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Critical review

The ridership performance of the built environment for BRT systems: Evidence from Latin America

C. Erik Vergel-Tovar[a,*], Daniel A. Rodriguez[b]

[a] *Programa Gestión y Desarrollo Urbanos, Facultad de Ciencia Política, Gobierno y Relaciones Internacionales, Universidad del Rosario, Bogotá, Colombia*
[b] *Department of City and Regional Planning, Institute for Transportation Studies, University of California, Berkeley, United States*

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ABSTRACT

Despite the increasing popularity of BRT worldwide, there is a lack of empirical evidence regarding the built environment characteristics that determine BRT ridership. We examine associations between BRT station level demand and built environment attributes for 120 stations in seven Latin American cities. Using direct ridership models, we study whether underlying built environment factors identified using factor analysis and the package of these factors embodied in station "types" identified using cluster analysis were associated with higher ridership. Of the nine factors identified, those describing compactness with dominant multifamily residential uses and stations with public and institutional land uses along the corridor were positively associated with ridership, while factors describing single-family residential development away from the CBD were negatively associated with ridership. Thirteen station types were identified, of which six were associated with BRT ridership. Relevant station types for ridership included those with a high mixture of land uses, the presence of institutional uses and public facilities, major transfer nodes in peripheral areas, and stations with a strong pedestrian environment. Taken together, our findings suggest that the mix and dominance of various land uses around the stop, the location of BRT stations relative to the CBD, the developable land around the station, and the integration of the station to the urban fabric are important characteristics that determine BRT ridership. These insights will help substantiate the case for prioritizing-built environment changes as a means to build more prosperous and sustainable mass transit systems.

1. Introduction

There is wide recognition about the importance of the built environment for supporting transit use. By determining the origins and destinations around stations, defining the physical environment for access to and egress from the transit system, and linking the station to the fabric of the city, the built environment can play an important role as a facilitator or barrier to transit use. As a result, planners have paid increased attention to the characteristics of the current built environment as they make decisions about the alignment of BRT systems and identify actions taking to promote environmental changes.

Transit oriented development (TOD) frequently exemplifies many of the built environment attributes that support transit ridership. TOD is characterized by development that is compact, with a mix of land uses and housing types, containing a well-connected and supportive pedestrian and cycling environment, and that is well-integrated with mass transit (ITDP, 2017). Indeed, current evidence suggests that TOD can increase transit ridership by concentrating user demand (Cervero, 2007; Suzuki et al., 2013), decreasing access and egress time, and leveraging transit's economies of density (Guerra and Cervero, 2011). When planned as multiple development nodes, TOD can also help balance flows and concentrate destinations for travelers. Others have argued that TOD can also create appropriate conditions for the application of value capture techniques to support transit financing (Page et al., 2017).

Although many studies have examined the importance of the built environment for transit use, very few have focused on bus rapid transit (BRT) demand. This is a significant gap for several reasons. First, there is a growing popularity of BRT in developing and developed cities, more than 160 cities have implemented BRT and 121 are in the process of planning for it (BRTDATA.ORG, 2017); second, because cities and countries are now explicitly promoting TOD around BRT as a strategy to mitigate and adapt to the challenges of climate change (Winkelman, 2016); and third, because it is not clear that associations between the built environment and rail ridership identified in prior literature will also hold for BRT service. Although distrust of BRT among developers and public officials is receding as the popularity of BRT grows, it is not clear that the ridership bonus brought by TOD is necessarily capitalized

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* Corresponding author.
E-mail addresses: erik.vergel@urosario.edu.co (C.E. Vergel-Tovar), danrod@berkeley.edu (D.A. Rodriguez).

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in BRT systems.

In this paper, we study associations between the built environment and BRT ridership in seven Latin American cities. We focus on examining ridership impacts of salient aspects of the built environment identified in prior research focused around rail systems, as well their "packaged" combination under different types of stations. This information can be used by planners, firms, and decision-makers to plan for future transit systems, modify the areas around existing stations, promote compact urban forms, and encourage non-motorized travel around BRT stations.

In the next section we begin by reviewing the extant literature to inform our main questions. Then, we present our methodology, describing study areas, data collection, and analytic strategy. Next, we present results and put them into the context of the broader body of related research. Finally, we conclude and explore the implications for planners, engineers, and policy-makers.

2. Review of the literature

A prevailing framework to examine the built environment relies on identifying a set of underlying dimensions that characterize the physical environment. Cervero and Kockelman (1997) initially suggested the density, diversity, and design of the environment, with Lee and Moudon underscoring the importance of the quality of routes (Lee and Moudon, 2006). In the context of transit demand, destination accessibility and distance to transit have been shown as relevant (Cervero, 2007; Ewing and Cervero, 2010) while others have suggested consideration of demographic and housing characteristics (Atkinson-Palombo and Kuby, 2011; ITDP, 2017) (Lund et al., 2004) and parking (Chatman, 2013; Manville, 2017; Marsden, 2006).

The empirical evidence persuasively suggests that density plays an important role in explaining rail ridership. Density conveys not only the concentration of population at stations, but also the concentration of employment and destinations. For example, density has been positively associated with heavy rail use in Taiwan, (Lin and Shin, 2008), New York City (Loo et al., 2010), Seoul (Choi et al., 2012; Jun et al., 2015; Sung and Oh, 2011), Montreal (Chan and Miranda-Moreno, 2013), and Nanjing (Zhao et al., 2013). Several other studies have found positive associations between population density and light rail-transit (LRT) ridership (Cervero, 2006; Kuby et al., 2004; Lane et al., 2006; Parsons Brinckerhoff Quade, and Douglas, Cervero, Howard/Stein-Hudson Associates, and Zupan, 1996).

For BRT, only three studies have examined density and ridership. Based on a sample of 69 BRT stations in Los Angeles (USA), positive associations between population density and BRT ridership were identified (Cervero et al., 2009). A similar model examining built environment attributes around a sample of 51 BRT stations in Mexico City found a positive association, but density was only measured with three categories (low, medium and high) due to the absence of more accurate data (Duduta, 2013). At the city-level, Cervero and Dai (2014) conducted a city-level ecological analysis of city density and transit ridership for 119 cities, finding an elasticity of demand with respect to population density of 0.39.

Results for land use are slightly less consistent than for density. For heavy rail, positive associations between land use mix and ridership have been found for Montreal, Nanjing, and Seoul, but negative associations were found for Hong Kong (Loo et al., 2010). Development characteristics around Hong Kong's rail system, focused mostly around land use, may explain this result (Cervero and Murakami, 2009). Another study examining 67 LRT stations found positive associations between residential and retail uses with ridership as well as between the presence of facilities such as schools and hotels with ridership levels (Foletta et al., 2013). We could not identify any studies examining the association between land use mix and BRT ridership.

