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The impacts of built environment characteristics of rail station areas on household travel behavior

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ABSTRACT

Transit-oriented development (TOD) has gained popularity worldwide as a sustainable form of urbanism by concentrating developments near a transit station so as to minimize auto-dependency and maximize ridership. Existing TOD studies, however, have limits in terms of small sample size and aggregate-level analysis. This study examines various travel outcomes – VMT, auto trips, transit trips, and walk trips – in rail-based station areas in eight U.S. metropolitan areas in order to understand the role of neighborhood built environment characteristics. Two-stage hurdle models handle excess zero values in trip count variables and multi-level models deal with three-level data structure – household within station areas within regions. The final models show that automobile use is associated with land-use diversity and street network design of a station area; transit use is strongly related to transit availability and land-use diversity; and walking is related to transit availability, land-use diversity, and street network design. The weakest influence among station-area environment factors is density. In sum, a TOD, a station area having a dense, mixed-use, walkable, and transit-friendly environment, motivates residents to walk more and take transit more while driving less.

1. Introduction

Contemporary urban and transportation planning deals with urban form, land use, and/or transportation facilities in a way to promote sustainable transportation modes such as walking, biking, or taking transit while minimizing automobile-dependency. Many studies have examined associations between the built environment and travel behavior (for meta-analysis of this subject, see Ewing & Cervero 2010; Stevens 2017). In particular, access to transit stations encourages transit use and walking (Ewing & Cervero 2010; Handy 2005; Pikora, Giles-Corti, Bull, Jamrozik, & Donovan 2003). In a way to achieve the contemporary planning goals, transit-oriented development (TOD) has gained popularity worldwide as a sustainable form of urbanism.

The term transit-oriented development (TOD) was coined by Peter Calthorpe (1993), who stated a TOD is a mixed-use community within an average 2000-foot (0.38-mile) walking distance of a transit stop and a core commercial area. Although it has been defined in various terms during the last two decades, the professional transit community agrees on what constitutes a TOD: dense, diverse, pedestrian-friendly land uses near transit nodes that, when successfully implemented, turn out to maximize transit ridership and minimize auto dependency (Cervero 2004). On the contrary, transit-adjacent development (TAD) is often defined as a failure of a TOD. A TAD is a non-compact, segregated neighborhood development that calls for automobile uses instead of inviting walk trips (Belzer & Autler 2002; Cervero & Duncan 2008; Dittmar & Ohland 2012).

Potential benefits of TOD could be multiple from promoting active modes of transportation to improving access to opportunities such as jobs or entertainment, to offering alternative mobility options and affordable housing for low-income people, to reducing greenhouse gas emissions, and to stimulating public and private investments in community (Center for Transit-Oriented Development (CTOD) 2011; Noland, Ozbay, Dipetrillo, & Iyer 2014). Thus, TOD serves interrelated goals of making communities socially, economically and environmentally more robust and sustainable. In order to achieve these multiple goals, a TOD should first create settings that prompt people to drive less and ride public transit more (Cervero 2004). The Center for Transit-Oriented Development (CTOD) (2010) identifies vehicle miles traveled (VMT) as the key performance measure for TOD. Station areas with low VMT tend to have low rates of automobile ownership, more transit ridership, and higher rates of walking and biking than high VMT areas (Center for Transit-Oriented Development (CTOD) 2010).

Regarding its benefits on travel outcome, much of the literature verifies that TODs reduce car usage and enhance the use of public

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transport or active transportation (Cervero 1993, 2004; Cervero & Arrington 2008; Hale 2014; Langlois, Van Lierop, Wasfi, & El-Geneidy 2015; Nasri & Zhang 2014; Olaru & Curtis 2015; Venigalla & Faghri 2015). Based on data from 17 TOD projects in the U.S., Cervero and Arrington (2008) show that residents living in TOD areas are two to five times more likely to commute by transit than their non-TOD counterparts. Nasri and Zhang (2014) find that people living in TOD areas tend to drive less, reducing their VMT by around 21–38%, compared to the residents of the non-TOD areas even with similar land use patterns in Baltimore and Washington, D.C. regions. Hale (2014) finds that the mode share by active transportation including transit, walk, and bike in TOD areas is about 50–80%, which is much higher than 25–40% in non-TOD areas. Olaru and Curtis (2015) confirm that better biking and pedestrian infrastructure results in the higher bike and walk mode shares along with higher transit ridership in TOD precincts.

