Transportation Research Part D 78 (2020) 102205

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Traffic generated by mixed-use developments—A follow-up 31-region study

Guang Tian[a,*], Keunhyun Park[b], Reid Ewing[c], Mackenzie Watten[d], Jerry Walters[d]

[a] Department of Planning and Urban Studies, University of New Orleans, United States
[b] Department of Landscape Architecture and Environmental Planning, Utah State University, United States
[c] Department of City and Metropolitan Planning, University of Utah, United States
[d] Fehr & Peers, Walnut Creek, CA, United States

ARTICLE INFO

Keywords:
Trip generation
Built environment
Mixed-use development
Internal capture
Mode choice
Multi-modal transportation

ABSTRACT

This study aims to improve a previously-developed methodology for predicting the traffic impacts of mixed-use developments (MXDs). In 31 diverse metropolitan regions across the United States, we collected consistent regional household travel survey data and computed built environment characteristics—D variables—of MXDs. Multilevel modeling (MLM) was employed to predict the probability of trips captured internally within MXDs, walking on internal trips, and travel mode choice on external trips, by trip purpose. Larger, denser, mixed-use, and more walkable MXDs show a larger share of trips internally, compared with conventional suburban developments. Those MXDs with good access to transit, employment, and destinations also show higher levels of walking, biking, and transit shares on external trips, thus helping to reduce traffic impacts on the external road network. Perhaps the most impressive finding is that well-designed MXDs have walk shares of more than 50 percent on internal trips. A k-fold cross-validation supports the robustness of our analyses.

1. Introduction

Over a half of the world's inhabitants reside in urban areas today, which is projected to reach to two thirds in 2050 (United Nations, 2018). With population growth and urbanization, many cities are experiencing traffic congestion, urban sprawl, physical inactivity and obesity, and air pollution due to separated land-use and car-oriented development patterns. Mixed-use development (MXD) is a significant element of smart growth strategies that aim to reduce auto dependency. It can happen in a single building, a block, or a neighborhood. By putting different uses close to each other, MXDs concentrate destinations and provide opportunities of working, living, shopping, or recreating in the same place. As such, they can capture trips internally and promote alternative modes of transportation, specifically walk, bike, and transit. However, when it comes to accurately estimating the traffic impacts of MXDs for communities to assess MXD proposals, there is a lack of reliable methodology.

This paper is a follow-up to Ewing et al. (2011) and Tian et al. (2015) that seeks to improve the methodology for predicting the traffic impacts of MXDs. It differs from the earlier papers in four key respects. First, the sample sizes of trips, MXDs, and regions have been significantly increased. This reduces sampling error and gives us more degrees of freedom, particularly at the regional level in a multi-level modeling framework where degrees of freedom have heretofore been severely limited, making it unlikely that regional variables would prove significant.

* Corresponding author at: 378 Milneburg Hall, 2000 Lakeshore Dr., New Orleans, LA 70148, United States.
E-mail address: gtian@uno.edu (G. Tian).

https://doi.org/10.1016/j.trd.2019.102205

Second, this is the first paper to analyze mode choices for trips internal to MXDs. The earlier papers were focused exclusively on estimating external automobile trip rates, or trip generation in the parlance of the Institute of Transportation Engineers (ITE). The earlier methodology successively discounted ITE trip generation rates first for internal trips and then for external walk, bike, and transit trips. But in light of growing interest in development impacts other than external traffic, particularly physical activity and health benefits, we are also interested in the mode of travel on internal trips. Indeed, we have every reason to expect that active travel modes are chosen more frequently for internal trips within MXDs than external trips from inside to outside MXDs (or vice versa).

Third, this paper employs multinomial logit (MNL) models to estimate mode choices for external trips. The earlier papers treated external mode choices as binary choices (choice of walk versus other, choice of bike versus other, and choice of transit versus other) and multiple binomial logit (BNL) models were estimated. In fact, mode choices are made among these multiple discrete modes (walk, bike, transit, or auto) as a choice set, and MNL is the more appropriate model.

Fourth, this is the first paper to validate our models for general use using k-fold cross-validation. The first paper (Ewing et al., 2011) showed that the MXD method predicted external automobile trips more accurately than the ITE method when compared to automated cordon counts at entrances to MXDs, but did not show that the models were generally applicable to regions across the United States. This paper does so.

2. Literature review

2.1. Traffic impact of MXDs

The relationship between people's travel choices and the built environment is one of the most studied areas in urban planning literature (Stevens et al., 2019). A meta-analysis study by Ewing and Cervero (2010) categorized the built environment variables impacting travel behavior into the five Ds: Density, Diversity, Design, Destination accessibility, and Distance to transit. Of which, diversity is the one that measures the degree to which different land uses are mixed in a given area. Entropy and job-population balance are the two most widely operationalized variables of diversity in travel studies.

Numerous empirical studies have found consistently a positive relationship between alternative means of travel (walking, biking, and transit use) and land use mix (Ewing and Cervero, 2010; Stevens, 2017). People living in neighborhoods with mixed land uses do more walking, biking, and transit use, compared to those living in single-use neighborhoods. They may generate the same or more total trips, but fewer private vehicle trips and vehicle miles traveled (VMT).

A related study investigated trip generation rates for 30 smart-growth locations in California, where smart-growth locations were defined as "places where many common activities (e.g., workplaces, parks, coffee shops, stores, other homes) are located within a convenient walking distance of where many people live and work" (Schneider et al., 2012, p. 1). The results showed that although the total trip generation rates at these locations were similar to single-use developments, a large share of these trips was made by walking, biking, or transit (Schneider et al., 2013).

Two studies examined the travel behavior at 42 MXDs in Austin (Zhang et al., 2009; Pang, 2014). The results showed that trip frequency was generally higher for households living in MXDs compared to those living in non-MXDs. However, the average trip distance was 0.8 miles shorter in MXDs. Residents of MXDs traveled 1.2 miles less on a typical workday than those who lived in non-MXDs. These MXDs also captured approximately 40 percent more trips internally than non-MXDs.

2.2. ITE trip generation methods for MXDs

In practice, when it comes to estimating the traffic impacts of MXDs, engineers and planners usually use a standard procedure based on Chapter 6 of the ITE *Trip Generation Handbook* (Institute of Transportation Engineers, 2017a). The workflow is as follow. Firstly, the amounts (could be square footage, number of units, number of employees, etc.) of different land use categories (retail, restaurant, office, residential, hotel, and cinema/entertainment) are determined. Secondly, the preliminary estimate of trip generation is calculated by multiplying these amounts by ITE's trip rates per unit. Thirdly, based on the look-up tables provided in the book, a certain proportion of the preliminary estimate is considered as internal trips captured by MXDs.

This procedure has several significant limitations, as summarized by Ewing et al. (2011) and Tian et al. (2015). First, there are two look-up tables based upon the suburbs of Florida, Georgia, and Texas, which limits the predictive power of the methodology. The handbook itself acknowledges this limitation and suggests users look for comparable local projects, collect the data, and produce locally-valid look-up tables (Institute of Transportation Engineers, 2017a). Second, the ITE method does not take the scale of development into account. It seems reasonable to assume that a large site is likely to produce more internal trips than a small site. Third, it ignores the surrounding land use context where development projects are located. Projects in remote locations may capture more trips internally than those located in areas with similar trip attractions nearby, but will not generate as many external walk and bike trips. Fourth, sites with quality transit services and walking environment are not assigned any trip reduction on external trips. Particularly for infill projects that are located in urban contexts, significant vehicle trip reduction can be generated due to mode shifts on external trips.