Other dimensions of the built environment around stops such as street design and connectivity, parking, and housing mix have been less studied relative to transit demand. Design aspects of the built environment arguably have been the hardest to measure and the most inconsistently associated with traveler behavior. At the individual level, Fan (2007) found that daily transit use increased with higher street connectivity, and other studies have identified associations between connectivity and transit mode choice. For BRT, Estupinan and Rodriguez did not find a statistically significant association between demand and street connectivity around the 62 BRT stops in Bogota. However, they did find that the pedestrian environment was positively associated with BRT demand. Other studies have found similar associations for BRT (Jiang et al., 2012) and bus systems (Ryan and Frank, 2009), although effect size tends to be small.

In contrast to attempts to disentangle the unique contribution of particular built environment attributes, few studies have examined associations between the package characteristics and transit stop ridership. This is surprising given the potentially synergistic effects among TOD features. For example, street connectivity, a pedestrian friendly environment, and a high mixture of land uses are likely to have a greater impact on ridership when population density is high. Evidence from California, Washington DC, and Portland suggests that TOD residents are much more likely to use public transportation than non-TOD residents (Cervero, 2007; Cervero, 1994; Dill, 2008) although travel patterns vary significantly between weekdays and weekends (Lin and Shin, 2008).

Taken together, the literature on transit use and the built environment has mainly focused on rail-based transit systems, with very few studies conducted for BRT. Population density, land use mix, and the pedestrian environment, all attributes related to TOD, have emerged as important predictors of transit demand. Whether associations identified for rail systems are also relevant for BRT remains to be examined. Furthermore, the scant evidence examining TOD and transit ridership suggests that it is possible that a richer set of built environment attributes will moderate these associations. Thus, in the next section we present the methods used to examine associations between the built environment and BRT ridership in a sample of stations in seven Latin American cities. Consistent with the literature reviewed, we focus on salient features as summarized by underlying dimensions that characterize the built environment as well as their joint contribution within station types.

3. Methodology

3.1. Study areas

We examined 120 BRT stations in seven cities (Bogota, n = 31; Sao Paulo, n = 12; Curitiba, n = 16; Goiania, n = 11; Ciudad de Guatemala, n = 9; Quito n = 30; and Guayaquil, n = 11) representing four Latin American countries (Colombia, Brazil, Guatemala and Ecuador). The emphasis on Latin America is the result of the early and eager adoption of BRT in this area of the world. Cities were selected according to the following criteria: i) the BRT systems have been under operation for ten or more years; ii) the BRT infrastructure includes segregated bus lanes, high-quality stations, and off-vehicle fare collection; and, iii) the BRT ridership levels of these systems are higher than 200,000 passengers per day. Together, these cities represent 14% of world BRT ridership (BRTDATA.ORG, 2017).

3.2. Data collection and management

We identified a non-random sample of stations in each BRT system in consultation with local transportation and city planners to ensure that the stops were generally representative of other stops in the city's BRT system (i.e., not too unique) and that they had sufficient secondary built environment data available to support the analysis. Outcome data for the study consist of BRT station boardings provided by local authorities or identified in published documents. For Sao Paulo ridership

Table 1
Built environment variables collected, definition, and scale of data collection.

Variable	Definition	Level at which data was collected
Population		
Population density	Population by station area (persons/hectares)	Station
Portal	1 = BRT terminal; 0 = non-terminal	Station
Density		
Building heights		
No buildings	Proportion of segment with no buildings	Segment
Single story	Proportion of segments with building heights~ 1 story	Segment
Low-rise	Proportion of segments with building heights ~ 2 to 3 stories	Segment
Low-Medium-rise	Proportion of segments with building heights ~ 4 to 5 stories	Segment
Medium-rise	Proportion of segments with building heights ~ 5 to 10 stories	Segment
High rise	Proportion of segments with high-rise developments	Segment
Built-up density		
Low built-up density	Proportion of segments with low density development	Segment
Medium built-up density	Proportion of segments with medium density development	Segment
High built-up density	Proportion of segments with high density development	Segment
Development level		
Low development level	Proportion of segments with limited development, considerable vacant land	Segment
Medium development level	Proportion of segments with some development and some vacant land	Segment
High development level	Proportion of segments highly developed; no undeveloped land	Segment
Diversity		
Land uses		
Institutional	Proportion of segments with institutional uses	Segment
Industrial	Proportion of segments with industrial uses	Segment
Exclusively commercial	Proportion of segments with commercial land uses	Segment
Mixed commercial	Proportion of segments with commercial and other land uses	Segment
Residential single family (attached)	Proportion of segments with residential single uses	Segment
Residential multifamily	Proportion of segments with residential multifamily uses	Segment
Mixed: Industrial-commercial	Proportion of segments with industrial-commercial uses	Segment
Mixed: commercial residential	Proportion of segments with commercial residential	Segment
Vacant	Proportion of segments with vacant uses	Segment
Open Green Area	Proportion of segments with undeveloped open green spaces	Segment
Land use mix variables		
Land use index	# of land uses in station (1-10)	Segment
BRT-oriented land uses	Density of commercial, residential, and institutional uses	Segment
Other land uses	Density of industrial, industrial & commercial, and vacant uses	Segment
Entropy	Evenness in the distribution of commercial, residential and institutional land uses	Segment
Design		
Street density	# of segments within station area	Station
Number of blocks	# of blocks within total station area	Block
Number of two-lane street segments	# of segments with 2 lanes within station area	Segment
Number of three-lane street segments	# of segments with 3 lanes within station area	Segment
Vacant land along BRT corridor	% of segments with vacant land on BRT corridor	Segment
Average street segment distance to station	Average distance of street segment centroid to BRT station	Station
Average street segment length	Average segment length within station area	Station
Segments on BRT corridor	# of street segments facing the BRT right of way within station area	Station
Access to destinations		
Centrality	Distance to the CBD (Km)	Station
Parking		
On-street parking	Proportion of segments with parking on street	Segment
Off-street parking	Proportion of segments with buildings/structure entirely or partially offering off-street parking	Segment
Commercial and parking uses	Proportion of segments with commercial and parking uses together	Segment
Off-street parking on vacant parcel	Proportion of segments with vacant parcels with undeveloped lots devoted to off street parking	
NMT infrastructure		
Density of green areas	Density of parks, squares, pocket squares, green areas, boulevards within station area	Block
Pedestrian segments density	Density of pedestrian segments within station area	Station
NMT friendliness	Density of parks, squares, pocket squares, boulevards, pedestrian segments, pedestrian bridges, bike-paths within station area	Block
Average block size	Average size of blocks within the buffer area in square meters within station area	Block
Park density	Density of # parks, squares, pocket squares within station area	Block
Socioeconomic characteristics and building conditions		
Affordable housing	Proportion of segments with affordable housing	Segment
Informal settlements	Proportion of segments with informal settlements	Segment
High urban decay	Proportion of segments with high decay of the urban fabric	Segment
Medium urban decay	Proportion of segments with moderate decay of the urban fabric	Segment
Low urban decay	Proportion of segments with low decay of the urban fabric	Segment
Facilities and public space		
Public uses index	Index of seven (schools, hospitals, temples, libraries, market squares, sports, recreational) public uses within station area	Block

(*continued on next page*)

Table 1 (*continued*)

Variable	Definition	Level at which data was collected
Public uses density	Density of public uses within station area	Block
BRT-oriented public use index	Index of hospitals, libraries, markets/squares, churches (0-4) within station area	Block
BRT-oriented public use density	Density of hospitals, libraries, markets/ squares, churches within station area	Block

data were only available for BRT terminals so we collected primary data during three weekdays in October 2014 for seven BRT stations in Sao Paulo.

