Traffic Generated by Mixed-Use Developments – A Six-Region Study Using Consistent Built Environmental Measures

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Abstract

Current methods of traffic impact analysis, which rely on rates and adjustments from the Institute of Transportation Engineers, are believed to understate the traffic benefits of mixed-use developments (MXDs), leading to higher impact fees, exactions, and negotiated payments than should be the case and discouraging development of otherwise desirable projects. The purpose of this study was to develop new methodology for more accurately predicting the traffic impacts of MXDs. Standard protocols were used to identify and generate datasets for MXDs in six large and diverse metropolitan regions. Data from household travel surveys and GIS databases were pooled for these MXDs, and travel and built environmental variables were consistently defined across regions. Hierarchical modeling was used to estimate models for internal capture of trips within MXDs, walking and transit use on external trips, and trip length for external automobile trips. MXDs with diverse activities on-site are shown to capture a large share of trips internally, reducing their traffic impacts relative to conventional suburban developments. Smaller MXDs in walkable areas with good transit access generate significant shares of walk and transit trips, thus also mitigating traffic impacts. Centrally located MXDs, small and large, generate shorter vehicle trips, which reduces their impacts relative to outlying developments.

Word Count: 6,700
Tables: 9
Figures: 2

Introduction

A diverse group of stakeholders is interested in the traffic impacts of mixed-use developments (MXDs). Internal capture rates for trips between land uses are constantly debated by developers who want to minimize traffic mitigation and communities that want to hold existing residents harmless from traffic impacts, and by planners who tend to favor mixed-use developments for a host of reasons and traffic engineers who are skeptical about their traffic benefits. Absent reliable trip generation methodology, communities face a dilemma: Do they err on the conservative side and potentially discourage worthwhile projects, or err on the liberal side and risk unmitigated traffic impacts.

Being able to more accurately estimate the proportion of trips captured internally by MXDs is critical if communities are to make the most effective use of available land and realize master and comprehensive plan objectives without triggering debilitating traffic congestion. As important as the ability to estimate internal capture rates is the ability to estimate the proportion of external trips captured by alternative modes, and the length of private vehicle trips bound for destinations outside the development.

This study innovates in the following respects: (1) pooling travel and land use data for six diverse regions; (2) testing many consistently defined built environmental variables from the six regions; (3) analyzing travel as a multi-level phenomenon, with trips nested within developments and developments nested within regions; (4) focusing on MXDs as geographic units of analysis; (5) including internal capture of trips within developments as a travel outcome measure (along with conventional measures, mode choice and trip distance); (6) measuring effects of MXD on vehicle trip generation rates as opposed to modal splits and incidence of walking, as has been the case in most prior work (see Ewing and Cervero, 2001); and (7) feeding directly into traffic engineering practice through a project sponsor, the Institute of Transportation Engineers.

Current ITE Method

Virtually all traffic impact analyses rely on trip generation rates compiled in the ITE *Trip Generation* manual (7th Edition, 2003). The ITE rates are largely representative of individual, single-use suburban developments whose trips are by private vehicle and whose origins or destinations lie outside the development.

For mixed-use development projects, an ITE member survey found that nearly two-thirds of practitioners estimate internal capture rates using a procedure outlined in Chapter 7 of the ITE *Trip Generation Handbook*. The procedure works this way:

- The analyst determines the amounts of different land use types (residential, retail, and office) contained within the development.
- These amounts are multiplied by ITE's per-unit trip generation rates to obtain a preliminary estimate of the number of vehicle trips generated by the site. This preliminary estimate is what the site would be expected to generate if there were no interactions among the on-site uses.

- The generated trips are then reduced by a certain percentage to account for internal capture of trips within MXDs. The reductions are based on the following two look-up tables:

Strengths of the Current ITE Method

From the viewpoint of the practicing engineer, the ITE internal capture methodology has some important advantages:

- It seems objective. Two analysts given the same data will arrive at exactly the same result. There is no room for negotiation or interpretation (and so no reason to pressure the analyst to skew the results in a pre-determined direction).
- It seems logical. Most engineers readily accept the idea that the degree of internalization will be determined by how well the productions and attractions match for each trip purpose.
- It is fast. With a spreadsheet template an analyst can input the data and have an answer in a matter of minutes.