These limitations have several implications for planning practice: inaccurate investment decision-making; overestimation of environmental impacts; fewer incentives for mixed-use development. Improvements are needed before ITE methodology can be considered a valid source to predict the trip rates for urban downtowns and multi-use sites (Currans, 2017; Westrom et al., 2017).

2.3. Adjustment of ITE methods

There have been recent efforts to improve on the ITE methodology, including ITE itself. The ITE's *Trip Generation Manual* (Institute of Transportation Engineers, 2017b) is the first edition to include data specifically classified by trip type such as person or vehicle, and by placetype such as suburban, urban, or city core. ITE expects moving forward to receive more data in this classification format. However, in this edition, the sample sizes for land uses commonly found in MXDs were only appropriate for traditional ITE manual parameters of suburban placetype vehicle trips. Further research and application will consider and monitor the growth of the new ITE data to determine if appropriate for use. This study and its application for the time being continue to use ITE suburban placetype vehicle trip rates.

Another effort, a bottom-up approach, simply added more sites to current ITE MXD database. The 3rd edition of ITE's *Trip Generation Handbook* (2017a) added three additional MXD sites for the internal capture calculations in addition to the original sites in the 2nd edition (Institute of Transportation Engineers, 2004) for a total of six sites. These three sites came from NCHRP Project 8-51, which was codified as NCHRP Report 684 (Bochner et al., 2011) and then accepted by ITE as the internalization procedure described in ITE's handbook Chapter 6. The handbook recommends as a first step to judge whether the current methodology is appropriate for a specific project depending on the MXD development type, location, size, land use mix, and time period for analysis. Based on the development data used to derive the methods, these checks can often rule out the use of the Handbook method for specific applications.

Empirical studies have shown that compact developments characterized by high density, land use mix, and better accessibility can 'degenerate' vehicle trips. These include transit oriented developments (TODs; Arrington and Cervero, 2008; Ewing et al., 2017; Tian et al., 2017), urban infill sites (Kimley-Horn and Associates, Inc., 2009), and smart growth development sites (Handy et al., 2013).

A third effort, a top-down approach, related trip generation rates of MXDs to their built environmental characteristics—the D variables—by estimating statistical models. Ewing et al. (2001) was the first study done taking this approach. They found that the two most powerful D variables as the predictors of MXDs' internal capture rates were development scale (the size of the MXD) and regional destination accessibility. Larger MXDs that were less accessible to the rest of the region captured a higher share of trips internally than others. However, this result was hard to generalize due to its small sample size in a single region—20 mixed-use developments in the Miami–Fort Lauderdale–West Palm Beach metropolitan area.

Ewing et al. (2011) and Tian et al. (2015) followed this approach and aimed to provide more generalizable results by gathering data for more MXDs from more diverse regions (239 MXDs from six region in the former study and 412 MXDs from 13 regions in the latter study), using consistently defined D variables and travel outcomes, and predicting not only internal capture probability but also external mode choices. The results showed that the probability of trips being captured internally is higher within MXDs with various on-site activities. External trips were more likely taken by walking or using transit within MXDs with good walkability and transit service.

3. Methodology

3.1. Selection of MXDs

Chapter 6 of the ITE's Handbook (2017a) covers something called a multi-use development. In the ITE Handbook, the term multi-use development is said to exclude traditional downtowns, suburban activity centers, and developments covered by existing ITE land use classifications, specifically shopping centers, office parks with retail uses, office buildings with retail, and hotels with limited retail. Taken literally, this definition contains inconsistencies as compared to mixed-use definitions from other authoritative sources.

The Urban Land Institute (ULI) defines an MXD as having "three or more significant revenue-producing uses …; significant physical and functional integration of project components …; and development in conformance with a coherent plan …" (Levitt and Schwanke, 2003, pp. 4-5). If we rephrase this as "two or more uses," it becomes a generic definition of mixed use. Functional and physical integrations are critical; this implies the availability of local interconnecting streets. Conformance to a plan may also be important. The plan may be a downtown development/redevelopment plan or a suburban activity center plan or a neighborhood plan. It does not have to be a development plan put forth by a single master developer. The pattern of land use and street connection is more important than the pattern of parcel ownership.

In general, our sample MXDs conform to the ITE Handbook definition of a multi-use development. However, where the ITE definition is open to interpretation, we've opted to be consistent with the criteria used to select survey MXDs for the NCHRP 8-51 study, an ITE-guided study on mixed-use trip generation. Building upon ITE's multi-use development definition, a more general definition of MXD was created in order to include existing mixed land use development patterns:

> "A mixed-use development or district consists of two or more land uses between which trips can be made using local streets, without having to use major streets. The uses may include residential, retail, office, and/or entertainment. There may be walk trips between the uses."

Following the same bottom-up, expert-based process as the earlier studies, local planners in regions with regional household travel surveys were contacted by phone or email. They were presented with the definition of an MXD and asked to name the MXDs within their jurisdictions (they all have names), draw the boundaries, and catalog the land uses. In some regions, it required dozens of contacts with local planners to complete the process. For example, Dallas-Ft. Worth required us to contact 200 municipalities to identify 19 MXDs. This was painstaking work.

Table 1
Sample statistics.

	Survey year	MXDs	Mean acreage per MXD	Total daily trip ends	Mean daily trip ends per MXD
Albany, NY	2009	2	160	30	15
Atlanta, GA	2011	49	123	2574	53
Austin, TX	2005	42	206	1504	36
Boston, MA	2011	39	52	9995	256
Dallas, TX	2009	19	119	874	46
Denver, CO	2010	25	123	3381	135
Eugene, OR	2009	4	93	2931	733
Greensboro, NC	2009	2	92	215	108
Hampton Roads-Norfolk, VA	2009	13	205	650	50
Houston, TX	2008	48	445	3929	82
Indianapolis, IN	2009	3	24	76	25
Kansas City, MO	2004	16	113	1280	80
Madison, WI	2009	15	98	183	12
Miami, FL	2009	22	95	614	28
Minneapolis-St. Paul, MN-WI	2010	36	124	8469	235
Orlando, FL	2009	13	555	350	27
Palm Beach County, FL	2009	51	325	1671	33
Phoenix, AZ	2008	18	274	792	44
Portland, OR	2011	46	119	6252	136
Provo-Orem, UT	2012	2	15	16	8
Richmond, VA	2009	9	227	179	20
Rochester, NY	2011	7	102	1778	254
Sacramento, CA	2000	25	179	2487	99
Salem, OR	2010	2	111	1696	848
Salt Lake City, UT	2012	25	101	2968	119
San Antonio, TX	2007	5	46	262	52
Seattle, WA	2014	58	233	18,902	326
Springfield, MA	2011	9	65	801	89
Syracuse, NY	2009	1	145	191	191
Tampa, FL	2009	14	274	596	43
Winston-Salem, NC	2009	2	178	293	147
Total		622	193	75,939	122

3.2. Final samples

Table 1 shows the statistics of the final MXD samples by region. There were 622 MXDs identified in 31 regions with a low of one MXD in Syracuse, New York and a high of 58 in Seattle, Washington. The average size was 193 acres with an average of 122 trips for a typical workday. The 622 individual MXDs varied in every aspect of the D variables. The development scale ranged from four acres to over 5000 acres. Transit services ranged from high-quality buses and rail to none at all. The locations ranged from infill developments in a region's core urban area to new planned developments in a region's suburban fringe.