To measure the built environment around each station, we relied on the domains identified in the review to collect data on development density, land use, street design, access to destinations, parking, the pedestrian environment, housing characteristics and building conditions, and facilities and public spaces along all street segments within 250m of stops, and 500m for terminals were collected in person between 2011 and 2014. Additional details on the data collection process are described by Rodriguez and Vergel-Tovar in a previous study (Rodriguez, D.A., Vergel-Tovar, C.E., 2017).

Briefly, the density domain variables measure compactness in a given segment. Variable include building heights (from no buildings to high rises), the prevailing development density (low to high), and the proportion of vacant land (low to high) along a segment. The diversity domain contains variables measuring the presence of a variety of land uses, ranging from different individual types of residential to industrial and green spaces, as well as their vertical mixture (industrial-commercial and commercial-residential uses). The overall mixing of uses is measured through four different variables (entropy, a land use index, BRT oriented land uses which include commercial, residential, and institutional uses, and mixture of other land uses). The design domain contains variables of street density, connectivity, street segment length, the presence of vacant land along the BRT corridor (making for a less desirable pedestrian environment) and street segment location relative to the BRT station. Regional access was measured by the distance to the central business district (CBD). The parking domain measures the supply of on and off-street parking, as well as the presence of that parking within commercial areas or on surface, undeveloped lots on vacant parcels. The non-motorized transportation domain includes variables measuring average block size, density of pedestrian-only street segments, density of parks and of green areas (including parks, plazas, pocket squares, plazas, and boulevards), and an index of pedestrian and bicycle friendliness combining many of the previous variables but also including the presence of bicycle paths and pedestrian bridges). The socioeconomic characteristics and building conditions domain includes variables measuring the presence of informal settlements (housing units developed through self-help, mostly at the periphery) and affordable housing (low income housing units developed mostly with the support of the government). Variables in this domain also measure the quality of the urban environment (using a subjective metric of urban decay ranging from low to high). Finally, the facilities and public space domain includes variables measuring institutional and public uses of land and facilities (such as schools, hospitals, temples, libraries, market squares, sports, and recreational facilities).

For data collection, a segment was defined as a block front, between two street intersections. For a segment to be considered, the midpoint of the segment should lie within the buffer of the study area. Blocks were the areas surrounded by street segments. Typically, a square or rectangular block was surrounded by four street segments. For a block to be included in the analysis, it should be intersected by the circle of the buffer area of the station. Blocks intersected partially by the buffer area were included in the analysis by including only data within the catchment area of the station. The larger catchment area for BRT terminals responds to previous research suggesting catchment areas varied by station type (Jiang et al., 2012). Secondary data provided by local governments and governmental agencies allowed us to measure population density, evenness in the distribution among institutional, mixed-commercial, single and multifamily residential land uses, and distance to the central business district (CBD).

Because the station level is the unit of analysis, all segment and block level data were aggregated to the station level. The aggregation was performed by calculating either the proportion or percent of segments within station influence area containing a given attribute or by simply adding up the number of instances within the influence area of the station. The list of the complete built environment variables collected and the unit of analysis at which they were collected (street segment, at the block and segment levels) is described in Table 1.

3.3. Statistical analysis

To examine associations between station-level demand and the built environment, we estimate direct ridership models. These are reduced-form regression models with station level ridership regressed against a set of stop-specific independent variables, including the built environment characteristics surrounding the station (Cervero, 2006; Estupiñán and Rodríguez, 2008). Since we have a large number of potential independent variables, we reduced them using exploratory factor analysis and estimated a factor score for each. Our first set of ridership models use factor scores as independent variables in the regression equations. For our second set of models, we used cluster analysis to identify like stations based on their factor scores and use dummy variables to denote cluster membership in the reduced regression models. In all models we used a log-transformation for ridership, a city fixed effect, and whether the station is a BRT terminal or not.

4. Results

Descriptive statistics of ridership levels and all built environment variables are shown in Table 2 organizing the variables a priori into the density, diversity, design, parking, non-motorized transportation, housing mix, and population socioeconomics domains. As expected, there is high variation in ridership levels across the BRT stations sampled. Daily station boardings ranged between 210 and 272,829 passengers, with 24,713 average ridership. This wide variation reflects not only the heterogeneity of stations under consideration, but also differences across the various BRT systems. For comparison, the ten busiest stops of the MBTA in Boston carried an average of 18,700 passengers in 2013 while for BART in San Francisco the top 10 averaged 22,100 passengers in 2017 in a typical weekday. Some of the BRT systems perform like quasi rail systems, with high frequencies, competitive travel times, and high passenger volumes, while others resemble lower level of service traditional bus systems. Ultimately, these demand figures represent also the allure of the operational flexibility of BRT.

The variables measuring the density domain suggest most BRT stations are in already urbanized areas with low and medium building heights developments and only few with high-rise developments within the buffer area. The diversity domain indicates a high mixture of land uses in the sample of BRT stations with a considerable presence of supportive BRT land uses. The street design domain suggests there is high level of connectivity especially in already consolidated and urbanized areas. Accordingly, segment lengths are short, reflecting the

Table 2
Descriptive statistics BRT ridership and built environment variables by domain (N = 120)

