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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

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

Table 1
Model parameters for individuals and modes of transportation.

Model parameters					
Individual parameters based on SES					
SES	Percentage of agents	Income per person per day for transportation only US $	Percentage spent on transportation	Probability of having a car	Relative importance of resources α
SES 1	9.5%	$1.85	12.4%	0.04	1
SES 2	40.3%	$1.97	9.9%	0.05	0.8
SES 3	36.2%	$3.08	9.0%	0.17	0.72
SES 4	9.2%	$5.04	7.0%	0.49	0.56
SES 5	3.0%	$6.16	5.0%	0.64	0.4
SES 6	1.5%	$7.70	5.0%	1.00	0.4
Transportation parameters based on mode of transportation					
Mode	Cost (US dollars)[a]	Speed (km/h)	Access time (min)	Waiting time (min)	
Car	$0.50 * d_{hw}$	26.88	0	2	
Taxi	$0.83 + 0.33 * d_{hw}$ minimum $1.71	22.38	0	5	
Bus	0.7	18.28	$1.37\ (d_{hs} + d_{ws})$	10	
TM	0.85	27.96	$1.37\ (d_{hs} + d_{ws})$	10	
Walking	0	4.38	0	0	

$d_{hw} = distancehomework.$
$d_{hS} = distancehomethenerareststation.$
$d_{ws} = distanceworkthenearestestation.$
[a] One dollar is equal to 2.000 Col pesos. Price for 2014.

From these three equations, we established the probability $p(k)$ of taking mode k. At each time step we use a random number to choose a particular transportation mode for each agent.

2.6. Model assessment

Model Assessment included four steps. The first step was decalibration process which compares the model output for walking behavior with Bogota's distance decay for walking calculated from the Bogota mobility survey. This survey included a representative sample of 16.157 persons (Steer Davies — Centro Nacional de Consultoría, 2012). Distance decay is a function of both spatial structure and interaction behavior (Eldridge and Jones, 1991; Yang and Diez-Roux, 2012). It is well accepted that the negative exponential function form is used for walking since walking involves short distances (Yang and Diez-Roux, 2012).

$$P(t) = \exp(-\beta t) \tag{4}$$

where $P(t)$ denotes de cumulative percentage of walking trips with time equal or longer than t. The parameter β was used for calibration and was estimated by least-squares fit (FindFit in Mathematica 9). The second step was examining the use of transport modes among agents by SES. Lower SES are more prone of using public transport and less likely to use car or taxi, higher SES more prone of using car and taxi and less likely to use the bus or TM (Steer Davies — Centro Nacional de Consultoría, 2012). The third step compares the prevalence of walking among agents according to distance and SES. Adults from lower SES are more likely to walk for transportation compared to adults from higher SES (Besser and Dannenberg, 2005; Saelens et al., 2014). Finally, the fourth step evaluated the probability of using TM according to the distance agents must walk. Users of TM are more likely to live within 500 m of a TM station (Lemoine et al., 2016).

The calibration scenario was run four times, for 40 days. Since walking levels become stable after 10 days. The analysis is based on only the last 30 days of the simulation.

2.7. Model assessment results

Overall the model generates a similar distance decay function. The β parameter for Bogotá is 0.091 and model's β parameter is 0.095 (Fig. 1a), a SES-related mode distributions that mirrors Bogota's (Fig. 1b), different walking prevalence per SES as observed in prior empirical studies (Fig. 1c) and a higher probability of using TM among those closer to a TM station (Fig. 1d). The model shows that as in Bogotá agents from a lower SES are more likely to walk for transportation or use public transport, while those with a higher SES are more likely to take a car or taxi, with the largest model-versus-data difference being in the use of a taxi, specially in SES 4 and 5. In terms of the decision to walk per SES seventy five percent of SES 1 agents with a ten minute walk to work decided to walk, while only a 10% of SES 6 agents with a five minute walk to work chose to walk. Finally, as observed in other studies (Lemoine et al., 2016) agents with access to TM are more likely to use TM.

