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Using agent based modeling to assess the effect of increased Bus Rapid Transit system infrastructure on walking for transportation

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ABSTRACT

The effect of transport infrastructure on walking is of interest to researchers because it provides an opportunity, from the public policy point of view, to increase physical activity (PA). We use an agent based model (ABM) to examine the effect of transport infrastructure on walking. Particular relevance is given to assess the effect of the growth of the Bus Rapid Transit (BRT) system in Bogotá on walking.

In the ABM agents are assigned a home, work location, and socioeconomic status (SES) based on which they are assigned income for transportation. Individuals must decide between the available modes of transport (i.e., car, taxi, bus, BRT, and walking) as the means of reaching their destination, based on resources and needed travel time. We calibrated the model based on Bogota's 2011 mobility survey.

The ABM results are consistent with previous empirical findings, increasing BRT access does indeed increase the number of minutes that individuals walk for transportation, although this effect also depends on the availability of other transport modes. The model indicates a saturation process: as more BRT lanes are added, the increment in minutes walking becomes smaller, and eventually the walking time decreases. Our findings on the potential contribution of the expansion of the BRT system to walking for transportation suggest that ABMs may prove helpful in designing policies to continue promoting walking.

1. Introduction

A 25% decrease in physical inactivity (PI) could prevent over 1.3 million deaths every year (Lee et al., 2012) from non-communicable diseases (NCDs). Hence, walking for transportation may be an important contributor in meeting physical activity (PA) recommendations to prevent NCDs (WHO, 2007; Gordon-Larsen et al., 2009). Walking is associated with reductions in the risk of cardiovascular disease (Gordon-Larsen et al., 2009), type 2 diabetes, obesity, cancer, and improvement in overall fitness (Hamer and Chida, 2008). Studies on public transportation have shown that walking is the most natural and important mode for accessing public transport (Daniels and Mulley, 2013; Cervero, 2001).

Nevertheless, the findings on the association between the use of and access to public transit systems and walking for transportation are mixed (Ding et al., 2013), implying an urgent need to understand the relation between transport infrastructure and PA promotion.

Several studies exploring this relation have identified a positive association between walking and access to Bus Rapid Transit (BRT) systems (Cervero et al., 2009; Hino et al., 2011; Lemoine et al., 2016).

Specifically, by applying statistical models to estimate the association between built environment characteristics and walking for transportation, these studies have shown that BRT users are more likely to meet PA recommendations. This finding is highly relevant given that during the last four decades BRTs have been implemented in over 180 cities with an increasing ridership that already numbers over 30 million passengers per day (Hidalgo and Gutiérrez, 2013). Therefore, BRT systems are an important part of the built environment and a growing trend around the globe.

Evidence is still lacking, however, on whether a substantial increases in BRT access can lead to an increase in walking for transport (Saelens et al., 2014). To assess the shape of this trend we must account for

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neighborhood distribution, the dynamic relations and interactions between infrastructure environment and individuals (Yang et al., 2011). One promising framework for analyzing these complex relations is agent based models (ABM), which inherently consider the relation between agents and the environment. These models are thus able to throw light on the actual decision making processes within a system (Olaya, 2012). ABMs have already been used to study pedestrian movement (Davidson et al., 2007; Varas et al., 2007; Willis et al., 2004; Yang et al., 2011), as they help to identify the nonlinear relations and feedback with the physical environments. However, ABMs have been rarely applied as a public health tool (Yang et al., 2011). In fact, no ABM studies, as far as we know, have modeled the relation between walking for transportation and BRT systems. We aim to close this gap by constructing a spatial ABM model that simulates individual transport decisions in the city of Bogotá. The model may also be used to aid policy making and urban development.

2. Methods

For the present case, we constructed a hypothetical city based on Bogota, Colombia, and its BRT, named *TransMilenio* (TM). The model can be considered an activity based travel demand model (Davidson et al., 2007) with the capacity to explain patterns observed in Bogota's mobility survey (Steer Davies — Centro Nacional de Consultoría, 2012).

2.1. Model development

The model, developed in Matlab® (Mathworks, MA), is time discrete, with a day time step that covers only adults who travel twice a day on work days. These trips have two characteristics: they are always made to the same place (Vega and Reynolds-Feighan, 2009), and they occur on every work day (Akkerman, 2000).