3.3. Data sources and variables

Household travel surveys, collecting households' daily travel diaries, are widely used to study people's travel behavior. They are also the fundamental input for regional travel demand modeling and forecasting by metropolitan planning organizations (MPOs) across the U.S. In the last 10 years, we have been contacting MPOs and collecting household travel survey data. For this study, the XY coordinates of trip ends are needed to identify trips generated by MXDs. Not every region was willing to provide XY coordinates due to confidentiality concerns. We ended up with data for 31 regions. In addition to the survey, other GIS data were also collected in order to compute the D variables, including traffic analysis zones (TAZs) with socioeconomic information, street networks, transit stops, travel times among TAZs by auto and transit, and land use data at the parcel level. All these supportive data were for the same or close enough to the same years that household travel surveys were conducted.

Based on these data, seven types of built environmental D variables were computed consistently for all regions and modeled to forecast the travel outcomes for MXDs. Table 2 provides the definitions of all variables. For the travel outcomes, we are interested in whether a trip is internal or external to the MXD. An internal trip is a trip starting and ending within the same development. An external trip is a trip where either the origin or destination is outside the development. If it is internal, we would like to know if it is a walking trip or not. If it is external, we would like to know if it is a walk, bike or transit trip. A seventh D, demographics, is measured by the size of a household and vehicles per capita in a household. The other six Ds – density, diversity, design, destination accessibility, distance to transit, and development scale – are as commonly measured in the literature.

Table 2
Variable definition and description.

Outcome variables		Definition
INTERNAL		Dummy variable indicating that a trip remains internal to the MXD (1 = internal, 0 = external).
INTERNAL WALK		Dummy variable indicating that the travel mode on an internal trip is walking (1 = walk, 0 = other).
EXTERNAL MODE		The travel mode on an external trip (1 = walk, 2 = bike, 3 = transit, 4 = auto)
Explanatory variables		
	Level 1 individual/household level	
Demographics	HHSIZE	Number of members of the household.
	VEHCAP[a]	Number of motorized vehicles per person in the household.
	Level 2 MXD explanatory variables	
Development scale	AREA	Gross land area of the MXD in square miles.
	DEVLAND	Proportion of developed land within the MXD.
Density	ACTDEN	Activity density per square mile within the MXD. Sum of population and employment within the MXD, divided by gross land area.
	EMPMILE	Total employment outside the MXD within one mile of the boundary. Weighted average for all traffic analysis zones (TAZs) intersecting the MXD. Weighting was done by proportion of each TAZ within the MXD boundary relative to an entire TAZ area (i.e., "clipping" the block group with the MXD polygon).
Diversity	JOBPOP	Index that measures balance between employment and resident population within MXD. Index ranges from 0, where only jobs or residents are present in an MXD, not both, to 1 where the ratio of jobs to residents is optimal from the standpoint of trip generation. Values are intermediate when MXDs have both jobs and residents, but one predominates. [b]
	LANDMIX[a]	Another diversity index that captures the variety of land uses within the MXD. This is an entropy calculation based on net acreage in land-use categories likely to exchange trips[c]. The entropy index varies in value from 0, where all developed land is in one of these categories, to 1, where developed land is evenly divided among these categories.
Design	INTDEN[a]	Number of intersections per square mile of gross land area within the MXD.
Destination accessibility	EMP30T[a]	Percentage of total regional employment accessible within 30-min travel time of the MXD using transit.
	EMP10A, EMP20A, EMP30A	Percentage of total regional employment accessible within 10, 20, and 30-min travel time of the MXD using an automobile at midday.
Distance to transit	STOPDEN[a]	Number of transit stops within the MXD per square mile of land area. Uses 25 ft buffer to catch bus stops on periphery.
	RAILSTOP	Rail station located within the MXD (1 = yes, 0 = no). Commuter, metro, and light rail systems are all considered. Uses 25 ftbuffer to catch rail stations on periphery.
	Level 3 regional explanatory variables	
REGPOP		Population within the region.
GASPRICE		Average state gasoline price for the year of household travel data.

[a] When log transforming, one (1.0) was added to the value of the variable to handle the problem of zero values. Note that all explanatory variables but RAILSTOP were log-transformed in our models.
[b] JOBPOP = 1 − [ABS(employment − 0.2 * population)/(employment + 0.2 * population)]; ABS is the absolute value of the expression in parentheses. The value 0.2, representing a balance of employment and population, was found through trial and error to maximize the explanatory power of the variable.
[c] The entropy calculation is LANDMIX = − [single-family share * LN(single-family share) + multifamily share * LN(multifamily share) + commercial share * LN(commercial share) + industrial share * LN(industrial share) + public share * LN(public share)]/LN(5), where LN is the natural logarithm.

3.4. Multilevel logistic regressions

This study modeled three travel outcomes: choice of internal destination, choice of walking on internal trips, and choice of walking, biking, transit, or auto on external trips. Models were estimated separately by trip purpose: home-based work (HBW), home-based other (HBO), and non-home-based (NHB). This was done to make it possible to distinguish peak hour trips from non-peak trips. Multilevel modeling (MLM) was used because the data structure is nested; see details in the earlier study (Tian et al., 2015). Three multilevel (three levels – individual, MXD, and region) logit regressions were estimated using the software package HLM 7: multilevel binomial logit regression for the probability of internal trips and the probability of walking on internal trips; multilevel multinomial logit regression for mode choices on external trips. During the modeling process, all independent variables except for RAILSTOP were log-transformed. By doing so, the coefficients in the modeling results become elasticities or measures of effect size, which reflect the odds of choosing one specific mode with respect to each specific independent variable. The elasticities can be interpreted in the same way at any spatial level.

4. Results

4.1. Descriptive statistics

The internal capture rates differ from MXD to MXD and region to region. Among regions, the average internal capture rates range from a low of 0% in Provo-Orem, Utah to a high of 47.1% in Syracuse, New York (Table 3). The overall average internal capture rate

Table 3
Average Internal Capture Rates, Mode Shares for Internal and External Trips to/from MXDs, and the Aggregated MXD-Leve Built Environment Variables.