2.8. Scenarios

To increase our understanding of the influence of the TM and bus on walking for transportation, we create two types of scenarios. For the first scenario type, we simulated the growth of the BRT system by varying the number of lanes from 0 to 10 lanes and decreasing the number of bus lanes from 33 to 23 lanes to reflect BRT substitution. For the second scenario, we randomly distribute bus and BRT stations throughout the city at differing densities of 0%, 3%, 7%, 10%, 13%, 17%, and 20%. A 3% density means that on average agents must walk 680 m in a bus/TM trip, with a 7% density on average agents must walk 460 m when using bus/TM, and a 20% density means that agents must walk on average 210 m in a bus/TM trip. Thus, in the scenario with 3% bus and 7% BRT density agents must walk on average 680 m to use the bus and 460 m to use the TM. In all cases, all the other parameters remain the same.

All scenarios were run four times for forty days and only the last 30 days were used for the analysis.

3. Results

3.1. Scenarios with the added BRT lanes

Increasing the number of TM lanes produces an increment in the number of minutes walked for transportation. This increment is also observable among nonusers of the TM (Fig. 2a). Nevertheless, the increment in the number of minutes walked decreases, suggesting that walking time saturates as TM lanes are added to the system. Specifically, the average walking time for TM users increases 1 min as the number of