Looked at another way, any new methodology that lacks these qualities may not find wide acceptance within the engineering community.

Weaknesses of the Current Method

The ITE methodology also has significant weaknesses.

- The two look-up tables are based on data for a "limited number of multi-use sites in Florida" (specifically six sites analyzed by the Florida Department of Transportation, ITE 2001, p. 123). The accuracy of forecasts is thus dependent on how closely the site being analyzed matches the sites used in the tables' creation. The handbook acknowledges this problem and instructs the analyst to find analogous sites locally and collect their own data to produce locally-valid look-up tables.
- The land use types that can be analyzed are limited to the three present in the original sites and embodied in the look-up tables. Uses other than residential, retail, and office defy analysis.
- The scale of development is disregarded. Clearly, a large site with many productions and attractions is more likely to produce "matches" between them than is a small site, and the look-up tables for large sites should have higher cell percentages than the tables for small sites. Development scale was the most significant influence on internal capture rates in a study of South Florida MXDs, and more than half of all trips were found to be internalized by community-scale MXDs, far in excess of any rate obtainable with the handbook method (Ewing et al., 2001).
- The land use context of development projects is ignored. Common sense and the literature tell us that projects in remote locations are more likely to capture trips on-site than are those surrounded by competing trip attractions. For MXDs in South Florida, the

second most important determinant of internal capture rates was accessibility to the rest of the region (second after the scale of development). Conversely, projects in areas of high accessibility are more likely to generate walk trips to external destinations.

- The possibility of mode shifts for well-integrated and transit served sites is not explicitly considered. This may not bias results for free-standing sites, but infill projects within an urban context may capture few trips internally but still have significant vehicle trip reductions relative to the ITE rates.

Conceptual Framework

In this study, travel to/from MXDs is conceived as a series of choices (see conceptual framework in Figure 1). The choices relate directly to the methodology we are proposing to adjust ITE trip generation rates downward.

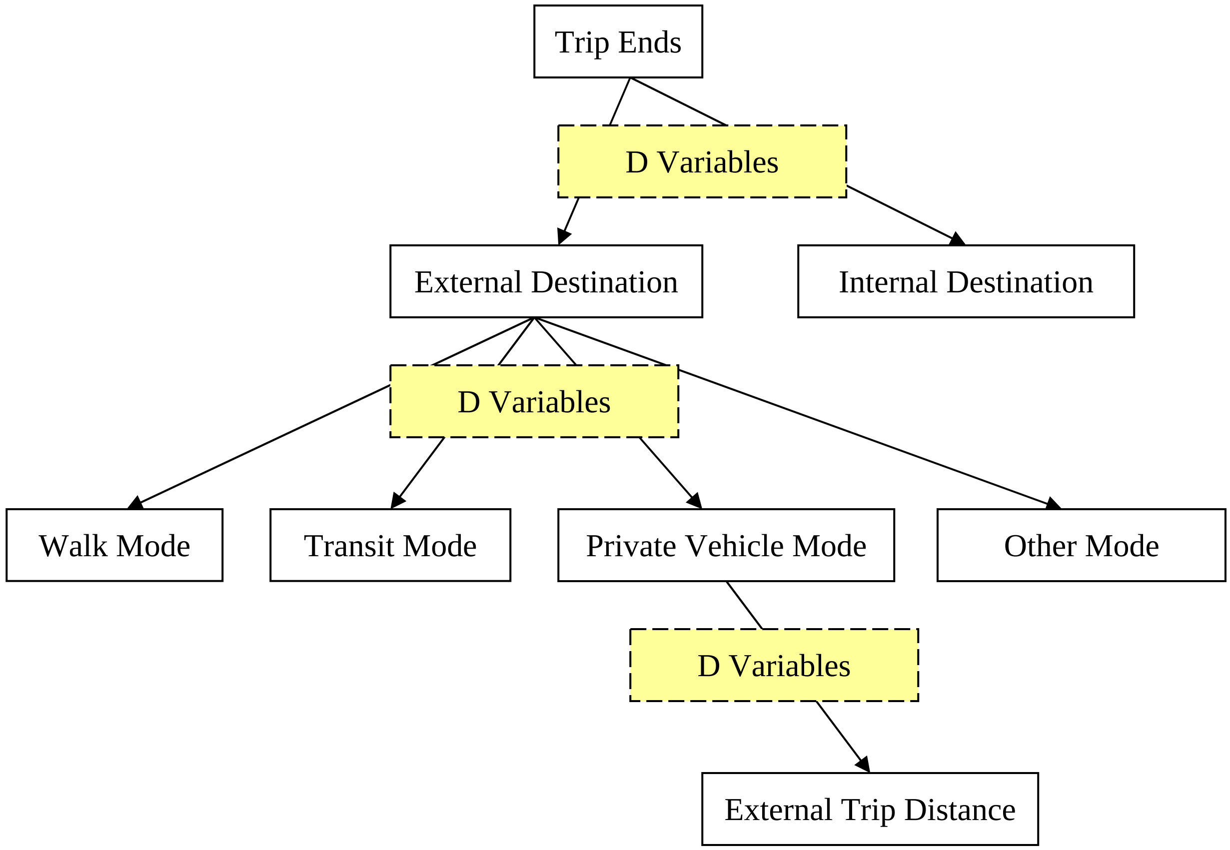
The first adjustment to ITE rates is for trips that remain within the development. Destination choice is conceived as dichotomous. A traveler may choose a destination within the development, or a destination outside the development. Internal trips are treated as 100 percent deducts from ITE trip generation rates.