Region	Internal capture of all trips (%)	Mode share for internal trips (%)	Mode share for external trips (%)				Means of aggregated MXD-level built environment variables				
		Walk	Walk	Bike	Transit	Sum	ACTDEN	LANDMIX	INTDEN	EMP30T	STOPDEN
Albany, NY	33.3	80	60	0	0	60	4311.07	0.34	266.21	24.96	174.24
Atlanta, GA	9.6	50	4.1	1.1	2.6	7.8	714.03	0.34	230.57	27.27	25.46
Austin, TX	16.8	16.7	1.4	1.8	0.2	3.4	3376.96	0.46	212.83	44.14	32.14
Boston, MA	21	94.4	36.7	2.2	28.3	67.2	4387.36	0.65	466.05	37.96	151.4
Dallas, TX	19	78.3	3.1	0	3.8	6.9	12,607	0.45	358.91	11.64	117.64
Denver, CO	26.5	30.4	7.2	1.4	6.9	15.5	1216.86	0.38	265.75	20.76	83.78
Eugene, OR	24.8	71.6	9.6	5	13.2	27.8	3243.52	0.60	299.93	77.47	117.91
Greensboro, NC	14.7	29.4	1.5	0	1	2.5	617.06	0.46	58.2	19.53	0
Hampton Roads-Norfolk, VA	20	61.5	2.3	1.3	0.6	4.2	4545.55	0.66	146.58	5.51	18.86
Houston, TX	14.8	20.6	1.2	0.4	1.5	3.1	5766.2	0.42	193.86	6.89	19.43
Indianapolis, IN	7.9	0	2.9	0	0	2.9	276.2	0.63	487.93	0	0
Kansas City, MO	11.1	46.5	2.6	0.9	2.9	6.4	2273.4	0.69	181.49	16.08	51.11
Madison, WI	24	68.2	8.6	8.6	2.9	20.1	5222.66	0.74	280.78	33.97	42.37
Miami, FL	9.1	39.3	5.6	0.9	4.1	10.6	3490.7	0.58	223.41	15.35	63.57
Minneapolis-St. Paul, MN-WI	18.7	73.3	10.7	2.4	12.4	25.5	6063.76	0.44	203.97	46.43	145.5
Orlando, FL	27.4	54.2	5.1	0	2.4	7.5	4698.78	0.55	154.48	9.04	18.58
Palm Beach County, FL	29.6	35.2	3.2	0.9	0.2	4.3	3951.22	0.56	103.43	55.74	14.68
Phoenix, AZ	29.3	54.3	2.1	0.2	2.5	4.8	8150.75	0.64	147.56	8.56	60.62
Portland, OR	25.6	82.5	13.6	4.5	12.4	30.5	3323.44	0.46	214.27	7.71	71.09
Provo-Orem, UT	0	0	0	0	6.3	6.3	167.28	0.26	40.37	11.5	26.92
Richmond, VA	17.9	43.8	7.5	0.7	2.7	10.9	3411.06	0.64	163.65	14.47	39.59
Rochester, NY	10	66.3	5.3	2.4	6.1	13.8	6242.37	0.66	235.45	56.4	69.89
Sacramento, CA	16.4	7.4	2.9	0.4	0.4	3.7	2064.62	0.44	184.13	12.65	23.48
Salem, OR	23.1	74	10.7	2.1	7.7	20.5	4392.58	0.49	359.65	96.88	185.93
Salt Lake City, UT	10.4	30.3	6.1	1.1	3.5	10.7	1654.32	0.51	160.91	6.87	67.7
San Antonio, TX	4.6	33.3	2.4	0.8	6	9.2	2711.85	0.11	173.92	50.19	732.35
Seattle, WA	34.9	78.9	15.3	3.7	14.9	33.9	10207.3	0.62	235.51	17.55	82.89
Springfield, MA	23.5	90.4	17.1	1	12.7	30.8	1398.95	0.64	1086.2	12.02	60.15
Syracuse, NY	47.1	80	13.9	0	5.9	19.8	17209.7	0.39	283.1	56.73	132.7
Tampa, FL	11.4	44.1	4.2	0.9	0.8	5.9	6970.56	0.64	289.63	7.95	78.94
Winston-Salem, NC	10.9	60	2.4	0	4.1	6.5	6852.87	0.51	133.53	61.64	419.34
Overall	23.3	69.4	12.9	2.3	11.3	26.5	4618.28	0.52	236.37	24.69	68.99

for all regions is 23.3%. In more than half of regions, the dominant mode for internal trips within MXDs is walking. The overall average walking mode share for internal trips is 69.4%. The overall average external non-automobile model share for all regions is 26.5%. These high percentages suggest the fallacy of applying ITE trip generation rates, without adjustment, to MXDs, or even applying some small default reduction (often 10 percent) to MXD trip rates to account for internal capture.

4.2. Internal capture

Table 4 shows the model results of the multilevel binomial logit regression for internal capture. At the individual level, the likelihood of a trip being captured internally by an MXD decreases with household size and vehicle per capita for all three trip purposes. That means trips generated by households with more members and owning more private vehicles are less likely to stay within an MXD. In general, households with more members have more diverse travel demands that are more likely to be met outside of an MXD. Owning more vehicles provides greater flexibility in traveling beyond the boundary of an MXD.

At the MXD level, the odds of an internal trip are related to five of the six built environment variables for at least one of the three trip purposes: development scale, density, diversity, design, and distance to transit. MXDs that are larger in size can provide more nonresidential uses as destinations within the development. High activity density and good balance between jobs and population values translate into higher chances of working, living, shopping, and recreating in the same place. And high intersection density

Table 4
Multilevel binomial logistic regression for internal capture (log-log form).

		Home-based work			Home-based other			Non-home-based		
		Coef.	*t*-ratio	*p*-value	Coef.	*t*-ratio	*p*-value	Coef.	t-ratio	*p-value*
	Constant	−2.760			−10.101			2.305		
Level 1	HHSIZE	−1.166	−7.405	< 0.001	−0.568	−4.523	< 0.001	−0.278	−6.128	< 0.001
	VEHCAP	−1.781	−3.816	< 0.001	−1.336	−5.107	< 0.001	−0.535	−8.688	< 0.001
Level 2	AREA	0.598	3. 120	0.002	0.812	6.098	< 0.001	0.475	8.669	< 0.001
	ACTDEN	0.565	2.309	0.021	–	–	–	0.166	0.055	0.003
	JOBPOP	0.675	3.574	0.001	0.649	6.387	< 0.001	–	–	–
	EMPMILE	–	–	–	–	–	–	−0.200	−3.266	0.002
	INTDEN	0.840	3.217	0.002	0.309	2.192	0.029	–	–	–
	STOPDEN	−0.399	−2.582	0.010	–	–	–	0.140	3.318	0.001
	RAILSTOP	–	–	–	0.867	3.432	0.001	0.329	3.918	< 0.001
Level 3	REGPOP	−0.896	−4.465	< 0.001	–	–	–	−0.198	−1.804	0.082
	GASPRICE	6.635	2.258	0.032	7.905	3.968	0.001	–	–	–
Pseudo-R^2			0.16			0.33			0.28	

Note: '–' = not significant.

creates more street crossing opportunities and routing choices, which makes travel more interesting and routes shorter. The relationship to EMPMILE indicates that the destinations just outside the MXD attract trips that would otherwise be internal. It is less clear why home-based internal work trips are negatively related to transit stop density. One possible explanation is that good transit service provides MXD residents with another travel option for commuting outside MXDs. The existence of a rail station within the MXD can bring visitors to the MXD and keep them traveling inside.

At the regional level, the probability of a trip being captured internally by an MXD decreases with regional population and increases with the regional average gasoline price. More specifically, using home-based work trips as an example, the estimated coefficients for regional population and gasoline price are −0.896 and 6.635, respectively. Thus their elasticities are $-0.69 = -0.896 * (1–0.233)$ and $5.09 = 6.635 * (1–0.233)$. That means with a 1% increase in regional population or gasoline price, the probability of a trip being captured internally decreases 0.69% or increases 5.09%, respectively. Within a bigger metropolitan area, there are more destinations outside the MXD. With higher gasoline prices, it is an economical choice to stay within the MXD.

4.3. Mode choice for internal walking trips

In Table 5, the model results of the multilevel binomial logit regression for the choice of walking on internal trips are shown. At the individual level, the likelihood of walking decrease with household size for home-based other trips and decrease with vehicle per capita for all trips. Households with more members are less likely to walk due to more opportunities to carpool and trip chain, as shown in the 2017 National Household Travel Survey (NHTS) that trip frequency (trips per person) for household decreases with household size. Owning more vehicles can lower the generalized cost of auto use and make walking less attractive.