Existing TOD studies, however, have limits in terms of small sample size and aggregate-level analysis. Most studies cover only single or a few regions. In contrast, this study includes eight metropolitan areas in the U.S. as diverse as Boston and Portland at one end of the urban form continuum and Atlanta at the other. Also, a total of 549 stations in the eight regions covers various rail systems – heavy, commuter, and light rail. In addition, although Renne and Ewing (2013) study 54 regions across the US, the outcome variable is only the percentage of people who commute via public transportation at the aggregate Census tract level. On the other hand, the data in this study is collected from household travel surveys in eight regions with exact XY coordinates for households and trip ends. The surveys are comparable to the National Household Travel Survey (NHTS) and include various travel outcomes such as automobile trips, transit trips, walk trips, and VMT.

In sum, this study seeks to examine the impacts of TOD characteristics of rail-based station areas on household travel behavior, using household-level survey data from eight U.S. regions. We expect to find that a TOD, a station area having a dense, mixed-use, walkable, and transit-friendly environment, motivates its residents to walk more and take transit more while driving less. There is broad interest in the planning and policy communities in accurate tools to predict the consequences of TOD on the generation of transit ridership and reduction of automobile usage. Our analysis will help guide transportation planners and decision makers to evaluate TOD projects relative to their performance.

2. Research design

2.1. *Study regions and household travel data*

This study includes eight metropolitan regions meeting three criteria (Table 1). First, they must have household travel survey data with XY coordinates for households and trip ends. Second, a region must provide land use databases at the parcel level with detailed land use classifications so that we can study land use mix for the same years as the household travel surveys. Third, they must have had a rail-based transit system before the survey was conducted.

For the eight regions (Table 2), household travel surveys were conducted between 2006 and 2012. While being conducted by individual regional 'organizations such as metropolitan planning organizations (MPOs), the regional household travel surveys have quite similar structure and questions, akin to U.S. DOT's National Household Travel Survey (NHTS). To gather comprehensive data on travel and transportation patterns, the survey data consistently includes, but is not limited to, household demographic information, vehicle information, and data about one-way trips taken during a designated 24-hour period on a weekday, including travel time, mode of transportation, and purpose of trip information. The survey data have exact XY coordinates so we could geocode the precise locations of households and estimate the lengths of trips while the NHTS provides geocodes of households only at the Census Tract level. The regional survey data was acquired from individual MPOs or state DOTs with confidentiality agreements.

Table 1
Characteristics of eight study regions.

No	Region	Population	Employment	Area (square miles)	Compactness index (Hamidi & Ewing 2014)
1	Atlanta, GA	5,173,196	2,173,573	6404	41.0
2	Boston, MA	4,459,130	2,394,530	2864	142.0
3	Denver, CO	2,796,466	1,425,431	3608	107.1
4	Miami, FL	2,475,945	1,125,068	634	144.1
5	Minneapolis-St. Paul, MN	2,854,015	1,421,211	2977	88.7
6	Portland, OR	1,453,978	754,099	430	109.9
7	Salt Lake City, UT	2,085,315	1,176,975	4255	107.0
8	Seattle, WA	3,467,641	1,765,592	6875	116.1

Source: Atlanta (Atlanta Regional Commission); Boston (Boston Region MPO CTPS); Denver (Denver Regional Council of Governments); Miami (Miami-Dade TPO); Minneapolis-St. Paul (Metropolitan Council); Portland (Portland Metro); Salt Lake City (Wasatch Front Regional Council); Seattle (Puget Sound Regional Council).