Variable	Definition	Mean	Std. Dev.	Min	Max
Dependent variable					
BRT ridership	Number of passengers per day boarding each station	24,713	49,998	210	272,829
Population					
Population density	Population by station area (persons/hectares)	74.74	70.32	0.48	390.18
Portal	1 = BRT terminal; 0 = non-terminal	0.27	0.44	0.00	1.00
Density					
Building heights					
No buildings	Proportion of segment with no buildings	0.17	0.14	0.00	0.71
Single story	Proportion of segments with building heights~ 1 story	0.33	0.24	0.00	0.91
Low-rise	Proportion of segments with building heights ~ 2 to 3 stories	0.71	0.17	0.22	1.00
Low-Medium-rise	Proportion of segments with building heights ~ 4 to 5 stories	0.18	0.14	0.00	0.56
Medium-rise	Proportion of segments with building heights ~ 5 to 10 stories	0.14	0.19	0.00	0.83
Built-up density					
Low built-up density	Proportion of segments with low density development	0.58	0.22	0.02	1.00
Medium built-up density	Proportion of segments with medium density development	0.32	0.16	0.00	0.74
High built-up density	Proportion of segments with high density development	0.09	0.12	0.00	0.60
Development level					
Low development level	Proportion of segments with limited development, considerable vacant land	0.08	0.11	0.00	0.61
Medium development level	Proportion of segments with some development and some vacant land	0.25	0.21	0.00	0.95
High development level	Proportion of segments highly developed; no undeveloped land	0.67	0.27	0.00	1.00
High-rise buildings					
High rise buildings	Proportion of segments with buildings > 10 stories	0.14	0.18	0.00	0.79
Diversity					
Land uses					
Institutional	Proportion of segments with institutional uses	0.08	0.08	0.00	0.46
Industrial	Proportion of segments with industrial uses	0.05	0.14	0.00	0.88
Exclusively commercial	Proportion of segments with commercial land uses	0.14	0.14	0.00	0.78
Mixed commercial	Proportion of segments with commercial and other land uses	0.19	0.16	0.00	0.63
Residential single family (attached)	Proportion of segments with residential single uses	0.35	0.22	0.00	0.91
Residential multifamily	Proportion of segments with residential multifamily uses	0.16	0.18	0.00	0.88
Mixed: Industrial-commercial	Proportion of segments with industrial-commercial uses	0.08	0.15	0.00	1.00
Mixed: commercial residential	Proportion of segments with commercial residential	0.26	0.15	0.00	0.75
Vacant	Proportion of segments with vacant uses	0.14	0.14	0.00	0.67
Open Green Area	Proportion of segments with undeveloped open green spaces	0.09	0.09	0.00	0.42
Land use mix variables					
Land use index	# of land uses in station (1-10)	7.93	1.16	4.00	10.00
BRT-oriented land uses	Density of commercial, residential, and institutional uses	0.79	0.32	0.03	1.53
Other land uses	Density of industrial, industrial & commercial, and vacant uses	0.41	0.27	0.03	1.34
Entropy	Evenness in the distribution of commercial, residential and institutional land uses	0.65	0.20	0.08	0.97
Design					
Street density	# of street segments (from intersection to intersection) within station area	348.24	168.96	25.46	982.94
Number of blocks	# of blocks within station area	31.53	23.06	3.00	121.00
Number of two-lane street segments	# of street segments with 2 lanes within station area	80.86	69.21	2.00	368.00
Number of three-lane street segments	# of street segments with 3 lanes within station area	25.30	18.01	0.00	108.00
Vacant land along BRT corridor	Proportion of segments with vacant land on BRT corridor				
Average street segment distance to station	Average distance of street segment centroid to BRT station	224.28	81.30	131.25	413.59
Average street segment length	Average segment length within station area	92.01	27.68	55.36	269.03
Segments on BRT corridor	# of street segments facing the BRT right of way within station area	37.61	19.25	6.37	106.95
Destination accessibility					
Centrality	Distance to the CBD (Km)	5.40	3.65	0.00	15.64
Parking					
On-street parking	Proportion of segments with parking on street	0.38	0.20	0.00	0.90
Off-street parking	Proportion of segments with buildings/structure entirely or partially offering off-street parking	0.17	0.12	0.01	0.60
Commercial and parking uses	Proportion of segments with commercial and parking uses	0.19	0.17	0.00	0.73
Off-street parking on vacant parcel	Proportion of segments with vacant parcels devoted to off street parking	0.03	0.03	0.00	0.17
NMT pedestrian infrastructure					
Density of green areas	Density of parks, squares, pocket squares, green areas, boulevards within station area	43.93	43.16	0.00	224.09
Pedestrian segments density	Density of pedestrian segments within station area	17.23	39.96	0.00	269.93
NMT friendliness	Density of parks, squares, pocket squares, boulevards, pedestrian segments, pedestrian bridges, bike-paths within station area	50.04	65.73	0.00	336.13
Average block size	Average size of blocks within the buffer area in square meters within station area	9582.66	6557.94	3161.36	57724.33
Park density	Density of # parks, squares, pocket squares within station area	19.52	21.87	0.00	137.51
Socioeconomic characteristics and building conditions					
Affordable housing	Proportion of segments with affordable housing	0.01	0.05	0.00	0.24
Informal settlements	Proportion of segments with informal settlements	0.06	0.13	0.00	0.65
Urban decay	Proportion of segments with highly deteriorated urban fabric	0.14	0.18	0.00	0.88

(*continued on next page*)

Table 2 (*continued*)

Variable	Definition	Mean	Std. Dev.	Min	Max
Medium deterioration	Proportion of segments with moderately deteriorated urban fabric	0.44	0.23	0.00	0.94
Low deterioration	Proportion of segments with low deterioration of urban fabric	0.42	0.28	0.01	1.00
Facilities and public space					
Public uses index	Index of seven (schools, hospitals, temples, libraries, market squares, sports, recreational) public uses within station area	2.76	1.50	0.00	6.00
Public uses density	Density of public uses within station area	24.55	22.34	0.00	122.23
BRT-oriented public use index	Index of hospitals, libraries, markets/squares, churches (0-4) within station area	0.90	0.85	0.00	3.00
BRT-oriented public use density	Density of hospitals, libraries, markets/ squares, churches within station area	6.61	10.61	0.00	61.12
City (n= # BRT stations)					
Bogota (n=31)					
Sao Paulo (n=12)					
Curitiba (n=16)					
Goiania (n=11)					
Ciudad de Guatemala (n=9)					
Quito (n=30)					
Guayaquil (n=11)					

Source: BRT agencies, Transportation authorities (2013, 2014), DANE (Colombia), INEC (Ecuador), IBGE (Brazil), Local governments, GIS.

traditional block structure that characterizes cities in Latin America. The parking domain confirms parking is plentiful around BRT stations. The NMT domain confirms important heterogeneity in terms of cycling and pedestrian infrastructure. The socioeconomic characteristics domain suggests that the presence of informal settlements and affordable housing is low across BRT stations, while the public facilities domain suggests a scant presence of facilities around BRT stations.