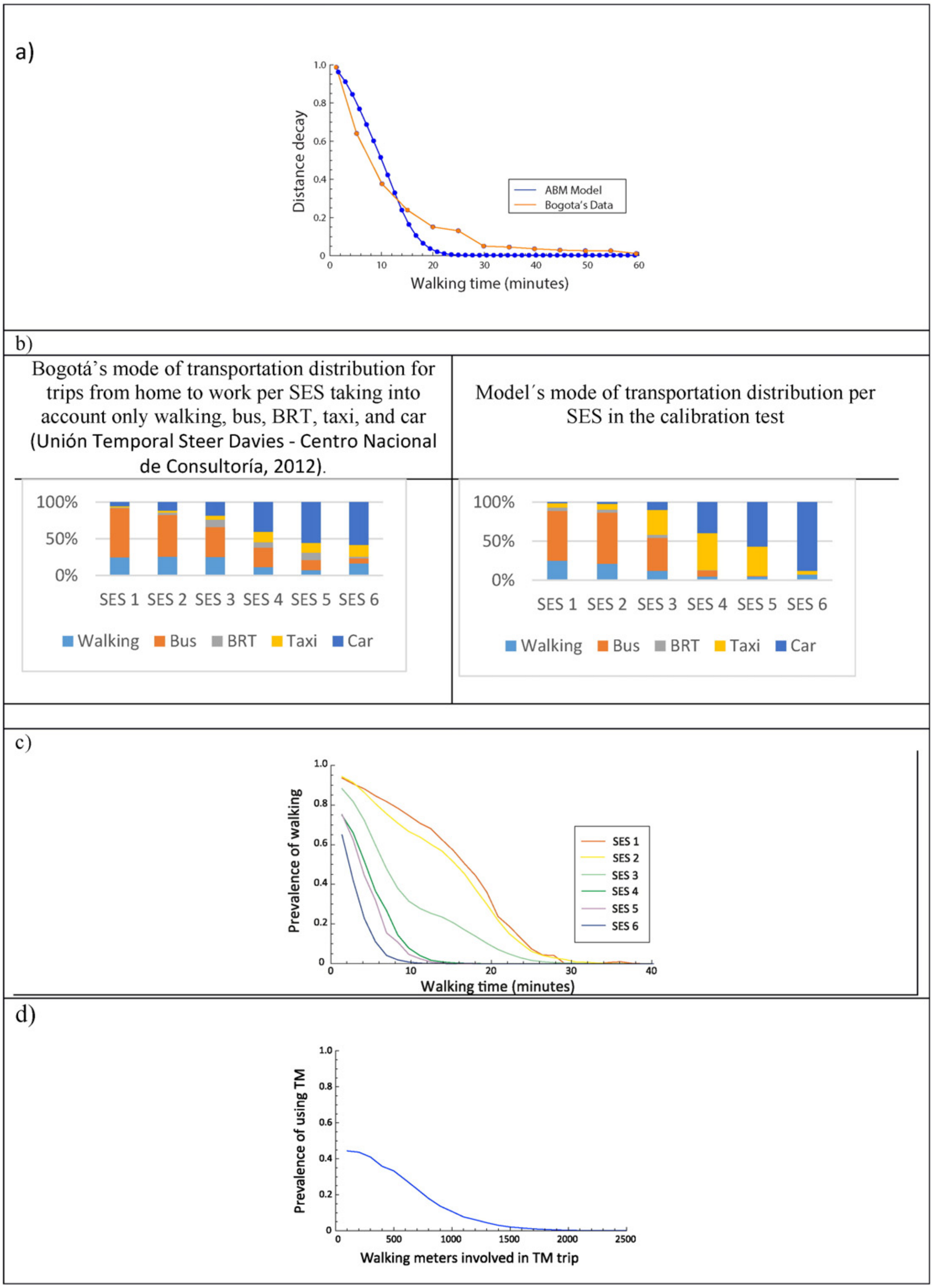

Fig. 1. Model assessment results: (a) distance decay function for walking obtained in the calibration model compared to Bogota's distance decay for walking to work; (b) comparison mode distribution per SES for Bogotá versus the ABM model for the calibration case, revealing a similar pattern: lowest SES = higher likelihood of using public transport/walking; highest SES = higher likelihood of car/taxi. c) Prevalence of walking per travel time by SES in the calibration test case, showing that the lower the SES, the higher the likelihood of walking. d) Prevalence of using TM according to accessibility. Agents who live and work near a TM station are more likely to use TM.

TM lanes increases from 2 to 4, but the increment is only 0.5 min for an increase from 8 to 10 TM lanes. Similar behavior is observable among nonusers of the TM: the introduction of the first two TM lanes yields an increment of 1.5 min, but practically no increment occurs between 8 and 10 BRT lanes (Fig. 2b). The city's average of minutes walked for transportation increases from 5.0 to 10.4, with the largest increment occurring after the introduction of the first two lanes but slowly diminishing thereafter.

3.2. Scenarios with random distribution of BRT and bus stations

Fig. 3a and b shows the average minutes walked for transportation based on TM and bus densities in three dimensional and two dimensional space, respectively. These figures indicate that in the absence of the TM or bus, agents must walk great distances for an average of 93.4 min. The prevalence of walking is over 90% among SES 1 and 2 and over 50% among SES 3, whereas for SES 4, 5, and 6 it is similar to

