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Probability distribution of walking trips and effects of restricting free pedestrian movement on walking distance

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ABSTRACT

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 it. First, using empirical data from Berlin, London, Sydney and Santiago, it is shown that the proportion of walking as a function of travel distance approximately follows an exponential distribution. Then, probabilities of walking and expected walking distances are calculated under two alternative configurations –free vs constrained pedestrian crossing. Assuming an exponential distribution, we find that average walking distance increases by $L/2$ plus any extra walking distance due to the crossing itself (e.g., stairs, accessways to pedestrian overpasses), when pedestrian crossing is forced to be made every L metres. The model is applied in Santiago, on a road where a normal avenue was replaced by a segregated highway with pedestrian overpasses in specific locations to allow crossing. We show that the segregated facility decreases the probability of walking to places where walking distance has 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. This is an estimation of the barrier effect produced by this type of segregated transport infrastructure.

1. Introduction

Walking is healthy, free, enjoyable and has no noticeable external costs. The layout of cities, neighbourhoods and suburbs influences the greater or lesser willingness to walk; a quiet, safe and comfortable environment for walking is reflected in communities with greater social cohesion and accessibility to services and workplaces. Nevertheless, walking, cycling and other non-motorised means of transport often play a secondary role in transport investment decisions, and may even be considered as less attractive or contrary to an image of progress and modernity in cities (Peng, 2005), even though 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 larger than the cost, becoming more beneficial for society than other interventions on the transport system. In spite of the great potential of improving conditions for non-motorised travellers, policies that encourage walking have been undervalued in the social assessment of transport projects (Litman, 2003). Thus, it is not surprising that in many situations transport authorities are inclined to prefer the construction of traffic facilities and roads for motorised transport, often making the movement of pedestrians and cyclists more difficult.

Narrow streets and roads with little traffic are essential for a pedestrian-friendly neighbourhood. On the contrary, wide avenues, highways or severely congested streets may result in a problem for pedestrians if crossing them is difficult, slow or dangerous, inhibiting the willingness to walk and becoming a barrier that separates the city and threatens against social integration and cohesion, a phenomenon referred to as *barrier effect* or *barrier cost*, within the broader concept of *severance* (Russell and Hine, 1996; TRB, 2001; Litman, 2003; Bradbury et al., 2007; Geurs et al., 2009). Community severance as a transport externality has three dimensions (DfT, 2005a): (i) *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; (ii) *psychological barriers* such as traffic noise and fear of accidents due to insufficient facilities for pedestrians; and (iii) *social impacts*, like the disruption of a quiet lifestyle and social interaction between neighbours. These barriers (physical or sensory) affect the quality of life of neighbours and visitors, and may have large impacts on the local economy, as a result of the loss of accessibility to places

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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, 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 infrastructure projects for motorised transport will likely result 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 (Handy, 2003; Litman, 2003; DfT, 2005a; Laird et al., 2013). This is the main reason to disregard barrier effects in transport planning practise (Russell and Hine, 1996). Nevertheless, barrier effects have been taken into account in the social evaluation of projects, even with quantitative methods that estimate the additional delay and risk for pedestrians to cross a road, using functions based upon variables such as traffic flow, speed and the number of heavy goods vehicles (DfT, 2005b). However, when these monetisation approaches are considered as simplifications of a more complex phenomenon, they have been replaced by qualitative analysis such as the judgment of specialists and experts.

In this context, the contributions of this paper are twofold. First, we analyse the probability distribution of walking trips as a function of walking distance bands using empirical data from four cities: Berlin, London, Sydney and Santiago. Interestingly, a common pattern for all cities is found, namely that the probability distribution of walking trips as a function of trip length is well approximated by an exponential distribution in which the average walking distance is the parameter to estimate. Second, the exponential distribution is used to provide estimations of one dimension of the barrier effect produced by the existence of segregated transport infrastructure: the increase in walking distance when the crossing of a highway or railway is constrained to be made in predefined locations such as crosswalks, pedestrian bridges and overpasses. We obtain analytical expressions for the expected trip length and the probability of walking to a location where walking distance has increased.

In order to make probabilistic calculations, a geometric probability approach is applied 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 determine relationships between objects distributed probabilistically over an area, in particular, to estimate travel times and distances given assumptions on the shape of the areas under study (rectangular, triangular, circular, and general) and the distribution of objects over the plane. A number of problems can be addressed with geometric probability, including finding the optimal location of taxi stations given the distribution of pickup calls, and the design of a response district for ambulances given the distribution of medical assistance requirements (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 remainder of the paper is organised as follows. In Section 2 the distribution of walking trips is analysed using empirical data. In Section 3 model assumptions are explained. In Sections 4 and 5 probabilities of walking trips and their expected length are calculated in a given area, for two different road configurations representing free and limited pedestrian mobility. In Section 6 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 7.

2. Distribution of walking trips

In this section, we analyse the distribution of walking trips as a function of travel distance based on the origin-destination surveys of four cities: Berlin (Ahrens et al., 2009), London (TfL, 2009), Sydney (BTS, 2011) and Santiago (SECTRA, 2001). Fig. 1 shows that a common pattern for the evolution of the proportion of walking trips as a function of travel distance bands for all the surveyed cities. We find that an exponential random variable with probability density function given by Expression (1) fits well the observed distributions:

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

where s is the travel distance and $1/\lambda$ is the expected value of the random variable s. Only trips that are fully made on foot are considered, except for the case of Sydney in which the data includes both full trips on foot (“Sydney (walk only)” in Fig. 1) and walking as an access mode to public transport (“Sydney (walk linked)”). In the case of Berlin, two plots are also presented as the database distinguishes between trips inside and outside the city centre (known as “Großer Hundekopf”). Table 1 presents the estimation of the average walking distance $1/\lambda$ for each case, made with the statistics software package SPSS. Comparisons between cities are to be made with caution because each city has its own methodology for the execution of origin-destination surveys. However, we can be more confident about differences within cities: in Sydney, average trip length is shorter for walk linked trips (699 m) vs walk only trips (795 m) and the difference is statistically significant at the 5% confidence level. On the other hand, trips tend to be longer in Outer Berlin relative to Inner Berlin (773 vs 691 m), but the 95% confidence intervals overlap. Predicted walking trip proportions per distance band with the estimated exponential distributions are depicted in Fig. 1.

An analytical expression for the probability distribution of walking trips based on empirical data is useful to assess the impact on pedestrian mobility of restricting free movement, for example with fences along highways or railways. The exponential distribution (1) is used in the next sections to estimate the increase in the expected length of walking trips and the reduction of the probability of walking to a region that is less accessible due to the existence of pedestrian barriers. In other words, we are going to use a distribution found to explain walking mobility patterns at city-wide levels, as a first approximation to the problem of estimating the impact of pedestrian barriers at a local level. Certainly, the validity of such approach is subject to further scrutiny in situations in which more detailed information on land use and spatial distribution of walking trips is available; however, the limited evidence available suggests that an exponential distribution is also satisfactory to model walking trips at more local levels. Lacono et al. (2010) studied walking and cycling trips as a function of both travel time and distance, within a nearly rectangular area in South Minneapolis of approximately 6.5 × 5.5 square kilometres, and found that an exponential form fits well as travel impedance in a gravitational model for non-motorised accessibility (either as

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[1] MathWorld- A Wolfram Web Resource. http://mathworld.wolfram.com/GeometricProbability.html, *accessed May 2014.*