4.1. Built environment features and BRT demand

4.1.1. Factor analysis results

Some variables were excluded because they had had little variation, were perfectly predicted by other variables, or were already included in other variables. Variables excluded were commercial-only land uses, mixed commercial, number of blocks, street segments types (2 lanes, 3 lanes, and pedestrian), medium development and built-up density, pedestrian segments density, and medium deterioration. The resulting exploratory factor analysis scree test suggested the retention of nine factors based on the eigenvalues criteria ≥ 1.00 (Kim and Mueller, 1978). Of variables considered, 35 loaded $> |0.40|$ on one factor (Table 3) and 10 loaded $> |0.40|$ in more than one factor. The 9 factors account for 83.34% of the variance in the data. Even though Cronbach's alpha for factors 7, 8 and 9 are below 0.7, the average standardized Cronbach's alpha value for all factors is 0.78, ranging from 0.68 to 0.88.

The factors measure nine resulting dimensions which we subjectively interpreted as: high-rise multifamily with BRT-oriented mixed land uses, vacant and unconsolidated urban environments, green areas with non-motorized travel supports, industrial and commercial large blocks with off-street parking, single residential land uses with low building heights, BRT-oriented facilities with mixed use nearby, parking, institutional facilities facing the BRT corridor, and non-core affordable housing & informal settlements. These factors are consistent with the factors previously identified in a subsample of 81 stations (reference redacted to preserve anonymity) even though the current analysis has a sample that is 50% larger and considers vacant land, off-street parking, average block area, presence of affordable housing, presence of informal settlements, and average segment length as additional variables.

Attributes relevant to TOD are represented in several factors. Supports for pedestrian connectivity to the transit station are best captured in the third factor, where these supports tend to co-occur with the presence of green and open spaces. By contrast, the fourth factor described by industrial and commercial uses with large blocks performs poorly on pedestrian and bicycle supports. Compactness is well-represented in the first factor (high-rise multifamily with BRT-oriented mixed land uses) and by the ninth factor in the context of the high density provided by informal and affordable housing. Factor 2 performs poorly on compactness. Land uses are represented in different ways, either through factors that measure the specialization of stations by having a dominant use (factors 1 and 5 for different types of residential uses, factors 6 and 8 for institutional uses oriented towards the BRT, or factor 7 for parking supply) or a mixture of uses (such as factor 4 for industrial-commercial mix and factor 9 for the commercial-residential mix). Finally, other attributes like regional accessibility (measured as centrality) qualify other variables by highlighting (lack of) proximity to downtown (factors 5 and 9).

4.1.2. Built environment factors and BRT ridership

Associations between ridership and the estimated factors suggest that four factors are associated with ridership while five factors are not (Table 4). High-rise multifamily BRT-oriented land uses are positively associated with BRT ridership (coefficient 0.2184, $p < 0.05$). As suggested before, this factor represents both compactness as well as an emphasis on dominant residential uses with some mixing of commercial uses. Stations with single story residential development away from the CBD core are negatively associated with ridership (coefficient, -0.3250, $p < 0.01$), while stations with institutional land uses along the corridor are positively associated with ridership (coefficient, 0.2836, $p < 0.01$). Of note, neither the factors measuring compact development with non-motorized travel supports nor the factor measuring mixed land uses that are BRT oriented were statistically significant.

To address concerns about the small sample size, we also estimated regression models for each built environment factor individually while controlling for city and terminal fixed effects. The results of these models (not shown) were largely consistent in terms of direction, magnitude, and statistical significance to the result of Tables 4. The only exception was the coefficient for factor 6, which became statistically significant.

A way to visually summarize the estimated effects is to plot the value of an independent variable at every decile in the sample (x-axis) and the predicted ridership (y-axis), while holding all other variables constant. Fig. 1 depicts the relationship between ridership and the four factors associated with ridership: high-rise multifamily buildings that are BRT-oriented and with mixed land uses and the presence of institutional land uses along the corridor, are positively associated; while low-rise residential development and informal and affordable housing away from the core, are both negatively associated with ridership. The figure shows the two opposing trends, with ridership decreasing as low-rise residential and informal housing away from the core increase. The steepest ridership decreases occur when low-rise and informal

Table 3
Factor analysis results (rotated factor loadings > |0.40|, n = 120).

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9
	High-rise multifamily BRT-oriented mixed land uses	Vacant or low development	Built up, dense development, NMT friendly, with green areas	Industrial/ commercial uses with large blocks and off-street parking	Single story residential away from core	BRT-oriented facilities with mixed uses	Parking galore	Institutional uses along BRT corridor	Non-core affordable housing & informal settlements
Density									
Population density			0.4130						
No building		0.8033							
Single story					0.4884				
Low-rise		-0.4995						0.4070	
Low-medium-rise								0.4406	
Medium-rise	0.7732				-0.4658				
High rise developments	0.7803				-0.4208				
Low built-up density					0.7978				
High built-up density					-0.7436				
Low development level		0.7996							
High development level		-0.5027	0.4848						
Diversity									
Institutional								0.6387	
Industrial						-0.4167			
Residential single family (attached)					0.6609				
Residential multifamily	0.8633								
Mixed: Industrial-commercial	-0.4456			0.4896					
Mixed: commercial residential									0.4592
Vacant		0.874							
Open green area			0.6251						
Land use index						0.4963			
BRT-oriented land uses	0.8533								
Other land uses	-0.4985			0.4205					
Entropy	0.7271					0.3493			
Design									
Street density				-0.7599					
Vacant land along BRT corridor		0.7169							
Average distance to BRT station						0.6537			
Average street segment length				0.8724					
Segments on BRT corridor density				-0.4826		-0.4036		0.4048	
Access to destinations									
Centrality					0.5366				0.4293
Parking									
On-street parking							0.6295		
Off-street parking				0.5503			0.5294		
Commercial and parking uses							0.8048		
Off-street parking on vacant parcel		0.3422					0.5168		
NMT pedestrian infrastructure									

(*continued on next page*)

Table 3 (*continued*)

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9
	High-rise multifamily BRT-oriented mixed land uses	Vacant or low development	Built up, dense development, NMT friendly, with green areas	Industrial/ commercial uses with large blocks and off-street parking	Single story residential away from core	BRT-oriented facilities with mixed uses	Parking galore	Institutional uses along BRT corridor	Non-core affordable housing & informal settlements
Density of green areas			0.9336						
NMT friendliness			0.8551						
Average block size				0.8544					
Park density			0.8912						
Socioeconomic characteristic and building conditions									
Affordable housing									0.4603
Informal settlements									0.6239
Urban decay		0.4994							0.5075
Low deterioration	0.6257								
Public uses and public space									
Public uses index						0.8463			
Public uses density								0.6550	
BRT-oriented public use index						0.7366			
BRT-oriented public use density					-0.4448			0.4205	
Eigenvalue	8.49	5.59	4.50	3.14	3.00	2.33	2.08	1.39	1.16
Cronbach's Alpha	0.87	0.83	0.85	0.84	0.83	0.75	0.74	0.72	0.65

Note: factor loadings < |0.40|are left blank. After varimax rotation. The following variables were not included in the analysis because they had had little variation, were perfectly predicted by other variables, or were already included in other variables: Exclusively commercial, Mixed commercial, Medium built-up density, Medium development, Number of two-lane street segments, Number of three-lane street segments, Number of pedestrian street segments, Number of blocks, Pedestrian segments density and Medium deterioration.