Table 2
The number of transit stations by types and survey households[a].

No	Region	Year (survey)	Heavy rail	Commuter rail	Light rail	Total Stations	Survey Households (within ½ mile from a station)
1	Atlanta, GA	2011	38	0	0	38	138
2	Boston, MA	2011	49	121	72	239[b]	1586
3	Denver, CO	2010	0	0	36	36	152
4	Miami, FL	2009	22	4	24[c]	50	24
5	Minneapolis-St. Paul, MN	2010	0	4	16	20	97
6	Portland, OR	2011	0	7	87	94	304
7	Salt Lake City, UT	2012	0	1	36	37	114
8	Seattle, WA	2006	0	11	25	35[b]	16
	Total		109	148	272	549	2431

[a] This study includes only transit stations which had opened before a survey.
[b] The total number of station is not equal to the sum of the columns because there are some stations having two or more types of transit systems.
[c] Miami's People Mover, an automated guideway transit, is included under the LRT category.

Jurisdictional fragmentation of metropolitan areas means that parcel-level land use data must be obtained from large numbers of county tax assessors (sometimes with different land use codes and often with monetary charges). The regions included in our sample met all three criteria and, also, were able to supply GIS data layers for streets and transit stops, population and employment for traffic analysis zones, and travel times between zones by different modes, for calculating the various built environment variables.

In these eight regions, there are 549 rail-based transit stations according to the National TOD Database (Center for Transit Oriented Development, http://toddata.cnt.org/). Transit types include heavy rail (109 stations), commuter rail (148 stations), and light rail (272 stations). Boston has the greatest number of stations ($n = 239$), followed by Portland ($n = 94$) and Miami ($n = 50$), and Minneapolis-St. Paul has the smallest number ($n = 20$).

Station areas were drawn as a ½-mile buffer in network distance from each rail transit station. Then, we allotted individual households to their nearest station based on network distance. The resulting pooled data set in station areas consists of 24,535 trips by 2431 households in the eight regions (see Table 2). Then, we calculated vehicle miles traveled (VMT), automobile trips, transit trips, and walk trips by individual households. Dummy variables of the automobile, walking, or transit use for each household were first calculated and then the

Table 3
Descriptive statistics.

Variable	Description	N	Mean	S.D.
Dependent variables				
Any auto	Any household auto trips (1 = yes, 0 = no)	2431	0.71	0.46
Auto trips	Household car trips (for households with any auto trips)	1718	6.63	5.43
VMT (log-transformed)	Natural log of household VMT (for households with any VMT)	1718	2.49	1.16
Any transit	Any household transit trips (1 = yes, 0 = no)	2431	0.40	0.49
Transit trips	Household transit trips (for households with any transit trips)	977	3.42	2.37
Any walk	Any household walk trips (1 = yes, 0 = no)	2431	0.62	0.49
Walk trips	Household walk trips (for households with any walk trips)	1507	6.14	4.36
Independent variables – station area level				
Activity density	Activity density (sum of population and employment per square mile in 1000s)	376	31.43	43.72
Entropy	Land use entropy index	376	0.69	0.21
Intersection density	Number of intersections per square mile	376	213.48	100.22
Stop density	Number of transit stops (bus + rail) per square mile	376	83.55	105.08
LRT dummy	Light rail station dummy (1 = yes, 0 = no)	376	0.49	0.50
Commuter rail dummy	Commuter rail station dummy (1 = yes, 0 = no) (reference group)	376	0.30	0.46
Heavy rail dummy	Heavy rail station dummy (1 = yes, 0 = no)	376	0.22	0.42
Control variables – household level				
HH size	Number of people in a household	2431	2.07	1.18
HH workers	Number of workers in a household	2431	1.19	0.82
HH income	Real household income (in 1000s of 2012 dollars)	2431	82.51	58.59
Regional job accessibility	Percentage of regional employment within 30 min by transit	2431	35.42	13.02
Distance to transit	Network distance to the closest rail station (in miles)	2431	0.31	0.12
Control variables – region level				
Compactness index	A measure of regional compactness developed by Hamidi and Ewing (2014)	8	106.98	32.49

number of trips was counted only for households having any automobile, walk, or transit trips (Table 3).