At the MXD level, the odds of walking are related to four of the six built environment variables for at least one of the three trip purposes: development scale, density, distance to transit, and destination accessibility. The larger MXDs can lead to the distance of

Table 5
Multilevel binomial Logistic Regression for Walking on Internal Trips (Log-Log Form).

		Home-based work			Home-based other			Non-home-based		
		Coef.	*t-ratio*	*p-value*	Coef.	*t-ratio*	*p-value*	Coef.	*t-ratio*	*p-value*
	Constant	−15.810			−3.588			−3.597		
Level 1	HHSIZE	–	–	–	−0.545	−3.582	0.001	–	–	–
	VEHCAP	−1.301	−3.344	0.001	−2.019	−5.591	< 0.001	−1.193	−6.015	< 0.001
Level 2	AREA	−1.103	−3.083	0.004	−0.825	−3.422	0.001	–	–	–
	ACTDEN	0.682	2.126	0.038	–	–	–	–	–	–
	EMPMILE	1.081	5.426	< 0.001	0.566	6.074	< 0.001	–	–	–
	STOPDEN	–	–	–	−0.183	−1.832	0.068	0.419	2.796	0.006
	RAILSTOP	−1.086	−3.196	0.003	–	–	–	1.318	7.273	< 0.001
	EMP10A	−0.723	−1.985	0.052	–	–	–	−0.049	−2.115	0.061
	EMP30T	–	–	–	–	–	–	0.324	1.876	0.061
Pseudo-R^2			0.25			0.28			0.34	

Note: '–' = not significant.

Table 6
Multilevel Multinomial Logistic Regression for Mode Choice on External Trips, using auto as reference case (Log-Log Form).

			Home-based work			Home-based other			Non-home-based		
			Coef.	*t*-ratio	*p*-value	Coef.	*t*-ratio	*p*-value	Coef.	*t*-ratio	*p*-value
Walk		Constant	−16.353			−12.901			−8.203		
	Level 1	HHSIZE	−1.947	−9.053	< 0.001	−1.124	−12.618	< 0.001	−0.854	−14.177	0.021
		VEHCAP	−4.81	−27.278	< 0.001	−3.518	−11.266	< 0.001	−2.814	−17.32	< 0.001
	Level 2	AREA	−0.439	−4.075	< 0.001	–	–	–	−0.288	−3.496	0.001
		ACTDEN	–	–	–	–	–	–	0.791	5.451	< 0.001
		LANDMIX	1.219	2.072	0.039	–	–	–	0.843	1.649	0.099
		INTDEN	–	–	–	0.407	2.938	0.004	–	–	–
		EMPMILE	0.452	6.956	< 0.001	–	–	–	–	–	–
		RAILSTOP	–	–	–	0.349	2.75	0.007	0.451	3.876	< 0.001
		EMP10A	–	–	–	−0.031	0.011	0.006	–	–	–
		EMP30T	–	–	–	0.204	2.323	0.021	–	–	–
	Level 3	REGPOP	–	–	–	–	–	–	−0.188	−2.418	0.023
		GASPRICE	10.488	5.387	< 0.001	9.239	2.87	0.008	–	–	–
Bike		Constant	−32.261			2.183			−1.857		
	Level 1	HHSIZE	−0.492	−3.522	0.001	−0.794	−4.359	< 0.001	−0.756	−7.343	< 0.001
		VEHCAP	−3.969	−13.358	< 0.001	−3.036	−7.074	< 0.001	−2.699	−10.255	< 0.001
	Level 2	AREA	–	–	–	–	–	–	−0.369	−3.46	0.001
		ACTDEN	0.407	1.864	0.063	–	–	–	0.492	0.168	0.004
		JOBPOP	–	–	–	0.297	4.531	< 0.001	0.272	2.035	0.042
		INTDEN	0.412	1.981	0.048	0.333	2.436	0.015	–	–	–
		EMPMILE	–	–	–	0.248	3.374	0.001	0.223	1.862	0.063
		RAILSTOP	–	–	–	0.706	4.597	< 0.001	0.557	3.324	0.001
		EMP30A	0.967	2.295	0.022	–	–	–	–	–	–
	Level 3	REGPOP	–	–	–	−0.542	−3.69	0.001	−0.561	−2.169	0.039
		GASPRICE	19.162	2.825	0.009	–	–	–	–	–	–
Transit		Constant	−9.62			−7.159			−7.529		
	Level 1	HHSIZE	−0.962	−8.15	< 0.001	−1.227	−13.542	< 0.001	−1.107	−10.24	0.001
		VEHCAP	−4.363	−14.826	< 0.001	−4.82	−15.531	< 0.001	−3.607	−9.937	0.001
	Level 2	AREA	–	–	–	0.208	1.686	0.092	–	–	–
		ACTDEN	0.464	4.189	< 0.001	0.504	3.646	0.001	0.543	5.246	< 0.001
		STOPDEN	0.243	1.596	0.111	–	–	–	–	–	–
		RAILSTOP	–	–	–	0.681	2.05	0.04	0.988	4.934	< 0.001
		EMP10A	–	–	–	–	–	–	0.031	3.306	0.001
		EMP30A	0.687	2.861	0.005	–	–	–	0.291	1.82	0.069
		EMP30T	–	–	–	0.171	2.006	0.045	0.124	1.708	0.088
	Pseudo-R^2			0.34			0.16			0.43	

Note: '–' = not significant; auto is the reference level.

internal trips being longer and the destination less reachable by walking. Higher activity density on-site and more nearby job opportunities off-site encourage MXD residents to walk. The negative association between the existence of rail station for home-based trips, transit stop density for home-based trips, and destination accessibility by auto for all trips with walking for internal trips indicates that MXD residents are less likely to walk when destinations are accessible by other modes. For non-home-based trips, the positive signs of transit stop density, the existence of a rail station within the MXD, and destination accessibility by transit indicate that good transit service attracts people to come and then walk to various destinations within the MXD. The mixed signs of transit service and accessibility indicate that these two built environment variables can make MXD residents leave the MXD, while bringing outside visitors to the MXD.

4.4. Mode choice for external trips

In Table 6, the model results of the multilevel multinomial logit regression for the mode choice on external trips are shown. At the individual level, the odds of walking, biking, or transit use on external trips decreases with the size of a household and the number of vehicles owned per person for all trip purposes. These relationships were as explained previously.

At the MXD level, the odds of walking, biking, or transit use are related to all of the six built environment variables for at least one of the three trip purposes. The larger MXDs can lead to the distance of external trips being longer and the destination less reachable by walking or biking. In general, higher density, more mixed land uses, higher intersection density, better transit service, more accessible regional employment, and more nearby job opportunities make it more likely that external trips will be made by alternative travel modes rather than driving.

At the regional level, the likelihood of walking or biking decreases with regional population and increases with regional average gasoline price. The bigger the metropolitan population size, the lower the share of total destinations lying within easy walking or biking distance. The higher the regional gasoline price is, the higher the generalized cost of auto use.

4.5. Model validation

In this section, we evaluate the predictive power of our fifteen MXD models. For k-fold cross-validation (Borra and Di Ciaccio, 2010; Fielding and Bell, 1997; Hair et al., 1998), we first divided the data into *ten* equal partitions. Then we retained one partition as the validation data set (also called test data) and fitted a model with the remaining data (training data). This step was repeated ten times for ten training data-test data sets.