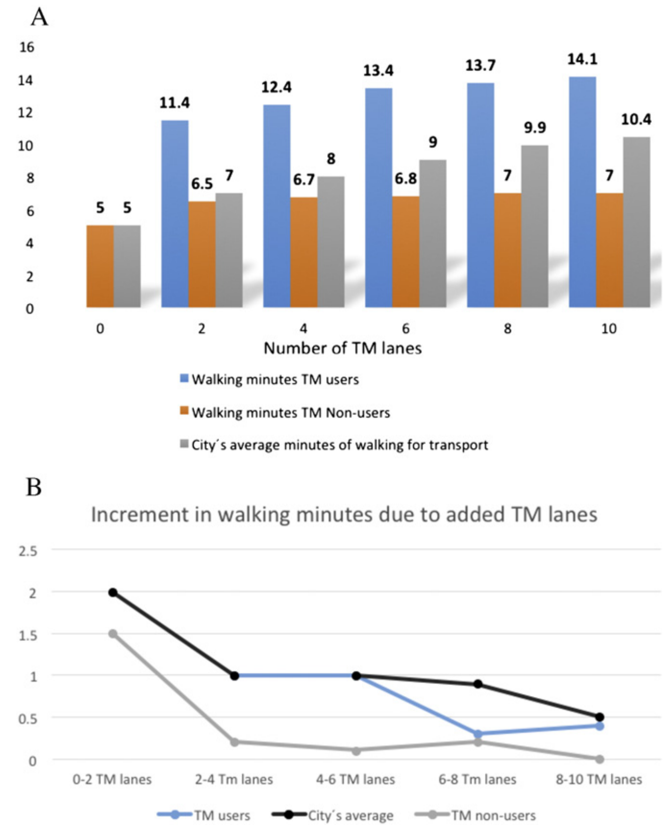

Fig. 2. a) Minutes spent walking by users and nonusers of the TM dependent on number of TM lanes. 5 b) Increment on minutes spent walking by users and nonusers of the TM dependent on number of TM lanes. The minutes walked for transportation increases with the number of TM lanes.

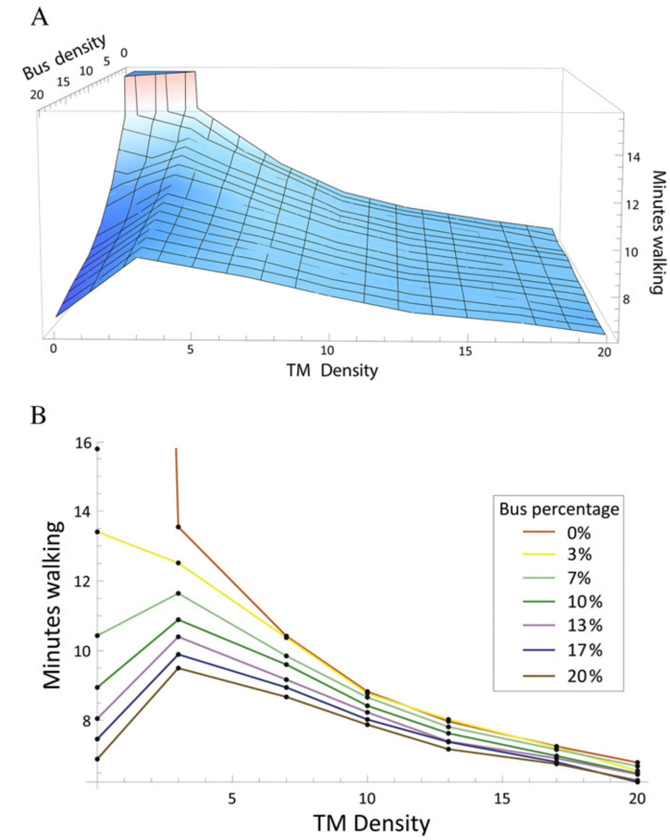

Fig. 3. Average minutes walked for transportation based on BRT and bus density in three dimensions (a) and in two dimensions (b). When the bus density is high (low), the introduction of BRT lanes increases (decreases) the average number of minutes walked.

that in the calibration scenario (not shown). As public transport becomes more available, the number of minutes walked decreases. The introduction of BRT at a 3% density (680 m average walking distance per trip) in scenarios that already have bus densities above 3% augments the number of minutes walked for transportation. While the introduction of TM lanes at a 3% density or above reduces them. Higher densities of BRT decrease walking as a means of transportation in all scenarios.

4. Discussion

The results show that walking for transportation is a product of commuters' relationship with their built environment and the existing modes of transport. Specifically the ABM indicates that the increment of BRT Infrastructure in a city with a high bus density like Bogotá will result in more minutes of walking for transport. In our hypothetical city, moving from two TM lanes to four lanes increases the average walking time in the city by 1 min per day. According to the model results the increment in BRT infrastructure will continue leading to more walking for transport. This ABM was able to reproduce behaviors observed in other studies, including a similar distance decay for walking, a higher willingness to walk among those with lower SES (Besser and Dannenberg, 2005), and a difference in walking behavior between users and nonusers of the BRT (Cervero et al., 2009; Day et al., 2014; Hino et al., 2011; Lemoine et al., 2016). Hence, by combining large survey data with ABM, we are able to identify certain robust elements that may shape the distribution of the time that users spend walking given the trip destinations and transport infrastructure in a city such as Bogotá.