2.2. Built environment data

In the literature, the most frequently studied factors for distinguishing a TOD from other types of station areas have been residential and/or employment density, land use diversity, street network design or connectivity, and transit accessibility (Brown & Werner 2011; Canepa 2007; Cervero & Gorham 1995; Cervero & Kockelman 1997; Jeihani et al. 2013; Kamruzzaman, Baker, Washington, & Turrell 2014; Kamruzzaman, Shatu, Hine, & Turrell 2015; Laaly 2014; Ngo 2012; Pollack, Gartsman, Boston, Benedict, & Wood 2014; Renne & Ewing 2013; Vale 2015; Werner, Brown, & Gallimore 2010; Zamir, Nasri, Baghaei, Mahapatra, & Zhang 2014). These variables are a part of so-called “D” variables that characterize influences of the built environment on travel – density, diversity, design, destination accessibility, and distance to transit (Ewing & Cervero 2001). While not part of the environment, demographics are the sixth D, controlled as confounding influences in travel studies.

Following the definition of TOD and the literature review, this study includes ‘density’ ‘land use diversity’ ‘street network design’ and ‘transit availability’ to measure the built environment characteristics of station areas. For ‘density’ variable, population and employment data for traffic analysis zones (TAZ) were summed to compute an overall activity density per square mile. Activity density is the sum of population and employment within the station area, divided by gross land area (Ewing et al. 2015). For ‘diversity’ variable, we computed an entropy index.[1] Each region provided parcel maps so that we could calculate the proportion of the area of each land use type – residential, commercial, and public – in a ½ mile buffer from each station. For the ‘street network design’ variable, we computed the number of intersections per square mile from street network shapefiles. For measuring ‘transit availability,’ the number of transit stops (bus stops and rail stations) was divided by land area – half-mile buffer in square mile – for a transit stop density variable.

The demographic variables are included at the household level. As important predictors of travel behaviors, household size, the number of workers in a household, and household income (adjusted in 2012 dollars) are included. In addition, we measured a ‘distance to transit’ variable as a network distance from a household location to the closest rail station because that might be an important determinant of mode choice. Also, regional accessibility is another important variable to predict travel behaviors (Ewing et al. 2015). That variable is defined as the percentage of jobs that can be reached within 30 min by transit, which tends to be highest at central locations and lowest at peripheral ones. We used travel time skims and TAZ-level employment data acquired from regional MPOs to compute this variable.

Finally, we also collected a control variable at the Metropolitan Statistical Area (MSA) level to account for regional differences in the survey sample. We used a compactness index developed by Hamidi and Ewing (2014) to measure the built-environment characteristics of the MSA, capturing whether the MSA is sprawling or compact. Higher values indicate a more compact MSA and lower values indicate a more sprawling MSA. Summary statistics of the variables are presented in Table 3.

2.3. Analysis method

This study's data and model structure are hierarchical. Thus, hierarchical modeling is the best methodology to account for dependence among observations, in this case, the dependence of household trips within a station area and dependence of station areas within a given region. Because this dependence violates the independence assumption of ordinary least squares (OLS) regression, standard errors of regression coefficients will be underestimated and regression coefficients

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[1] The entropy index measures balance between three different land uses. The index ranges from 0, where all land is in a single use, to 1 where land is evenly divided among the three uses. Values are intermediate when buffers have more than one use but one use predominates. The entropy calculation is:
entropy = − [residential share ∗ ln(residential share) + commercial share ∗ ln(commercial share) + public share ∗ ln(public share)]/ln(3), where ln is the natural logarithm of the value in parentheses and the shares are measured in terms of total parcel land areas (Ewing et al. 2015).

themselves will be inefficient (Raudenbush & Bryk 2002).