Receiver operating characteristic (ROC) curves and the areas under ROC curves (AUC) are common measures of predictive power of a logistic regression model; thus, are also appropriate for assessing our cross-validation results (Greiner et al., 2000; Hanley and McNeil, 1982; Meng, 2014; Zweig and Campbell, 1993). For the ROC curves, the rate of true-positives is plotted on the vertical axis and the rate of false-positives is plotted on the horizontal axis. Then the areas under ROC curves (AUC) provide the predictive accuracy of the logistic models, with values from 0.5 (no predictive power) to 1.0 (perfect prediction). From the ten iterations, we computed mean AUC values. The model validation was done in R 3.4.2 software with *glmer* function (*lme4* package) and *performance* function (*ROCR* package).

As a result, the mean AUCs range from 0.726 for the non-home-based internal capture model to 0.948 for the home-based-other external transit model (see Fig. 1). Following Swets (1988) and Manel et al. (2001), we consider models with an AUC value ranging between 0.7 and 0.9 as 'useful applications' and those with values greater than 0.9 as 'high accuracy.' Thus, all of our fifteen models can be viewed as either useful (ten models) or highly-accurate (five models) applications in planning practice.

5. Applications

From planning practitioners' standpoint, good models should have the capacity to separate the peak hour (morning or afternoon) trips from daily trips for internal and external vehicle trip predictions. Our models were designed to provide this capacity. They can predict travel choices for three separate trip purposes: home-based-work, home-based-other, or non-home-based, which can be examined based on purpose-specific trip generation rates in NCHRP Report 716, Travel Demand Forecasting: Parameters and Techniques (2012).

Here are the steps of how to apply these models to predict vehicle trip generation of MXDs for each trip purpose.

- Step 1: total trip generation is computed using trip rates from ITE's *Trip Generation Manual*;
- Step 2: the total is factored using NCHRP Report 716 percentages to obtain total trips by trip purpose;
- Step 3: the log odds of internal trips is computed using the model formula in Table 4: log odds = sum of coefficients * variables. Then this log odds is exponentiated to obtain the odds of internal capture by trip purpose and converted into probabilities: probability = odds/(1 + odds). These probabilities are then applied to each estimate of total trips generated for the three trip purposes to obtain internal trips by trip purpose;
- Step 4: these internal trips are subtracted from the total number of trips generated according to the ITE *Trip Generation Manual* to obtain total external trips generated by trip purpose.

Total external trips by trip purpose can then be divided up by mode of travel using the equations in Table 6.

- Step 5: the probabilities that external trips will be by walking, biking, and transit are:
  - probability(walk) = EXP(sum of coefficients(walk) * variables)/[1 + EXP(sum of coefficients(walk) * variables) + EXP(sum of coefficients(bike) * variables) + EXP(sum of coefficients(transit) * variables)];
  - probability(bike) = EXP(sum of coefficients(bike) * variables)/[1 + EXP(sum of coefficients(walk) * variables) + EXP(sum of coefficients(bike) * variables) + EXP(sum of coefficients(transit) * variables)];
  - probability(transit) = EXP(sum of coefficients(transit) * variables)/[1 + EXP(sum of coefficients(walk) * variables) + EXP(sum of coefficients(bike) * variables) + EXP(sum of coefficients(transit) * variables)].

These probabilities are then applied to each estimate of total external trips to obtain external trips by walking, biking, and transit and trip purpose.

- Step 6: these trips generated by alternative modes are then subtracted from the total number of external trips to obtain total external trips by automobile and trip purpose. These can be summed to obtain total external trips by automobile. This estimate, in ITE terms, is just site traffic generation. In addition, these numbers can be used to calculate the mode shares of walking, biking, and transit as well as vehicle trip reduction rate as a result of these alternative modes.

If an estimate of internal trips by walking is desired, the equations in Table 5 can be applied to the estimates of total internal trips in much the same way as above. This can be done by trip purpose, and the result can be subtracted from the total number of internal trips to obtain the number of internal automobile trips by trip purpose. These estimates by trip purpose can be summed and then used to scale internal infrastructure.

To apply these models to predict trip generation, the information about a development site is required, such as population,

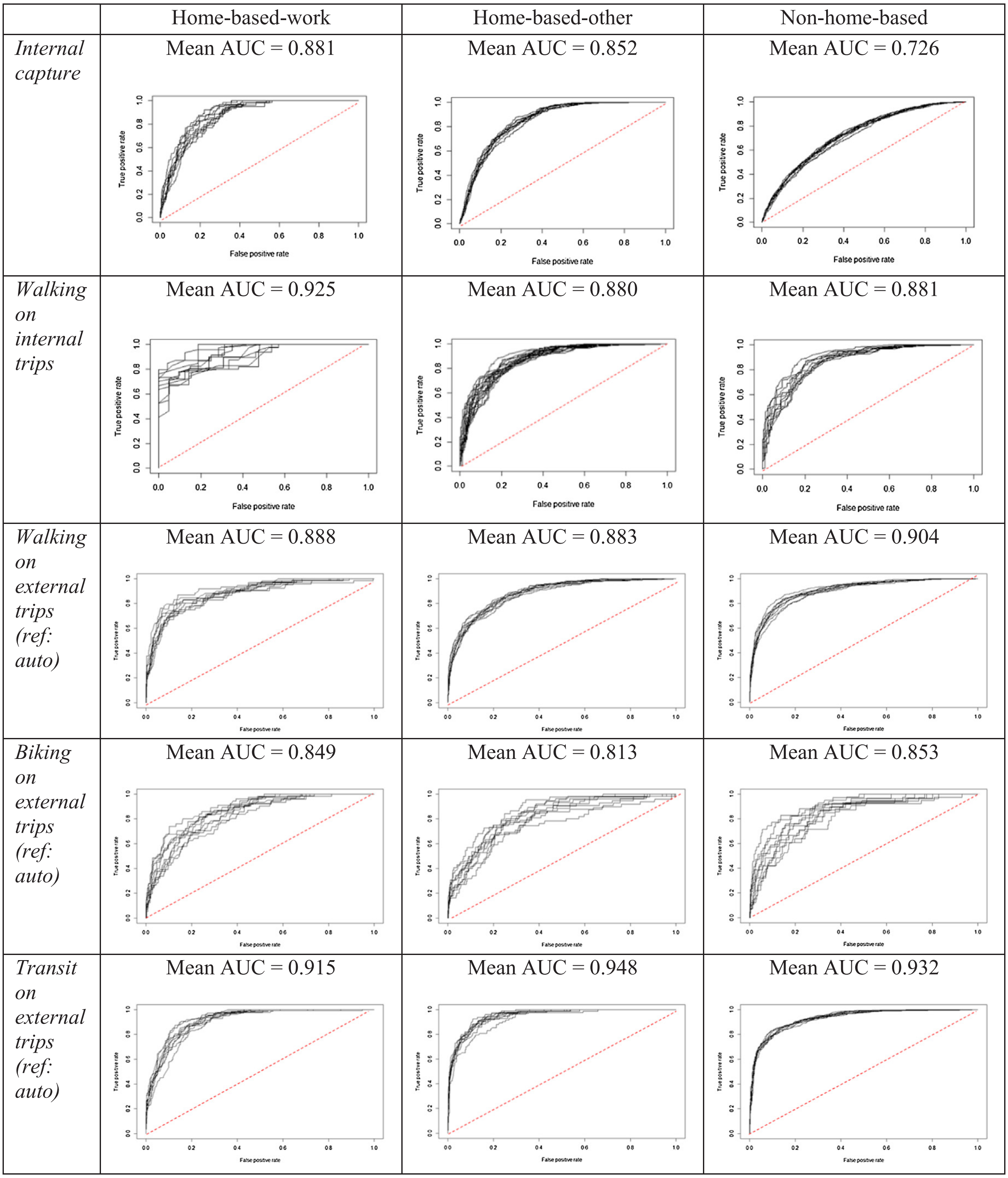

Fig. 1. Receiver operating characteristic (ROC) curves and the area under the ROC (AUC) statistics for model prediction.

employment, land use categories and areas, availability of transit service, etc. Most of this information is usually available from the project site plan. Others may need to be obtained from the jurisdiction or MPO's regional travel model, such as regional travel time skims. Based on this information, some GIS mapping and analysis may be also needed to compute the D variables before being incorporated into the equations. In addition, expert judgment is always helpful from case to case; for example, when the location context or the land use composition of a development proposal is unique.

