N-n)}\int_0^L\int_0^n\int_n^N\left(y_2 - y_1 + \frac{1}{\lambda} - \frac{e^{-\lambda x}x}{1-e^{-\lambda x}}\right)dy_2dy_1dx = \frac{1}{\lambda} + \frac{N}{2} - \frac{1}{L}\int_0^L\frac{e^{-\lambda x}x}{1-e^{-\lambda x}}dx \tag{15}$$

4.2 *Highways*

In this case, the mean length of vicinity trips made through the left crossing, of coordinates $(0,n)$ in Figure 4.b, is calculated (by symmetry, the result is the same for trips made on the crossing (L,n) to the right). As in 4.1, we will take into account trips with origin in the point (x_1, y_1) and destination in some other point (x_2, y_2), for a fixed height y_2. The condition for these trips to be made at the left crossing is $x_2 \in [0, L - x_1]$, since if $x_2 > L - x_1$, it is shorter walking on (L,n) to the right. Then, the closest point to (x_1, y_1) in this segment is $(0, y_2)$, separated by a distance of $y_2 - y_1 + \Delta + x_1$, and the farthest one is $(L - x_1, y_2)$ by a distance of $y_2 - y_1 + \Delta + L$. Thus, the expected length of trips to this segment is (x_1 is replaced by x):

$$\begin{aligned} E[s | y_2 - y_1 + \Delta + x < s < y_2 - y_1 + \Delta + L] &= y_2 - y_1 + \Delta + x + \frac{1}{\lambda} - \frac{e^{-\lambda(L-x)}(L-x)}{1-e^{-\lambda(L-x)}} \\ &= y_2 - y_1 + \Delta + \frac{1}{\lambda} + \frac{e^{-\lambda x}\cdot x - e^{-\lambda L}\cdot L}{e^{-\lambda x} - e^{-\lambda L}} \end{aligned} \tag{16}$$

And the mean value is obtained as in (15), hence[5]:

$$l_2 = \frac{1}{Ln(N-n)}\int_0^L\int_0^n\int_n^N\left(y_2 - y_1 + \Delta + \frac{1}{\lambda} + \frac{xe^{-\lambda x} - Le^{-\lambda L}}{e^{-\lambda x} - e^{-\lambda L}}\right)dy_2dy_1dx = \frac{1}{\lambda} + \frac{N}{2} + \Delta + \frac{1}{L}\int_0^L\frac{e^{-\lambda x}\cdot x - e^{-\lambda L}\cdot L}{e^{-\lambda x} - e^{-\lambda L}}dx \tag{17}$$

Consequently, using expressions (15) and (16), the extra walking distance imposed by the physical barriers can be estimated as $l_2 - l_1$, which is independent of the length *N* assumed for the rectangular area under analysis (this is a consequence of the "no-memory" property of an exponential random variable, presented in footnote 3). A particular case of (15) and (17) is the set of trips from one side of the carriageway to the other (i.e. crossing the road), for example, to visit a neighbour that lives on the other side of the road, purchases in a local store, etc. In this case, these expressions are still valid, taking *N/2=A*, where *A* is the width of the carriageway, and fixing the values of y_1 and y_2, such that $y_2 - y_1 = A$.

5. APPLICATION

This approach is applied to Vespucio Sur road in Santiago, where a normal avenue was replaced by a highway, segregated with barriers to prevent the crossing of pedestrians (Figure 5). When there was an avenue, it had a moderate traffic flow that allowed the road to be crossed at any point (despite that traffic rules forbade it). The length of the analysed route is 7 *km*. There are 17 locations where pedestrians may cross (12 pedestrian overpasses and 5 traffic overpass intersections). In Table 1, the probabilities *P* and *R* and the mean trip length

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[4] Note that the integral $\int_0^L x\frac{e^{-\lambda x}}{1-e^{-\lambda x}}dx$ is correctly defined, since its singularity in *x=0* is removable, as $\lim_{x\to 0} x\frac{e^{-\lambda x}}{1-e^{-\lambda x}} = 1$

[5] Expression (17) is correctly defined as well, since $\lim_{x\to L}\frac{e^{-\lambda x}\cdot x - e^{-\lambda L}\cdot L}{e^{-\lambda x} - e^{-\lambda L}} = L - \frac{1}{\lambda}$

l_1 and l_2 are shown, for walking trips from one side of the road to the other (A=40 m) and inside an area of length N=2000 m, for each of the 16 stretches between pedestrian crossings. In addition, the average of these values is calculated, weighted by the length of each segment.