Households (their characteristics and the associated trips) form Level 1 in the hierarchy, station areas form Level 2, and regions form Level 3. In the model estimations, only the intercepts were allowed to vary randomly across higher level units. All of the regression coefficients at higher levels were treated as fixed. These are referred to as random intercept models (Raudenbush & Bryk 2002). Models were estimated with the statistical package HLM 6.08. While the lower-level sample sizes are big (977 to 2431 households at level 1 and 376 stations at level 2), the highest-level (region) sample size is only eight. This could lead to biased estimates of level-3 standard errors (i.e., the impact of regional compactness index). However, the coefficient estimates, the variance components, and the standard errors at the lower levels are unbiased and accurate (Maas & Hox 2005).

The dependent variables are of two types: continuous (household VMT) and counts (household car trips, walk trips, and transit trips). One problem with trip count variables is excess zero values, which are usually handled using zero-inflated models. A total of 38% of households have no walk trips, and 60% have no transit trips. However, a better way to handle zero values is a two-stage hurdle model (Greene 2012). The theory of the hurdle model is that the household makes a decision on whether or not to "participate" in an activity and a separate decision how much to participate. The stage 1 model categories households as either generating walk/transit/auto trips or not and the stage 2 model estimates the number of walk/transit/auto trips generated by households with any positive walk/transit/auto trips.

The first stage is the estimation of logistic regression models to distinguish between households with and without walk/transit/auto trips. The second stage is the estimation of Poisson or negative binomial regression models for the number of trips by each mode for households that have such trips. While Poisson and negative binomial models could be used in these kinds of count variables, negative binomial regression is appropriate if the dependent variable is over-dispersed, meaning that the variance of counts is greater than the average. We found over-dispersion of all three trip count variables in the dataset, and a negative binomial model was therefore chosen over a Poisson model.

3. Results

3.1. Auto trips

The model for the dichotomous variable, any auto trip (1 = yes, 0 = no), is presented in Table 4. The likelihood of a household generating any auto trip decreases with land use diversity and intersection density of a station area. Regarding the other control variables, the likelihood of any auto trip declines with greater compactness index of a region and regional job accessibility and increases with household size, the number of workers, household income, and distance to closest rail station.

The number of household automobile trips decreases with activity density of a station area and when the station has a light rail system instead of commuter rail or heavy rail. Similar to the dichotomous any auto-trip model, automobile trip frequency declines with greater compactness index of a region and regional job accessibility for a household and increases with household size and the number of workers.

The model for the continuous variable natural logarithm of VMT (for households that generate VMT) is presented in Table 5. Results parallel those for the previous two models of the auto trip, though the exact specification of the model is different. Household VMT decreases with intersection density of a station area and regional job accessibility for a household and is lower when the station has light rail. Household VMT increases with household size, number of workers, and household income. These results show that those who live in dense, mixed, and walkable station areas are better able to travel with no or fewer car trips.

Table 5
Multilevel models of household VMT.

		VMT (log-transformed)[a] (n = 1718)	
		β (SE)[b]	*t*-Ratio
	Constant	**2.83 (0.37)*****	7.68
Level 3	Compactness	0.00 (0.00)	0.38
Level 2	Activity density	0.00 (0.00)	1.41
	Entropy	− 0.25 (0.15)*	− 1.73
	Intersection density	− **0.00 (0.00)*****	− 3.44
	Stop density	0.00 (0.00)	0.97
	Light rail (ref: commuter rail)	− **0.27 (0.08)*****	− 3.30
	Heavy rail (ref: commuter rail)	0.06 (0.10)	0.61
Level 1	HH size	**0.14 (0.03)*****	5.58
	HH workers	**0.22 (0.04)*****	5.70
	HH income	**0.00 (0.00)****	2.08
	Regional job accessibility	− **0.01 (0.00)*****	− 4.82
	Dist. to transit	0.12 (0.24)	0.50

Note: bold numbers represent significant variables at 0.05 significance level.