2.2. Setting

Bogotá has an estimated population for 2015 of 7.8 million, of which 1.7 million travel to work (Steer Davies — Centro Nacional de Consultoría, 2012) and an area of 1587 km^2 (Departamento Administrativo Nacional de Estadística (DANE), 2013.). The city's population is divided into six socioeconomic status (SES) (low = 1–2, middle = 3–4, high = 5–6) which have, in increasing SES, the following percentage of the population, namely, 9.6%, 40.0%, 36.3%, 9.6%, 2.6% and, 1.7%, respectively (Departamento Administrativo Nacional de Estadística (DANE), 2013). Commuting trips 15 min or longer are distributed as follows: 41% on public transport, 28% on foot, 14% by automobile, 5% by taxi, and the remainder using other modes of transport (Steer Davies — Centro Nacional de Consultoría, 2012). The highest density of jobs is located towards the central east part of the city (Braake, 2013).

The model represents a city of 188,300 adults with 100 km^2 that is mapped onto a 100 × 100 grid so that each cell represents a 100 × 100 m block. The distribution of socioeconomic status (SES) is based on Bogota's distribution (Steer Davies — Centro Nacional de Consultoría, 2012), with (a) SES 1 on the periphery, (b) SES 2 and 3 in the south, and (c) SES 4, 5, and 6 in the north. The number of blocks per SES and the number of adults per block are proportional to Bogotá's distribution (Steer Davies — Centro Nacional de Consultoría, 2012). Jobs are distributed 50% in the central eastern area and 50% uniformly within 20 blocks of each agent's home. For SES 6, 50% of the jobs are distributed in the central eastern area and 50% within 10 blocks of the agents' home to reflect their ability to live near their jobs. The distance between two points in the city, namely home to work d_{hw} is calculated using the Manhattan distance, which corresponds to the simple sum of the absolute value of the difference between the horizontal and vertical components of each position on the grid. The transportation network of (non-TM associated) public busses and TM are established on the grid according to each scenario. The model is assessed and calibrated using a scenario of 4 TM lanes and 29 bus lanes, which is equivalent to the current number of TM lanes in Bogotá but smaller than the number of bus lanes.

2.3. Agents

Agents represent the 188.300 adults from the simulated city. As outlined in Table 1, each agent was assigned a home and a place to work. The neighborhood to which the agent is assigned determines the SES and thus the money the agent receives, which is equal to the average portion of income associated with transportation per SES (Conpes, 2010). Agents are assigned a car which depends on a probability measured for each SES (Conpes, 2010) (Table 1).

2.4. Modes of transportation

For simplicity, we assessed the five most used modes of transportation in Bogotá: car, taxi, bus, TM, and walking (Steer Davies — Centro Nacional de Consultoría, 2012). Agents chose the mode of transportation based on total trajectory costs (c) and time (t) needed to reach the destination. See Table 1 for specific details and values for each mode of transportation. For car, taxi, and walking, t is the *waiting time* (w_t) plus the time needed to cover the distance from home to work d_{hw} at that particular mode's average speed (Conpes, 2010; CCB, 2008). For bus and TM, the model further takes into account the time needed to walk the distance d_{hs} (home ↔ station) and d_{ws} (work ↔ station), labeled the access time. The cost of a trip is calculated based on the standard fare for a one-way bus or TM trip, or the variable costs for the car usage or taxi fare.

2.5. Decisions on mode

The mode decision is based on a utility function that takes into account monetary cost and time, important attributes of mode choice (DeSalvo and Huq, 2005; Ortúzar and Wilumsen, 2011). For each agent, we calculated the probability of taking mode k as a function of the resources (time and cost) needed to arrive at the destination. If agents do not use all their available resources, they may use up to 50% of their savings the next day for transportation. The probability $p(k)$ of choosing mode k is thus a weighted geometric average of the influence of time u_k and resources r_k given by

$$p(k) = \sqrt{r_k^{\alpha} u_k^{2-\alpha}}. \tag{1}$$

We assume that α reflects the relative weight that agents assign to money when choosing a transportation mode, with each different SES having a different α (Table 1). A sensitivity analysis of these α values identifies no significant effect on walking patterns.

We define the resource index (r_k) of using mode k based on daily resources and the savings accumulated by each agent, namely,

$$r_k = \frac{S + I - C_K}{\sum\limits_{k \in G} (S + I - C_K)} \tag{2}$$

where G is the set of available modes (restricted by available resources), S is the amount of the agent's past savings, $I$is the agent's daily income, and C_k is the cost of traveling by mode k.

Because the exponential forms yield a better fit to the distribution of walking trips over distances (28), the time-based index u_k of taking mode k is inversely proportional to the exponent of the expected time t to reach the destination, given by

$$u_k = \frac{\exp(-t_k)}{\sum_{k \in G} \exp(-t_k)}. \tag{3}$$