Then, for trips that leave the development, adjustments are made for walking and transit use. Mode choices are conceived as dichotomous. A traveler may choose to walk or not. The traveler may choose to use transit or not. Walking and transit use may be treated as 100 percent deducts from ITE trip generation rates, or may be treated as partial offsets. It is reasonable to assume that transit trips substitute for personal vehicle trips, but walk trips may supplement as well as substitute for personal vehicle trips. The study team plans to propose substitution rates based on a review of literature.

Finally, for external personal vehicle trips, the traveler chooses a destination. This destination may be near or far. This outcome variable is continuous rather than dichotomous.

The D variables in Figure 1 are characteristics of travelers, MXDs, and regions, as defined below. The D variables determine, moderate, mediate, and confound travel decisions.

Figure 1. Traffic Impact Adjustments



Sample Selection

The main criterion for inclusion of regions in this study was data availability. Regions had to offer:

- regional household travel surveys with XY coordinates for trip ends, so we could distinguish trips to, from, and within small MXDs; and
- land use databases at the parcel level with detailed land use classifications, so we could study land-use intensity and mix down to the parcel level.

Most U.S. regions fall short on one or both counts. While nearly all metropolitan planning organizations (MPOs) have conducted regional household travel surveys as the basis for the calibration of regional travel demand models, most have geocoded trip ends only at the relatively coarse geography of traffic analysis zones. Likewise, while most MPOs have historical land use databases that are used in model calibration, these too provide data only for the relatively coarse geography of traffic analysis zones. Traffic analysis zones vary in size from region to region, but as a general rule, are equivalent to census block groups. They are large relative to many MXDs, and in any event, will ordinarily not coincide with MXD boundaries.

Thirteen regional household travel databases were identified that met the first criterion. This was narrowed down to six regions based on the availability of parcel-level land use data and the interest of planning researchers who had worked with these datasets.

All six travel databases were derived from large-scale regional travel diary surveys. All allowed us to classify trips by purpose and mode of travel. All allowed us to control for socioeconomic characteristics of travelers that may confound interactions between the built environment and travel. All had already been linked to built environmental databases. While the specific variables differed somewhat from database to database, there was the potential to reconcile differences and specify equivalent models.

Identifying MXDs

The ITE definition of multi-use development was modified to create a generic definition of MXD that would encompass many existing areas with interconnected, mixed land use 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."

To identify MXDs in the six study regions at the dates of the most recent regional household travel surveys, the team used a bottom-up, expert-based process in which planners for the different jurisdictions were queried about MXDs within their boundaries. Using this approach, a definition of an MXD would be read to local planners over the phone, and they would be asked to name, identify the boundaries, and list the uses contained within such areas.