[a] Pseudo-R2 = 0.18.

[b] $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 4
Multilevel two-stage hurdle models of auto trips.

		Any auto trips[a] (n = 2431)		Auto trips[b] (n = 1718)	
		β (SE)[c]	Exp(β)	β (SE)	Exp(β)
	Constant	**3.82 (0.62)*****	45.54	**1.79 (0.15)*****	5.98
Level 3	Compactness	− **0.01 (0.00)****	0.99	− **0.00 (0.00)****	1.00
Level 2	Activity density	− 0.00 (0.00)	1.00	− **0.00 (0.00)****	1.00
	Entropy	− **1.18 (0.35)*****	0.31	− 0.16 (0.09)*	0.85
	Intersection density	− **0.00 (0.00)****	1.00	0.00 (0.00)	1.00
	Stop density	− 0.00 (0.00)*	1.00	0.00 (0.00)	1.00
	Light rail (ref: commuter rail)	− 0.11 (0.17)	0.90	− **0.09 (0.04)****	0.91
	Heavy rail (ref: commuter rail)	0.01 (0.20)	1.01	0.01 (0.06)	1.01
Level 1	HH size	**0.29 (0.06)*****	1.34	**0.29 (0.01)*****	1.34
	HH workers	**0.19 (0.08)****	1.21	**0.02 (0.02)****	1.02
	HH income	**0.01 (0.00)*****	1.01	0.00 (0.00)*	1.00
	Regional job accessibility	− **0.04 (0.01)*****	0.96	− **0.01 (0.00)*****	0.99
	Dist. to transit	**1.81 (0.46)*****	6.14	0.05 (0.14)	1.05

Note: bold numbers represent significant variables at 0.05 significance level.

[a] Pseudo-R2 = 0.74.

[b] Pseudo-R2 = 0.37.

[c] $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 6
Multilevel two-stage hurdle models of transit trips.

		Any transit trips[a] (n = 2431)		Transit trips[b] (n = 977)	
		β (SE)[c]	Exp(β)	β (SE)	Exp(β)
	Constant	**− 4.60 (0.47)*****	0.01	0.74 (0.31)*	2.10
Level 3	Compactness	**0.02 (0.00)*****	1.02	0.00 (0.00)	1.00
Level 2	Activity density	**− 0.00 (0.00)****	1.00	**− 0.00 (0.00)*****	1.00
	Entropy	**0.56 (0.27)****	1.75	0.18 (0.13)	1.20
	Intersection density	0.00 (0.00)	1.00	0.00 (0.00)	1.00
	Stop density	**0.00 (0.00)*****	1.00	0.00 (0.00)	1.00
	Light rail (ref: commuter rail)	0.21 (0.13)	1.24	**− 0.16 (0.07)****	0.86
	Heavy rail (ref: commuter rail)	**0.34 (0.17)****	1.41	− 0.09(0.07)	0.92
Level 1	HH size	**0.11 (0.05)****	1.11	**0.11(0.02)****	1.12
	HH workers	**0.43 (0.07)*****	1.54	− 0.02(0.03)	0.98
	HH income	**− 0.00 (0.00)*****	1.00	**− 0.00 (0.00)*****	1.00
	Regional job accessibility	**0.03 (0.01)*****	1.03	**0.01(0.00)****	1.01
	Dist. to transit	**1.24 (0.40)*****	0.29	**− 0.39(0.18)****	0.68

Note: bold numbers represent significant variables at 0.05 significance level.

[a] Pseudo-R2 = 0.76.

[b] Pseudo-R2 = 0.11.

[c] $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

3.2. Transit trips

The model for any transit is presented in Table 6. The likelihood of a household having any transit trips increases with land use entropy and transit stop density of a station area and when the station has a heavy rail system instead of commuter rail. The negative effect of activity density on any transit trip variable is unexpected, but the effect is minimal (odd ratio: 0.996). Regarding the other control variables, the likelihood of any transit trips increases with greater compactness index of a region, regional job accessibility for a household, household size, and number of workers, and declines with household income and distance to closest rail station.