(a) View from a pedestrian overpass

(b) Barriers to prevent pedestrian crossings

(c) Pedestrian overpass

Figure 5: Vespucio Sur highway

Table 1: Trip lengths and probabilities of vicinity trips

			Probability		A=40 m			N=2000 m		
Segment	L [m]	Δ [m]	P	R	l_1 [m]	l_2 [m]	Difference	l_1 [m]	l_2 [m]	Difference
1	410	44	0.8%	0.5%	138	387	181%	1098	1347	23%
2	820	81	1.6%	0.8%	222	715	222%	1182	1675	42%
3	730	66	1.4%	0.8%	205	637	211%	1165	1597	37%
4	450	66	0.9%	0.5%	147	438	199%	1107	1398	26%
5	130	38	0.2%	0.2%	72	175	142%	1032	1135	10%
6	160	0	0.3%	0.2%	80	160	100%	1040	1120	8%
7	360	32	0.7%	0.5%	127	338	167%	1087	1298	19%
8	350	75	0.7%	0.4%	124	375	201%	1084	1335	23%
9	780	72	1.5%	0.8%	214	678	216%	1174	1638	39%
10	390	72	0.8%	0.5%	133	401	201%	1093	1361	24%
11	200	44	0.4%	0.3%	89	233	161%	1049	1193	14%
12	540	29	1.1%	0.7%	166	465	180%	1126	1425	27%
13	220	60	0.4%	0.3%	94	264	181%	1054	1224	16%
14	420	60	0.8%	0.5%	140	410	193%	1100	1370	25%
15	330	79	0.6%	0.4%	120	363	204%	1080	1323	23%
16	200	50	0.4%	0.3%	89	239	168%	1049	1199	14%
Weighted Average			**1.0%**	**0.6%**	**158**	**475**	**200%**	**1117**	**1434**	**28%**

Before analysing the results, it is necessary to point out that there are four alternatives for a vicinity trip in the case of the avenue, which is longer in the new situation (highway):

a) To change the destination to a place outside the vicinity. This is possible for "reassignable" trips, i.e. those whose activity can be done in a closer location given the new circumstances (e.g. shopping in a store). Nonetheless, trips to work or study can be hardly reassigned, as generally the activity is supposed to be done just in one place. Therefore, for this kind of trip, this alternative is not feasible.
b) To change the mode. This is subject to the availability of other modes to reach the destination, particularly, the private car. This is one of the worse externalities of building new traffic facilities for cars, if non-motorised transport is not properly considered, since the modal split for walking will diminish in the medium run, increasing the dependency on motorised transport.
c) To eliminate the trip. This is only possible for non-compulsory trips, such as leisure. It could happen if, for example, under the new circumstances the activity in the destination is at an unacceptable distance and there is no closer substitute (e.g., going to a park).
d) To walk anyway, in spite of the disadvantageous situation.

Under the assumption of uniformly distributed destinations, Table 1 reveals that, from the total number of trips generated in the study area, whose extension is $2M \cdot L \approx 70\,km^2$, 1% were made to the vicinity when there was an avenue, which are affected by the highway in the new situation. If these trips were reassignable to a destination outside the vicinity, only 0.6% will keep having their corresponding vicinity as destination, that is, 40% will migrate due to the increase in the walking distances. However, it is possible that less than 40% of trips are reassignable, resulting in R_{real}>0.6%. In addition, as it was previously discussed, some trips will be suppressed or changed to another mode. The estimation of all possible changes in travel behaviour due to the physical barriers imposed by the highway is outside the scope of this paper.

The amount of households in the zone is 244,840 and each household makes 5.3 walking trips per day in average (SECTRA, 2001). Thus, the number of trips affected in this segment of the highway can be estimated as $248,840\, household \cdot 5.3 \,{}^{trips}\!/_{household\text{-}day} \cdot 1\% = 13,189 \,{}^{trips}\!/_{day}$. If we consider that the highway has a total length of 23 *km*, the total number of affected trips is around $23/7 \cdot 13189 \,{}^{trips}\!/_{day} \approx 43,000 \,{}^{trips}\!/_{day}$. Note that there are other trips affected by the highway, not taken into account in the estimation, for example walking to bus stops and walking trips that cross the highway with destination outside the *vicinity* (which are affected only by the Δ increase in the walking distance). Therefore, the real number of trips affected should be higher than this estimation.