The application of this method, in some cases, proved challenging when local planners lacked historical knowledge of their jurisdictions back to time of the applicable travel surveys, had trouble identifying MXD boundaries due to the continuous nature of urban grids, or simply were unresponsive to repeated requests for interviews. When the first two problems arose, additional experts were consulted and/or planners were asked to make educated guesses. In the most unresponsive cases, we simply gave up and lost potential additions to our sample. Three smaller jurisdictions in the Portland region, for example, never returned phone calls or emails. Given our hit rate, we may have missed an MXD or two in the Portland region.

Final Samples

Sample statistics are shown in Table 1. The regions that contribute modest numbers of trip ends to the sample still add statistical power. The importance of Boston, Houston, and Sacramento lies in the number of MXDs each contributes, not in the number of trip ends. Also, the inclusion of the three regions doubles the number of regions in the sample. In a hierarchical analysis, statistical power is limited by the number of degrees of freedom at each level of analysis. There

are ample cases at Level 1, the trip end level, but a shortage of cases at Level 2, the MXD level, and a severe shortage at Level 3, the regional level.

Table 1. Sample Statistics

	Survey Year	MXDs	Mean Acreage per MXD	Total Trip Ends	Mean Trip Ends per MXD
Atlanta	2001	24	290	6,167	257
Boston	1991	59	175	3,578	60.6
Houston	1995	34	401	1,584	46.6
Portland	1994	53	116	6,146	116
Sacramento	2000	25	179	2,487	99.4
Seattle	1999	44	207	15,915	361.7

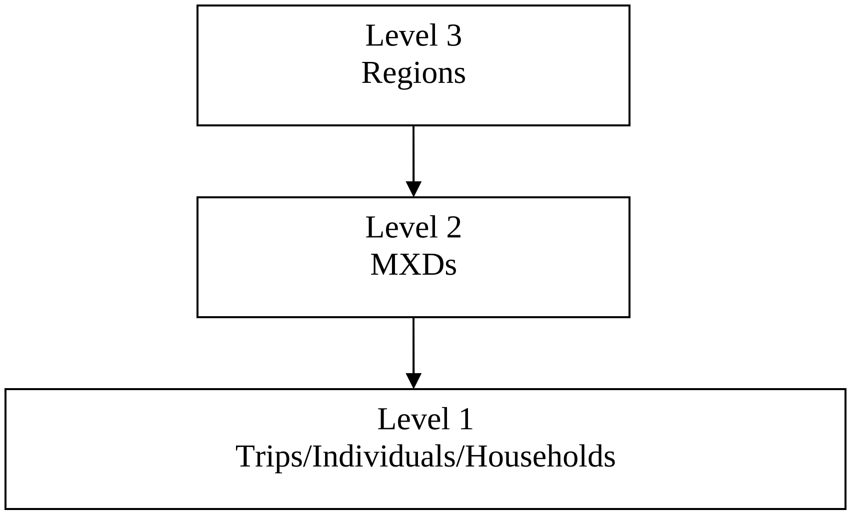
Data and Model Structure

Our data and model structure are hierarchical. Hierarchical modeling is required to account for dependence among observations, in this case the dependence of trips to and from a given MXD. All the trips to/from a given MXD share the characteristics of the MXD, that is, are dependent on these characteristics. This dependence violates the independence assumption of ordinary least squares ("OLS") regression. Standard errors of regression coefficients based on OLS will consequently be underestimated. Moreover, OLS coefficient estimates will be inefficient. Hierarchical (multi-level) modeling overcomes these limitations, accounting for the dependence among observations and producing more accurate coefficient and standard error estimates.

We initially conceived the data structure as a five-level hierarchy, with trips nested within individuals, individuals nested within households, households nested within MXDs, and MXDs nested within metropolitan regions. Upon review of the dataset, we found that the data are not so neatly hierarchical. Many of the individuals in the sample make trips to or from more than one MXD.

This has implications for modeling methodology. Rather than a five-level hierarchy, the choices facing travelers have to be modeled in a three-level framework. Individual trip ends are uniquely identified with MXDs. So trips (their characteristics and the associated characteristics of travelers and their households) form Level 1 in the hierarchy, MXDs form Level 2, and regions form Level 3 (see Figure 2).