The number of household transit trips decreases with activity density of a station area and is lower when the station has a light rail system instead of commuter rail. Likewise, the negative effect of activity density is minimal. Similar to the dichotomous any-transit model, transit trip frequency increases with household size and regional job accessibility for a household and declines with household income and distance to closest rail station. The two transit trip models show that land use mix (only in the transit trips model) and transit stop density (in both models), but not density or street design, are positively associated with household transit trips.

3.3. Walk trips

The model for the variable of any walk is presented in Table 7. The likelihood of a household making any walk trips increases with land use mix, intersection density, and transit stop density of a station area and is greater when the station has a light rail system instead of commuter rail. Regarding the other control variables, the likelihood of any walking increases with greater compactness index of a region, regional job accessibility for a household, household size, the number of workers and declines with household income.

The number of walk trips for the subset of households that make walk trips increases with transit stop density and slightly increases with land use entropy at station area level (Table 7). In addition, the walk trip frequency increases with the compactness index of a region, regional job accessibility for a household, and household size and declines with distance to closest rail station. The two walk trip models show that land use mix, street design, and transit availability, but not density, are positively associated with household walk trips in a station area.

Table 7
Multilevel two-stage hurdle models of walk trips.

		Any walk trips[a] (n = 2431)		Walk trips[b] (n = 1507)	
		β (SE)[c]	Exp(β)	β (SE)	Exp(β)
	Constant	**− 4.47 (0.60)*****	0.01	0.12 (0.26)	1.13
Level 3	Compactness	**0.01 (0.00)****	1.01	**0.00 (0.00)****	1.00
Level 2	Activity density	0.00 (0.00)	1.00	− 0.00 (0.00)	1.00
	Entropy	**0.77 (0.28)*****	2.17	0.22 (0.11)*	1.25
	Intersection density	**0.00 (0.00)****	1.00	0.00 (0.00)	1.00
	Stop density	**0.00 (0.00)*****	1.00	0.00 (0.00)	1.00
	Light rail (ref: commuter rail)	**0.41 (0.15)*****	1.51	0.02 (0.06)	1.02
	Heavy rail (ref: commuter rail)	0.35 (0.19)*	1.42	0.02 (0.07)	1.02
Level 1	HH size	**0.22 (0.05)*****	1.25	**0.19 (0.01)*****	1.21
	HH workers	**0.27 (0.07)*****	1.31	− 0.00 (0.02)	1.00
	HH income	**− 0.00 (0.00)*****	1.00	− 0.00 (0.00)*	1.00
	Regional job accessibility	**0.03 (0.01)*****	1.03	**0.01 (0.00)*****	1.01
	Dist. to transit	− 0.62 (0.42)	0.58	**− 0.45 (0.15)*****	0.64

Note: bold numbers represent significant variables at 0.05 significance level.

[a] Pseudo-R2 = 0.70.

[b] Pseudo-R2 = 0.19.

[c] $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

4. Discussion and conclusion

Generalizing across the preceding models, four conclusions emerge with great relevance to travel modeling in station areas. First, socioeconomic and built environment variables all influence household travel decisions in the station area, though based on the significance levels alone, the socioeconomic influences appear strongest. In particular, household income is consistently associated with more (or a greater probability of making any) auto trips and fewer (or a lower probability of making any) transit and walk trips.

Second, all the D variables influence household travel decisions, but consistent with the meta-analysis by Ewing and Cervero (2010), the strongest influences are diversity, street design, and destination accessibility, and the weakest influence in a multivariate context is density. Compared to the meta-analysis study (Ewing & Cervero 2010) and a nation-wide travel behavior study (Ewing et al. 2015) focusing on entire regions, the transit availability factor, measured as transit stop density, turns out to be more strongly associated with transit and walk trips in this station-area-specific study. This implies that in the planning of rail station areas, the availability of other types of public transit, especially local buses, needs to be considered to promote the overall ridership and use of active transportation.