With regard to the length of trips affected by the highway, the results reveal that trips from one side of the road to the other (mostly made by people living at the sides of the road), increase their length 200% on average, from a mean length of 158 *m* to 475 *m* in the study area. This is, probably, the most telling figure to illustrate the damage for pedestrians mobility imposed by the segregated new infrastructure. On the other hand, for trips inside a rectangular area of 2,000 *m* width, the length is increased by the same amount, as previously commented, representing a lower relative increase, which is expected when enlarging the impact area farther from the highway.

6. CONCLUDING REMARKS

A sustainable management of urban mobility should encourage pedestrian movement, bicycles and other non-motorised modes, because of all the benefits that they represent for human health (physical and psychological) as well as for cities and urban areas, since they are clean, silent, more efficient in the use of road space and consume less energy than motorised transport. Using geometric probability, in this paper we formulate and an analytical model to estimate some impacts on pedestrians, due to physical barriers such as fences that impede free mobility. The effects accounted for are the expected increase in length of walking trips and the decrease in probability of walking to areas where that increase in length is greater.

Traffic flow and barriers for pedestrians (physical or sensory) impose highly complex consequences on non-motorised transport and surrounding urban life, apart from the simple increase in walking distance. This approach provides a quantitative assessment of this impact, which can be used together with qualitative techniques to measure other externalities (the multiple effects of community severance, fear of accidents, visual intrusion, etc) in the social evaluation of transport infrastructure projects, in order to internalise in a more realistic way social groups that may be severely affected by the construction of new traffic facilities.

The results of the application on a real case are the expected: when the pedestrian crossing of a road is constrained, there is an increase in walking distances and a decrease in the probability of walking, relative to the free movement case. The main contribution of this approach is the measurement of both effects. The most affected are the residents living directly adjacent to the road, who suffer closely and more frequently the effects of the mobility restriction.

This approach has many other applications. It is suitable to measure the impact on pedestrian mobility of other transport facilities, such as segregated busways or railways. It is also useful to quantify the benefits of mitigation schemes for the segregated facility, such as new crossings or pedestrian bridges, since the decrease in walking length can be measured. On the other hand, restrictions on pedestrian mobility also have an impact on other modes, notably transit due to a reduction in accessibility to bus stops in local streets, which represents another problem for the development of sustainable policies on urban mobility. This framework may be used to estimate the increase in walking distance to bus stops.

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APPENDIX
On the calculation of probabilities *P* y *R*

A1. Calculation of *P*

Because of the geometry of the equidistance curves and the vicinity, the shape of area $A^{v}_{s_1,s_2}$ is a function of the trip length *s*. This is clear in Figure A1a, where there is no $A^{v}_{s_1,s_2}$ in Zone I, but it is a triangle in Zone II and a polygon in Zones III and IV. This is the reason for separating the area in cases for the calculation of *P* and *R*. In the case of *streets*, four zones are identified (Figure A1a), whose areas are $A^{v}_{s_1,s_2}$ and $A^{T}_{s_1,s_2}$, and probabilities P_{s_1,s_2} and $P^{v}_{s_1,s_2}$, shown in detail in Table 2, in which limits s_1 and s_2 of each zone are identified.