Figure 2. Data and Model Structure



Models were estimated with HLM 6 (Hierarchical Linear and Nonlinear Modeling) software. Hierarchical linear models were estimated for the continuous outcome (trip distance), while hierarchical nonlinear models were estimated for the dichotomous outcomes (internal vs. external, walk vs. other, and transit vs. other). Within a hierarchical model, each level in the data structure is formally represented by its own sub-model. The sub-models are statistically linked.

In our initial model estimations, only the intercepts were allowed to randomly vary across higher level units. All of the regression coefficients at higher levels were treated as fixed. These are referred to as "random intercept" models (Ewing et al. 2003; Ewing et al. 2006). As the sample of MXDs was expanded, we also tested for cross-level variable interactions with “random coefficient” models. It is certainly possible that the relationship between, say, walking and vehicle availability varies with size of the MXD, or the relationship between internal capture and MXD density varies from region to region.

Outcome Variables

The variables modeled were:

INTERNAL – Dummy variable indicating that a trip remains internal to the MXD (1=internal, 0=external)

WALK – Dummy variable indicating that the travel mode on an external trip is walking (1=walk mode, 0=other)

TRANSIT - Dummy variable indicating that the travel mode on an external trip is public bus or rail (1=transit, 0=other)

TDIST - Network trip distance between origin and destination locations for an external private vehicle trip, in miles

(Bike trips were not modeled because our samples contain relatively few of them.)

There is much variation in internal capture rates from MXD to MXD, and from region to region. Across regions, average internal capture rates vary from a low of 8 percent for Atlanta to a high of 28 percent for Houston (see Table 2). The high rate for Houston may reflect the fact that Houston's MXDs are, in general, larger and more remotely located than those in other regions.

Table 2. Internal Capture Rates for MXDs in the Six Study Regions

	Internal Capture
Atlanta	8.0%
Boston	9.4%
Houston	28.3%
Portland	13.0%
Sacramento	15.1%
Seattle	11.2%

In all household travel surveys, automobile, walk, and transit (bus or rail, where available) are identified as separate modes of travel. Bicycle is as well, but samples are too small to be reliably analyzed. Again, there is great variation in mode shares from MXD to MXD, and region to region. In all regions, the dominant mode for external trips to/from MXDs is the automobile ("private motor vehicle"). The essential choices facing travelers are to walk or use a private vehicle, or to take transit or use a private vehicle. For external trips, average mode shares by walking and transit combined vary from a low of 2 percent for Sacramento to a high of 18.9 percent for Boston (see Table 3).

Of the 35,877 trip ends generated by these MXDs, 6,378 (17.8%) involved trips within the mixed-use site, another 2,099 (5.8%) involved trips entering or leaving the site via walking, and another 1,995 (5.6%) involved trips entering or leaving via transit. Thus, on average, a total of 29% of the total trip ends generated by mixed-use developments put no strain on the external street network, generate very few vehicle miles traveled, and should be deducted from ITE trip rates for stand-alone developments. This 29% figure, we note, is a bit less than the 36% internal capture rate measured for the six MXD sites by the Florida DOT, as reported in the 2001 ITE *Trip Generation Handbook*.

Table 3. Average Walk and Transit Mode Shares for External Trips to/from MXDs

	Walk Share	Transit Share
Atlanta	3.2%	2.1%
Boston	13.2%	3.7%
Houston	2.7%	5.2%
Portland	7.1%	3.3%
Sacramento	1.8%	0.2%
Seattle	4.7%	8.7%

Trip distances are just as variable across regions. Average distances of external auto trips to/from MXDs range from 4.8 miles for MXDs in Boston to 13.6 miles for MXDs in Houston (see Table 4).

Table 4. Average Trip Distances for External Auto Trips to/from MXDs in the Six Study Regions (in miles)

	Distance (miles)
Atlanta	9.1
Boston	4.8
Houston	13.6
Portland	5.4
Sacramento	8.1
Seattle	7.9
Combined	7.5

Explanatory Variables

In travel research, urban development patterns have come to be characterized by "D" variables. The original "three Ds," coined by Cervero and Kockelman (1997), are *density*, *diversity*, and *design*. Three additional Ds have been labeled since then, *destination accessibility*, *distance to transit*, and *demographics*. An additional D variable is relevant to this analysis: *development scale*.