While the TOD literature finds that TODs reduce car usage and enhance the use of active transportation (Cervero 1993, 2004; Cervero & Arrington 2008; Hale 2014; Langlois et al. 2015; Nasri & Zhang 2014; Olaru & Curtis 2015; Venigalla & Faghri 2015), they do not explore which built environment factors are most effective. On the other hand, the multivariate models in this study find that personal vehicle use is most strongly related to regional job accessibility and secondarily to land-use diversity and street network design factors in the context of station areas. Transit use is strongly related to transit stop density and regional job accessibility variables, with land-use diversity as a third factor. Walking is related to measures of job accessibility, transit availability, land-use diversity, and street network design.

Thirdly, the decision to use a certain mode is influenced by different factors than the frequency of use once the decision is made, and the use of hurdle models is therefore warranted in household travel modeling. For example, a greater intersection density is associated with a higher probability of walk trip and a lower probability of auto trip. However, once the decision to walk (or not to drive) is made, that variable becomes not significant. The same pattern is found in land-use diversity and transit stop density variables for transit use, meaning that a mixed and transit-ample station area might increase the probability of household transit trips, but not its frequency.

Finally, after controlling household-level socioeconomic factors and neighborhood-level built environment factors, this study finds that regional compactness is consistently associated with fewer (or a lower probability of making any) auto trips and more (or a higher probability of making any) transit and walk trips of station-area households. This suggests that compact regions promote success of station area planning pertaining to encouraging sustainable travel behavior. However, given the small sample size at region level ($n = 8$), this conclusion needs careful interpretation.

Transit-oriented development is expected to minimize auto-dependency and maximize ridership of residents. Also, a higher mode share by walking is another goal of TOD. This study demonstrates that TOD, a station area having a dense, mixed-use, walkable, and transit-friendly environment motivates residents to walk more and take transit more while driving less. One application of the study results could be a traffic impact analysis of a TOD project. Our models can be used to adjust the Institute of Transportation Engineers' (ITE) trip rates, which are derived from car-oriented suburban developments, to reflect how greater densities and other environmental attributes would affect trip making.

This study has mainly three limitations. First, this study focuses exclusively on the home end of trips, when every trip has two ends. We set out to measure environmental conditions at all origins and destinations but discovered that the analytical requirements exceeded the capacity of our software and hardware, given our large sample of trips. Some variables that are included in our models, such as the percentage of regional employment accessible within a 30-minute travel time by transit, at least account for more than simple neighborhood effects.

Second, the variable list and the data need to be extended. The list of predictor variables omits certain variables that have presumptive effects on household travel. Among the D variables, design characteristics such as sidewalk coverage and building setbacks are unavailable in large datasets. Also missing are variables related to another D, demand management. Parking supplies and prices, particularly at the destination end of trips, may strongly affect mode choices of workers. In terms of a study subject, this study only deals with rail-based station areas, but there are many good examples of bus-based TOD (Cervero & Dai 2014; Currie 2006), which calls for future research.

Finally, we cannot draw strong causal inferences from a cross-sectional study such as this one. The main threat to causal inference is self-selection, where individuals who want to walk or use transit choose to live in walkable or transit-oriented neighborhoods. These individuals would be inclined to use active modes of travel wherever they lived. We have no ability to control for such effects in this multi-region study, as most of the underlying household surveys do not include relevant attitudinal questions. However, nearly all studies of residential self-selection have found ‘resounding’ evidence of statistically significant associations between the built environment and travel behavior, independent of self-selection influences (Bhat, Sen, & Eluru 2009; Cao, Mokhtarian, & Handy 2009; Cao, Xu, & Fan 2010; Ewing, Hamidi, & Grace 2016; Salon 2006; Zhou & Kockelman 2008).

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