Table 4
Log-linear regression of BRT ridership as a function of built environment factors (n = 120)

	Estimated coefficients †	Standard errors
BRT Terminal	14.4443***	0.3327
Built environment factors		
High-rise multifamily BRT-oriented mixed land uses (factor 1)	0.2170*	0.0854
Vacant or low development (factor 2)	-0.1101	0.0723
Built up, dense development, NMT friendly, with green areas (factor 3)	-0.1272	0.0934
Industrial/ commercial uses with large blocks and off-street parking (factor 4)	-0.0842	0.0817
Single story residential away from core (factor 5)	-0.2888**	0.0925
BRT-oriented facilities mixed use (factor 6)	0.0743	0.1137
Parking galore (factor 7)	0.1185	0.0891
Institutional uses along BRT corridor (factor 8)	0.2676**	0.0866
Non-core affordable housing & informal settlements (factor 9)	-0.1794*	0.0802
City fixed effects		
Bogota	(reference)	
Sao Paulo	-0.8038**	0.4936
Curitiba	-0.7280***	0.2380
Goiania	-0.8660***	0.3753
Ciudad de Guatemala	-0.7048*	0.4900
Quito	-0.8379***	0.1701
Guayaquil	-0.7534**	0.4164
Cons	9.3638***	0.4936
N	120	
R squared	0.7179	
Adjusted R squared	0.6740	
VIF (mean)	2.12	

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Built environment factors model heteroskedasticity test: chi2 (1) = 0.73, Prob > chi2 = 0.3916
†Coefficients for dummy variables are adjusted, as suggested by Kennedy (1981).

residential uses away from the core are scarce. By contrast, the other two built environment factors exhibit a positive slope and very similar association in magnitude.

4.1.3. Cluster analysis to identify station types

An agglomerative cluster analysis was run with the nine built environment factors identified in the factor analysis. Based on the Calinski-Harabasz and Duda criteria (Everitt, 2011), there are either 11 or 13 clusters. We selected 13 clusters on the basis of interpretability (Table 5). Mean values per cluster for each factor suggest wide variation in station types. Some station types are very unique, having only one station represented (cluster 6: Heritage area with institutional uses and limited parking), while others represent a fairly large number of stations (e.g., cluster 5: institutional pedestrian-friendly with mixed-uses and high-activity; and, cluster 8: Non-core transfer nodes, facilities, and mixed uses). As before, to examine whether the sample size was influencing the results, we estimated separate regression models for each cluster variable while controlling for city and terminal. The results of these models (not shown) were very similar to those presented in Table 6. The only exception was the coefficient for cluster 10, which became statistically significant.

Overall, the clusters embody different combinations of relevant dimensions of the built environment. Density, land uses (a single dominant use or a mixture of uses), and the pedestrian environment are represented by distinct clusters, while distance to the CBD and parking availability often qualify some of the clusters. Street design is represented insofar as it is represented by the pedestrian environment, although block lengths and street density co-occurred with industrial uses, so they are included in clusters with those characteristics (cluster 4: Non-core, industrial, low-connectivity areas, with parking and cluster 13: Industrial, non-core, low-density). Other attributes of street designed were not immediately salient from the clusters identified.

With respect to their transit orientation, stations exhibit a broad continuum of features. On one end of the continuum are stations that have distinguishing features hypothesized to be unsupportive of transit demand, such as industrial land uses or the presence of wide roads that impede pedestrian access (e.g., clusters 4 and 13 defined previously). On the other end of the continuum are stations hypothesized to support ridership, such as density, land use and housing mixing, transit orientation, and a pedestrian and bicycle environment. For example,

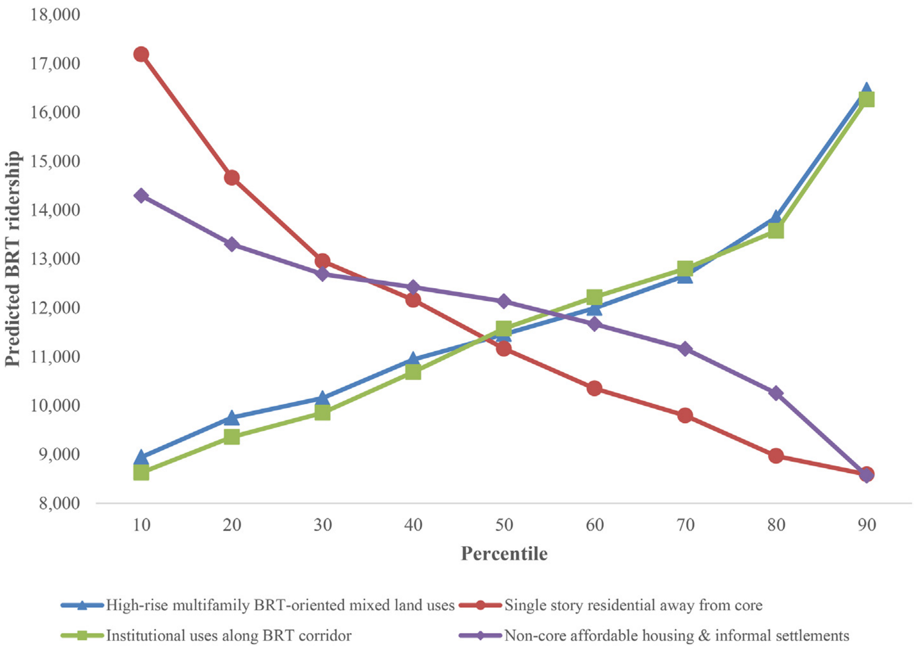

Fig. 1. Predicted BRT ridership with changes in four built environment factors.