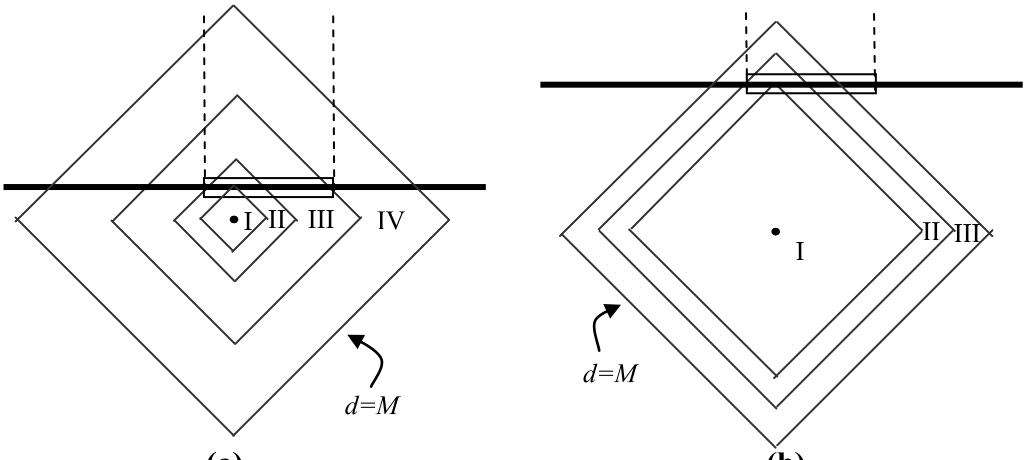

Figure A1: Different areas to calculate probability *P*

When the origin (*x,y*) is close to the road, all cases in Table 2 (Figure A1a) may take place, however, as the origin is moved away, close to the maximum walking distance ($y \approx M$), only some of the previous configurations are possible, as shown in Figure A1b, in which the origin is far away from the road and zones I, II and III take place. In all cases, the limit of the last zone is given by the equidistance curve *d=M*, under the assumption of pedestrians walking no longer than *M*. Therefore, taking into account these cases and the results in Table A1, *P*(*x,y*) turns out to have the form of equations (5) and (6).

A2. Calculation of *R*

In the case of *highways*, the area $A^{v}_{s_1,s_2}$ depends on the trip length *s* as well, but with zones of different shapes to those in Figure A1, due to the contraction of equidistance curves for vicinity *trips* (Figure 2). In this case it is also possible to identify four zones, whose characteristics are summarized in Table A2.

Table A1: Calculation of areas and probabilities, *street* case

Case	Limits		$A^v_{s_1,s_2}$	$A^T_{s_1,s_2}$	P_{s_1,s_2}	$P^v_{s_1,s_2}$
	s_1	s_2				
I	0	y	0	$2y^2$	$1-e^{-\lambda y}$	0
II	y	$x+y$	x^2	$2(x+y)^2-2y^2$	$e^{-\lambda y}-e^{-\lambda(x+y)}$	$\left(e^{-\lambda y}-e^{-\lambda(x+y)}\right)\frac{x}{2(x+2y)}$
III	$x+y$	$L-x+y$	$L^2/2-2x^2$	$2(L-x+y)^2-2(x+y)^2$	$e^{-\lambda(x+y)}-e^{-\lambda(L-x+y)}$	$\left(e^{-\lambda(x+y)}-e^{-\lambda(L-x+y)}\right)\frac{L^2-4x^2}{4(L-2x)(L+2y)}$
IV	$L-x+y$	M	$L(M-L+x-y)$	$2M^2-2(L-x+y)^2$	$e^{-\lambda(L-x+y)}-e^{-\lambda M}$	$\left(e^{-\lambda(L-x+y)}-e^{-\lambda M}\right)\frac{L}{2(M+L-x+y)}$

Table A2: Calculation of areas and probabilities, *highway* case

Case	Limits		$A^v_{s_1,s_2}$	$A^T_{s_1,s_2}$	P_{s_1,s_2}	$P^v_{s_1,s_2}$
	s_1	s_2				
I	0	$x+y+\Delta$	0		$1-e^{-\lambda(x+y+\Delta)}$	0
II	$x+y+\Delta$	$L-x+y+\Delta$	$\frac{(L-2x)^2}{2}$	$(L+y+\Delta)^2-(L-x+y+\Delta)^2+$ $+2xy+(L-x)^2-(L-2x)^2+x^2$	$e^{-\lambda(x+y+\Delta)}-$ $-e^{-\lambda(L-x+y+\Delta)}$	$\left(e^{-\lambda(x+y+\Delta)}-e^{-\lambda(L-x+y+\Delta)}\right)\frac{L-2x}{4(2y+L+\Delta-x)}$
III	$L-x+y+\Delta$	$L+y+\Delta$	$\frac{(L-x)^2}{2}-$ $-\frac{(L-2x)^2}{2}+\frac{x^2}{2}$	$(L+y+\Delta)^2-(L-x+y+\Delta)^2+$ $+2xy+(L-x)^2-(L-2x)^2+x^2$	$e^{-\lambda(L-x+y+\Delta)}-$ $-e^{-\lambda(L+y+\Delta)}$	$\left(e^{-\lambda(L-x+y+\Delta)}-e^{-\lambda(L+y+\Delta)}\right)\frac{L-x}{4L+4y-3x+2\Delta}$
IV	$L+y+\Delta$	M	$L(M-L-y-\Delta)$	$M^2-\frac{(L+y+\Delta)^2}{2}+\frac{(M-x+\Delta)^2}{2}-$ $-\frac{(M-L+x-\Delta)^2}{2}-\frac{x^2}{2}+$ $+L(M-L-y-\Delta)$	$e^{-\lambda(L+y+\Delta)}-$ $-e^{-\lambda M}$	$\left(e^{-\lambda(L+y+\Delta)}-e^{-\lambda M}\right)\frac{L}{2M+L+y}$