Based on expert practitioner applications, it was found that MXD internalization estimates could be used in conjunction with the internalization methods reported in the ITE *Trip Generation Handbook*, which are based on NCHRP Report 684 (Bochner et al., 2011), for improved results at a project level. The NCHRP Report 684 (2011) and original MXD method developed for the US Environmental Protection Agency (EPA) (United States Environmental Protection Agency, n.d.) each derive from different statistical research methodologies and produce different internalization estimates. They both focus on the general concept of MXD sites' contexts influencing travel behavior, but each contains different variables representing site context. Expert practitioners learned to select which method to employ based on a comparison of their capabilities as well as professional judgment. The authors of the individual studies decided to collaborate on a combined methodology to incorporate the best of both of the individual methodologies. The authors also focused and prioritized empirical validation to achieve greater accuracy than either method individually.

The combination approach, known as the MXD + method, combines the individual capabilities of NCHRP Report 684 and the EPA MXD method. The MXD + method leverages the common data and logic of the two methods. With their combined capabilities, MXD + can assess the full range of site contexts including specific land-use categories, spatial nature and separation of land uses, regional active transportation and transit accessibility, socioeconomic factors, density of nearby land uses, and the nearby density of the transportation network. The MXD + method combines the results of both the NCHRP Report 684 and the EPA MXD method by weighting their results by time period based on empirical evidence to create a more accurate method than either method individually.

The MXD model was originally use by the EPA with approval and peer-reviewed by leading researchers (Ewing et al., 2011; Shafizadeh et al., 2012), recommended by public agencies for use on smart growth developments (San Diego Association of Governments, n.d.). The MXD + model was detailed in an American Planning Association (APA) Planning Advisory Service (PAS) prepared by the authors of EPA MXD and NCHRP 684 (Walters et al., 2013) with the recommendation of using it to access traffic impacts of smart growth development, including infill and transit-oriented development.

The MXD model has been used by public agencies and consultants in hundreds of projects across the United States. It has been used at both the project and the regional planning scale. It has been integrated into the UrbanFootprint web platform, which has been used to analyze regional planning projects across the world including in China and Mexico City as well as across the United States in places such as Madison, Wisconsin; Columbus, Ohio; Sonoma, California; and Los Angeles, California. It has also been integrated into the Envision Tomorrow web platform, a scenario planning tool that is available with open access.

One final application of our models should be noted. Users of the models can test different inputs to the models to see how they affect model outputs, thus reverse engineering development patterns that will produce lower external vehicle trips and higher internal capture and internal walking. Given a parcel of land, a local zoning and parking code, and a desired Return on Investment, a TOD developer could find the optimal combination of land uses that minimizes impacts on the external street network and maximizes walk, bike, and/or transit trips.

6. Conclusion

As a major component of smart growth strategies, such as, transit-oriented development, MXDs can help reduce vehicle trip generation, which leads to traffic congestion relief, energy consumption reduction, and air pollution reduction. MXDs can increase walk and bike trip generation, which leads to physical activity increase and public health improvement. MXDs can also provide opportunities for sharing parking spaces among different uses that have different peak periods of travel demand, which enables investments on roadways and related infrastructures to be "descaled."

As shown in the models of this study, as important as putting co-dependent uses close to each other, MXDs also need appropriate density, well connected internal streets, and quality transit services to be successful. There is a need for a fundamental change in seriously considering non-private vehicle travel modes in traffic impact analyses. So, the investment and infrastructure for those alternative modes of transportation can be considered in the planning and design process in the first place.

Unless alternative methods or tools are provided, the limited ITE's trip generation methods will keep dominating traffic impact analysis in practice. This study is an effort to provide an alternative method to more accurately predict the traffic impacts of MXDs. We hope that it can help practitioners better assess MXD's traffic impacts and lead community developments toward smart growth.

We acknowledge that our models have several limitations. The first and foremost is the use of ITE *Trip Generation Manual* rates as our starting point. We are not referring only to the tremendous variance in trip rates from which averages and regression equations are derived by ITE (Shoup, 2018). But additionally to the fact base rates for suburban developments may not be applicable to urban and suburban MXDs. The actual rates of person trips to/from/within MXDs may be higher or lower than the ITE rates, before adjustments. MXDs are disproportionately located in areas of high regional accessibility, which may inflate base rates (Steiner, 1998). One could argue the reverse, that MXDs do not require as many person trips to support businesses, due to economies associated with mixed use development. This is a subject that desperately requires more research.

A second limitation of this study is the lack of variables to capture transit service quality beyond stop density and the existence of rail stations within a MXD. Neglect of service frequency, for example, may limit the predictive accuracy of external transit trips from these models.

The third limitation is that, although we included as many D variables as we could, there are still other variables omitted in this study that have been found to affect vehicle trip generation, such as demand management (parking supplies and prices), travel attitudes, and residential self-selection. In New York City, Guo (2013) found that convenient residential parking increased households' vehicle trips as much as 7.5 percent. In nine cities in the U.S., McCahill et al. (2016) found that an increase in parking provision from 0.1 to 0.5 parking space per resident and employee was associated with 30 percent increase in commuter automobile mode share. In California, Khordagui (2019) estimated that a 10% increase in parking prices led to a 1–2 percentage point decline in the probability of driving to work. For a specific development, the results estimated by using our models may need some adjustments to reflect the availability of the parking on site.

A fourth limitation is that we were unable to find significant cross-level interactions during the modeling process. It may be that the sample size is still not big enough, particularly at level 3. Further research is needed to investigate the possible various effects across MXDs or regions.

CRediT authorship contribution statement

Guang Tian: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Keunhyun Park:** Data curation, Validation, Writing - review & editing. **Reid Ewing:** Conceptualization, Writing - review & editing. **Mackenzie Watten:** Writing - review & editing. **Jerry Walters:** Writing - review & editing.

Declaration of Competing Interest

None.