Table 5
Mean values for built environment factors and selected TOD features by station type (n = 120)

	BRT station type												
	1	2	3	4	5	6	7	8	9	10	11	12	13
	Residential, dense, mixed-use, and ped friendly	Mixed-use strong activity centers	Commer-cial built up, ped friendly, with parking	Non-core, industrial, low-connecti-vity areas, with parking	Institu-tional pedestrian friendly mixed-use high-activity areas	Heritage area with institu-tional uses, limited parking	Strong high-activity nodes mixed-use, high transit orientation	Non-core transfer nodes, public facilities, and mixed uses	Vacant, non-core low-density residential areas	Paired-stations with institu-tional uses, low mix of uses, limited parking	Peripheral growth area with informal/ affordable housing	Non-core, high-density informal developments	Industrial, non-core, low-density
# of BRT stations per type	13	13	3	9	18	1	11	21	10	6	6	8	1
Built environment factors													
High-rise multifamily BRT-oriented mixed land uses	0.17	-0.22	-1.01	-0.94	0.58	-0.88	1.97	-0.10	-0.53	-1.31	-0.07	-0.35	-0.69
Vacant or low development	-0.42	-0.31	0.14	-0.80	-0.40	-0.53	-0.04	0.24	1.06	-0.37	2.59	-0.38	-1.44
Built up, dense development, NMT friendly, with green areas	1.34	-0.07	2.63	-0.44	0.09	1.75	-0.51	-0.37	-0.72	-1.07	0.13	0.30	0.04
Industrial/ commercial uses with large blocks and off-street parking	-0.22	0.10	-0.62	0.40	-0.58	-0.05	0.09	0.51	-0.93	-0.10	0.69	-0.25	6.44
Single story residential away from core	0.49	-0.88	-2.07	0.69	0.65	-1.20	-1.00	0.45	0.40	-1.86	0.27	0.26	-0.35
BRT-oriented facilities with mixed uses	-0.43	0.41	-0.31	-1.00	0.17	-0.38	-0.61	1.28	-0.74	0.32	-0.29	-0.45	-1.97
Parking galore	-0.44	0.70	1.63	1.41	0.07	-1.53	0.06	-0.06	-0.68	-1.37	-0.45	-0.23	-0.44
Institutional uses along BRT corridor	-0.92	0.17	-0.34	0.15	1.18	5.17	-0.75	-0.50	-0.27	0.43	0.46	-0.23	1.10
Non-core affordable housing & informal settlements	-0.44	-0.34	0.39	-0.20	-0.23	-0.28	0.15	-0.30	-0.83	-0.33	1.70	2.26	1.79
Indicators to assist with interpretation[a]													
Population density	0.73	-0.43	-0.12	-0.68	0.32	-0.50	0.22	-0.41	-0.18	-0.81	0.20	1.22	-0.81
BRT-supportive land uses	0.11	-0.52	-0.92	-0.80	0.88	-0.13	1.25	0.10	-0.26	-1.44	-0.17	-0.34	-1.21
Entropy	-0.34	0.20	-0.95	-0.87	0.90	-0.64	0.76	0.18	-0.68	-0.85	0.15	-0.41	-0.89
Segment density	0.30	-0.16	1.51	-0.60	0.61	0.68	-0.46	-0.65	0.62	0.43	-0.69	0.42	-1.91
Vacant land	-0.59	-0.38	-0.60	-0.34	-0.40	-1.00	0.06	0.33	0.89	-0.84	2.63	-0.26	0.39

[a] Variables shown to aid interpretation of clusters but were not included in cluster analysis. Standardized values shown.

Table 6

Log-linear regression of BRT ridership as a function of station types (n = 120)

	Estimated coefficients[a]	Standard errors
BRT Terminal	5.5305***	0.2688
BRT station types (clusters)		
Residential, dense, mixed-use, and ped friendly (cluster 1)	0.0359	0.3581
Mixed-use strong activity centers (cluster 2)	1.7118***	0.2938
Commercial built up, ped friendly (cluster 3)	0.8529	0.4040
Non-core, industrial, low-connectivity areas (cluster 4)	(reference)	
Institutional pedestrian friendly mixed-use high-activity areas (cluster 5)	1.4392***	0.2464
Heritage area with institutional uses (cluster 6)	2.0358***	0.2088
Strong high-activity nodes mixed-use, high transit orientation (cluster 7)	1.5503***	0.2359
Non-core transfer nodes, with public facilities and mixed uses (cluster 8)	3.1646***	0.4237
Vacant, non-core low-density residential areas (cluster 9)	0.1210	0.4886
Paired-stations with institutional uses, low mix of uses, limited parking (cluster 10)	0.8320	0.5143
Peripheral growth area with informal/ affordable housing (cluster 11)	0.1426	0.2884
Non-core, high-density informal developments (cluster 12)	0.7803	0.3412
Industrial, non-core, low-density (cluster 13)	-0.2123	0.5288
City fixed effects		
Bogota	(reference)	
Sao Paulo	-0.8504**	0.5395
Curitiba	-0.7731***	0.2733
Goiania	-0.8805***	0.3147
Ciudad de Guatemala	-0.6186	0.4479
Quito	-0.8614***	0.2119
Guayaquil	-0.8418***	0.4588
Constant	8.9679***	0.1832
N	120	
R squared	0.6950	
Adjusted R squared	0.6370	
VIF (mean)	2.38	

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

BRT station types model heteroskedasticity test: chi2 (1) = 3.29, Prob > chi2 = 0.0699

[a] Coefficients for dummy variables are adjusted, as suggested by Kennedy (1981).

cluster 2 (mixed-use strong activity centers) is characterized by an urban environment around BRT stations with public facilities, a mixture of land uses, and public facilities facing the BRT right of way. Cluster 5 is characterized by NMT features linking the presence of facilities, multifamily residential and commercial developments, and moderately high population densities. Cluster 7, for example exhibits a strong concentration of residential multifamily developments within a mixed use urban environment.

4.1.4. BRT station types and BRT ridership

Dummy variables denoting the membership of each station to a station type were used as independent variables in the second set of ridership models, while controlling for population density, centrality, whether the station is a terminal, and city. Because the dependent variable is the natural logarithm of ridership, coefficients for dummy variables can be interpreted as the proportion change in ridership for stations belonging to a given type, relative to the reference category (non-core industrial station type).

Five of the thirteen types have ridership that is statistically greater than the ridership for the reference station type, all else held equal. Relative to the reference station, transfer stations with public and institutional uses, a high mixture of land uses, and located away from the CBD had the highest ridership (316.46%) followed by the single historic station of Quito with institutional uses (203.58%), stations with compact development, mixed uses and a high transit orientation (171.18%), stations that are strong activity centers with mixed uses and ample parking (155.03%), and stations with institutional uses and NMT infrastructure with a pedestrian friendly design (143.92%). Fig. 2 depicts the estimated differences in ridership by station type with standard errors omitted for clarity.

Four lessons emerge from the cluster analysis: the importance of mixing land uses, the role of institutional uses and public facilities, the role of BRT network design, and the relevance of the pedestrian environment. First, the role of the mixing of land uses for ridership across significant clusters is striking. By contrast, stations that focused on singles land uses (residential, industrial or institutional) did not enjoy a similar ridership benefit. Railway stations in Hong Kong, with high orientation towards transit including mixed land uses and pedestrian infrastructure have been shown to increase the ridership levels at the station level (Cervero and Murakami, 2009). We found that high levels of mixed land uses, compact development, high density of segments, and the presence of public facilities help to make BRT successful.