Our results are consistent with the increment in walking for transportation observed because of BRT system construction in previous studies. The 5–7/day min associated in our model with BRT use for two trips is comparable to the 12 min estimated by Lemoine et al. (2016) for an average of 2.6 trips per day for BRT use in Bogotá; and the studies by Saelens et al. (2014) (12.4 min/transit day) (12). Our estimates however are lower than those by Besser and Dannenberg (2005) (19 min/transit day) and by Freeland et al. (2013) (18.2 min/bus transit day).

The increased walking for transportation results from BRT's speed, the distance to BRT's stations and the availability of other modes of transport. Our model explains these patterns and establishes that increased BRT infrastructure will continue leading to more PA as long as the average total walking distance for BRT trip is above 680 m. This result is within the international standard for accessibility, which usually falls between 400 and 800 m (Sony Sulaksono Wibowo, 2005). This explains the results obtained in New York where users of BRT walk more than bus users but less than subway users (Day et al., 2014). In Australia the mode of the public transport trip is the most important determinant of walking distance (Daniels and Mulley, 2013).

The model's outcomes also underscore the importance of high accessibility to public transport, especially for those with low SES. When BRT and bus densities are low, walking for transport increases substantially, especially among those with the lowest SES who live furthest from the city center in which most jobs are located. Walking such distances has been related to a lower quality of life (Sarmiento et al., 2010). This finding underscores the importance of taking into account different frameworks. The decision to walk has been modeled through a choice-based framework were all the population has access to different modes of transport (Yang et al., 2011; Yang and Diez-Roux, 2013), independent of their financial means. In middle and low income countries were car ownership remains low in comparison with high income countries, walking for transport may be more reflective of the financial restrictions rather than choice, because a large part of the population does not have other options for transportation (need-based framework) (Salvo et al., 2015; Salvo et al., 2014; Sarmiento et al., 2015).

4.1. Study strengths and limitations

The main strengths of the study are the fact that results are based on the simulation of the decision making process, the broad model assessment which includes a distance decay calibration, a comparison of the mode share per SES, the evaluation of walking attitudes by SES and the use of TM according to access and finally the model is able to simulate a wide variety of scenarios to assess the effect of increased Bus Rapid Transit system infrastructure on walking for transportation. The model does, however, have certain limitations. First, because Bogotá is much larger than our hypothetical city, trips are shorter, making taxi and car trips less expensive, which may partly explain the large taxi participation in our results. This difference in size does not seem to have a large influence on walking distributions due to the short distances related to walking. Second, mode choice is based solely upon resources and time, which have been considered main variables, however, other variables like comfort, weather, and safety might also play an important role in the decision (Ortúzar and Wilumsen, 2011). In terms of transport, other major components such as the running hours and service frequency were not taken into account, which might explain the differences in mode use per SES. Another limitation is our assumption that all agents from the same SES have the same income, including a sum of money large enough to grant access to the bus or TM. This assumption does not in fact hold for a city like Bogotá, in which 10.2% of the population lives below the poverty line (income less than US$100 per month) and therefore have insufficient resources to consistently access public transport. Such insufficiency occurs most frequently among those with the lowest SES, who live on the periphery and are forced to either remain where they are or walk great distances. This may partly explain the steepness of the model's distance decay function compared to Bogota's actual distance decay for large walking times, this difference implies that the model underestimates commuters' willingness to walk. These factors could be included in future studies.

4.2. Conclusion

Walking behaviors are related to transportation infrastructure. Thus its design could be considered as part of a public health policy. Specifically, the growth of BRT infrastructure is expected to continue promoting walking for transport. Therefore, 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. Such findings could inform high and low to middle income countries where expansion of BRT systems is expected to continue.

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Conflict of interests

All authors declare that they have no conflicts of interest.

Transparency document

The Transparency document associated with this article can be found, in the online version.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.ypmed.2016.03.015.

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