Acknowledgement

Thanks to Alexander Barton, Amanda Dillon, Brittney Harris, and Sadegh Sabouri at the University of Utah for contacting local planners to collect mixed-use development boundaries and land uses.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Arrington, G.B., Cervero, R., 2008. TCRP Report 128: Effects of TOD on Housing, Parking, and Travel. Transportation Research Board of the National Academies, Washington, DC, pp. 3.
Bochner, B.S., Hooper, K., Sperry, B., Dunphy, R., 2011. NCHRP Report 684: Enhancing Internal Trip Capture Estimation for Mixed-Use Developments. Transportation Research Board of the National Academies, Washington, D.C.
Borra, S., Di Ciaccio, A., 2010. Measuring the prediction error. A comparison of cross-validation, bootstrap and covariance penalty methods. Comput. Stat. Data Anal. 54 (12), 2976–2989.
Currans, K.M., 2017. Issues in trip generation methods for transportation impact estimation of land use development: a review and discussion of the state-of-the-art approaches. J. Plann. Literature 32 (4), 335–345.
Ewing, R., Cervero, R., 2010. Travel and the built environment: a meta-analysis. J. Am. Plann. Asso. 76 (3), 265–294.
Ewing, R., Dumbaugh, E., Brown, M., 2001. Internalizing travel by mixing land uses: study of master-planned communities in South Florida. Transport. Res. Record: J. Transport. Res. Board 1780 (1), 115–128.
Ewing, R., Greenwald, M., Zhang, M., Walters, J., Feldman, M., Cervero, R., et al., 2011. Traffic generated by mixed-use developments—six-region study using consistent built environmental measures. J. Urban Plann. Dev. 137 (3), 248–261.
Ewing, R., Tian, G., Lyons, T., Terzano, K., 2017. Trip and parking generation at transit-oriented developments: five US case studies. Landsc. Urban Plann. 160, 69–78.
Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ. Conserv. 24 (1), 38–49.
Greiner, M., Pfeiffer, D., Smith, R.D., 2000. Principles and practical application of the receiver-operating characteristic analysis for diagnostic tests. Prevent. Veterinary Med. 45 (1–2), 23–41.
Guo, Z., 2013. Home parking convenience, household car usage, and implications to residential parking policies. Transp. Policy 29, 97–106.
Hair, J.F., Anderson, R.E., Tatham, R.L., Black, W.C., 1998. Multivariate Data Analysis. Prentice-Hall, Upper Saddle River, NJ.
Handy, S., Shafizadeh, K.R., Schneider, R., 2013. California Smart-Growth Trip Generation Rates Study (No. CA13-1940). University of California, Davis Urban Land Institute and Transportation Center.
Hanley, J.A., McNeil, B.J., 1982. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 143 (1), 29–36.
Institute of Transportation Engineers, 2004. Trip Generation Handbook, second ed. ITE, Washington, D.C.
Institute of Transportation Engineers, 2017. Trip Generation Handbook, third ed. ITE, Washington, D.C.
Institute of Transportation Engneers, 2017. Trip Generation Mannual, 10th ed. ITE, Washington, D.C.
Khordagui, N., 2019. Parking prices and the decision to drive to work: evidence from California. Transp. Res. Part A: Policy Pract. 130, 479–495.
Kimley-Horn and Associates, 2009. Modeling of GDOT's Investing in Tomorrow's Transportation Today (IT3) Project. Presented at the Atlanta RegionalCommission. Retrieved from: http://www.atlantaregional.com/documents/tp_mug_IT3_022709.ppt.
Levitt, R.L., Schwanke, D., 2003. Mixed-Use Development Handbook. Urban Land Institute, Washington, D. C.
Manel, S., Williams, H.C., Ormerod, S.J., 2001. Evaluating presence–absence models in ecology: the need to account for prevalence. J. Appl. Ecol. 38 (5), 921–931.
McCahill, C.T., Garrick, N., Atkinson-Palombo, C., Polinski, A., 2016. Effects of parking provision on automobile use in cities: inferring causality. Transp. Res. Rec. 2543 (1), 159–165.
Meng, Q., 2014. Modeling and prediction of natural gas fracking pad landscapes in the Marcellus Shale region, USA. Landscape Urban Plann. 121, 109–116.
Pang, H., 2014. Mixed Land Use and Travel Behavior: A Case Study for Incorporating Land Use Patterns into Travel Demand Models. The University of Texas at Austin, Austin, TX.
San Diego Association of Governments. (n.d.). Smart Growth Trip Generation and Parking Study. Retrieved from < http://www.sandag.org/index.asp?projectid=378&fuseaction=projects.detail > .
Schneider, R.J., Shafizadeh, K., Sperry, B.R., Handy, S.L., 2013. Methodology to gather multimodal trip generation data in smart-growth areas. Transp. Res. Rec. 2354 (1), 68–85.
Schneider, R., Shafizadeh, K., Sperry, B., Bochner, B., & Handy, S., 2012. California Smart-Growth Trip Generation Rates Study, Appendix E: Data Collection Methodology and Results. Retrieved from University of California, Davis: < http://downloads.ice.ucdavis.edu/ultrans/smartgrowthtripgen/Appendix_E_Data_Collection_Method.pdf > .
Shafizadeh, K., Lee, R., Niemeier, D., Parker, T., Handy, S., 2012. Evaluation of operation and accuracy of available smart growth trip generation methodologies for use in California. Transp. Res. Rec. 2307 (1), 120–131.
Shoup, D., 2018. Truth in transportation planning. In: Parking and the City. Routledge, pp. 59–73.
Steiner, R.L., 1998. Trip generation and parking requirements in traditional shopping districts. Transp. Res. Rec. 1617 (1), 28–37.
Stevens, M.R., 2017. Does compact development make people drive less? J. Am. Plann. Assoc. 83 (1), 7–18.
Stevens, M.R., Park, K., Tian, G., Kim, K., Ewing, R., 2019. Why do some articles in planning journals get cited more than others? J. Plann. Ed. Res., 0739456X19827083.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240 (4857), 1285–1293.
Systematics, Cambridge; Brustlin, V. H.; Bhat, C., 2012. Travel Demand Forecasting: Parameters and Techniques. Washington, DC: Transportation Research Board, National Cooperative Highway Research Program.
Tian, G., Ewing, R., Weinberger, R., Shively, K., Stinger, P., Hamidi, S., 2017. Trip and parking generation at transit-oriented developments: a case study of Redmond TOD, Seattle region. *Transportation* 44 (5), 1235–1254.
Tian, G., Ewing, R., White, A., Hamidi, S., Walters, J., Goates, J.P., Joyce, A., 2015. Traffic generated by mixed-use developments: thirteen-region study using consistent measures of built environment. Transp. Res. Rec. 2500 (1), 116–124.
United Nations, 2018. World Urbanization Prospects 2018. Retrieved from. https://population.un.org/wup/.
United States Environmental Protection Agency., n.d. Mixed-Use Trip Generation Model. Retrieved from < https://www.epa.gov/smartgrowth/mixed-use-trip-generation-model > .
Walters, J., Bochner, B., Ewing, R., 2013. Getting Trip Generation Right: Eliminating the Bias Against Mixed Use Development. American Planning Association, Washington, D.C.
Westrom, R., Dock, S., Henson, J., Watten, M., Bakhru, A., Ridgway, M., et al., 2017. Multimodal trip generation model to assess travel impacts of urban developments in the district of Columbia. Transp. Res. Rec. 2668 (1), 29–37.
Zhang, M., Kone, A., Tooley, S., Ramphul, R., 2009. Trip Internalization and Mixed-Use Development: A Case Study of Austin Texas. Southwest Region University Transportation Center (US), Austin, TX.
Zweig, M.H., Campbell, G., 1993. Receiver-operating characteristic (ROC) plots: a fundamental evaluation tool in clinical medicine. Clin. Chem. 39 (4), 561–577.