Second, many of the station types with high ridership had an important presence of public facilities and institutional land uses. These include city administrative centers, community centers, hospitals, libraries, and churches. The deliberate targeting of institutional and public uses of land within BRT station catchment areas is noteworthy. It enables access to these services and uses not only by local community members, but also by those traveling by BRT. Thus, part of the ridership premium for these stations is the result of a strategy to place these main attractors within reach of the BRT station. This strategy seemed particularly salient for stations with affordable housing and informal settlements.

Third, we found that the design of BRT networks is likely to have a significant impact on station ridership. Network design has an immediate impact on ridership by determining where major transfer points are located and where exchanges between the BRT system and feeders take place. Furthermore, our findings suggest that network design also determines whether stations have land around them can be developed or redeveloped in support of the BRT. The two clusters with the highest ridership premium are located away from the CBD, in places with undeveloped land or land ripe for redevelopment. In these locations, the BRT can act as a trigger for development that if supportive of BRT ridership, can yield further strengthen ridership.

Finally, the findings confirm the importance of the integration between development and the transit station through an environment that includes NMT infrastructure with features that make the built environment pedestrian friendly. At least two clusters that enjoyed a

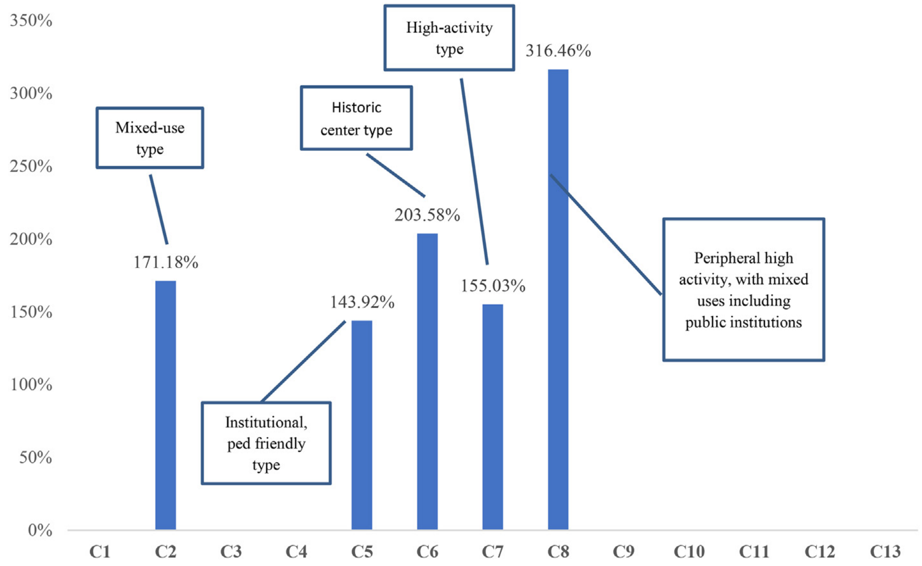

Fig. 2. Predicted BRT ridership change by station type, relative to industrial/commercial cluster with large blocks and off-street parking stations (cluster 4).

ridership premium had pedestrian-friendly environments, that when combined with the strategies such as mixing of land uses and institutional uses can further support BRT ridership.

5. Conclusions

Using factor and cluster analysis, we examined the built environment characteristics and station types associated with BRT ridership for 120 BRT stations in seven Latin American cities. Descriptive analyses of the raw data together with the regression analyses underscore the overall importance, but relative lack of attention paid to the built environment for BRT ridership. Both the factors and station types portray a large set of stations in these seven cities that are generally unsupportive of BRT ridership. Generous on- and off-street parking (mostly free, although this was not systematically collected), industrial uses, a poor pedestrian environment with long blocks, and relatively limited compactness conspire against increased BRT ridership.

At the same time, however, our results do confirm the importance of certain attributes of the built environment for encouraging transit use, such as mixing land uses, pedestrian infrastructure, and the presence of public facilities and institutional uses around the stations such as hospitals, libraries, markets, plazas, and churches. These attributes come together in particular stations or station types, and their ridership premium shows. Given that several cities are considering integrating TOD principles into the planning, implementation, and evaluation of their BRT stations, these insights will help substantiate the case for prioritizing TOD as a means to build more prosperous, sustainable mass transit.

Our results resulted in two additional takeaways for practice. First, our results have important implications for BRT station planning practice. Where stations are located relative to the CBD, the developable land around the station, and the integration of the station to the urban fabric appear to be important characteristics that determine ridership. In some cases, the deliberate location of public and institutional land uses next to the BRT station resulted in higher ridership. For low-income areas with informal settlements, amenities important to these residents, such as adequate pedestrian infrastructure, mixed land use, and accessible to public facilities also resulted in greater ridership.

Our second takeaway is that the mix and dominance of various land uses around the stop also plays a critical role for ridership in the current sample. Together, the factor and cluster analyses highlighted the importance of land uses in characterizing the built environment around stops. However, our findings go beyond conventional prescriptions regarding land use mix. We find that specific land uses such as green space, a dominant use (institutional or residential), a mixture of uses, or even the type of residential development (single family, multi-family, or informal) emerged as important station descriptors that influence ridership. The location of the station and the orientation of development towards the BRT were also important descriptors. Cervero and Murakami's (2009) categorization of station types for Hong Kong's rail system strongly hinged on land uses, partly because they mostly used land use variables. In this study, even though almost half of all variables considered were unrelated to land uses, it was the land use characteristics that best discriminated across various station types and that distinguished between high ridership and low ridership stations (we consider parking a use of land). This finding is all the more remarkable given the high level of land use mixes in Latin America cities. Street design characteristics such as connectivity and density, and the pedestrian environment, played a surprisingly muted role in describing the stations and, therefore, in explaining ridership.

Since this is a cross-sectional study design, it is not clear whether or how BRT has impacted the various stations studied. It is possible that the BRT alignment was chosen in part because of existing land uses or development patterns in specific locations. Regardless, theory and previous evidence suggest that the accessibility gains provided by BRT are likely to have noticeable impacts in specific station areas, sometimes at the expense of other locations in the city. The dynamics of these BRT station changes, including a longitudinal assessment of land use and built environments, remain to be examined. One limitation of our analysis is the relatively simple characterization of street design, the lack of microscale measures qualifying the public realm, and the omission of employment density and transit service characteristics. Service characteristics such as modal integration at BRT stations (Hensher and Li, 2012) and service frequency (Currie and Delbosc, 2011) are likely to be important confounders of the associations identified here.

BRT has transformed the mobility landscape in many Latin American cities. Although it is likely that BRT is also altering the urban landscape, our evidence is suggestive of how urban landscapes are also determining the success of BRT. Increased awareness of station level characteristics that can increase ridership such as land use mix, parking supply, compactness, and the pedestrian environment, is likely to enhance the social, environmental, and financial sustainability of BRT systems.

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