In this study, all seven types of D variables were measured and used to predict the travel characteristics of MXDs. The richness of the datasets varies from region to region. Portland and Atlanta have the most complete datasets. Houston and Sacramento have the least complete datasets. Variables available for all regions are shown in normal type. Those available for a subset of regions are shown in italics.

Trip-Level Explanatory Variables (Level 1)

HBO – Dummy variable indicating that the trip is home-based for purposes other than work (1=home-based other, 0=otherwise)

NHB – Dummy variable indicating that the trip is non-home-based (1=non-home-based, 0=otherwise)

(The reference category for trip purpose variables is home-based work.)

Traveler-Level Explanatory Variables (Level 1)

CHILD – Dummy variable indicating that the traveler is under 16 years of age (1=child, 0=adult)

WHITE – Dummy variable indicating that a traveler is a white caucasian (1=white, 0=other)

Race and ethnicity are available for all but Boston and Sacramento.

(The travel diary databases have more detailed ethnic classes, and actual age data.)

Household-Level Explanatory Variables (Level 1)

HHSIZE – Number of members of the household

VEHCAP – Number of motorized vehicles per person in the household

BUSSTOP – Dummy variable indicating that the household lives within ¼ mile of a bus stop (1=yes, 0=no)

MXD-Level Explanatory Variables (Level 2)

Development Scale Variables

POP – Resident population within the MXD

Prorated sum of the population for the census block groups which intersect the MXD. Prorating was done by calculating density of population per residential acre (tax lots designated single-family or multifamily) for the entire census block group, then multiplying the density by the amount of residential acreage within the block group contributing to the MXD, and finally, summing over all block groups intersecting the MXD area. For Houston, data at the TAZ level were prorated.

EMP – Employment within the MXD

Weighted sum of the employment within the MXD for all SIC industries. For Portland,

employment estimates were based on the average number of employees in each size category, summed across employer size categories. For other regions, data at the TAZ level were prorated.

ACTIVITY – Resident population plus employment within the MXD

Density Variables

POPDEN – Population density per net square mile within the MXD

Population within the MXD, divided by land designated for single-family or multifamily housing in tax lot records. Net population density is available for all but Houston.

EMPDEN - Employment density per net square mile within the MXD

Employment within the MXD, divided by land designated for employment uses in tax lot records. Net employment density is available for all but Houston.

ACTDEN - Activity density per square mile within the MXD

Sum of population and employment within the MXD, divided by gross land area.

FAR – Floor area ratio of all land uses within the MXD

Total square footage of all buildings divided by total square footage of all tax lots within the MXD. FAR is available for Portland, Seattle, and Atlanta.

DEVLAND – Proportion of developed land within the MXD

Diversity Variables

JOBPOP – Index that measures the balance between employment and resident population within the 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 the same as the region as a whole. Values are intermediate when MXDs have both jobs and residents, but one predominates. [1]

JOBMIX – Diversity index that captures the variety of employment within the MXD

Entropy calculation based on employment in SIC categories likely to exchange trips. For Portland, the four categories of employment factored into the index were: retail; services;

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[1] JOBPOP = 1 – [ABS (employment - a*population)/(employment + a*population)]
ABS is the absolute value of the expression in parentheses. a is the regional ratio of employment to residents.

finance/insurance/real estate; and transportation/communications/public utilities.[2] *For other regions, the categories were slightly different.*[3] *The index varies in value from 0, where all employment is in one of these categories, to 1, where employment is evenly divided among these categories. JOBMIX is available for Atlanta, Boston, Portland, and Seattle.*

BUILDMIX - Diversity index that captures the variety of land uses within the MXD

Entropy calculation based on building floor area in land use categories likely to exchange trips. In both regions, land uses were aggregated into three roughly equivalent categories: commercial, office, and public/institutional. The entropy index varies in value from 0, where all building area is in one of these categories, to 1, where building area is evenly divided among these categories BUILDMIX is available for Atlanta and Seattle.

LANDMIX – Another diversity index that captures the variety of land uses within the MXD

Entropy calculation based on net acreage in land use categories likely to exchange trips. For Portland,   the land uses were: residential, commercial, industrial, and public or semi-public.[4] For other regions, the categories were slightly different.[5] 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 Variables

STRDEN - Centerline miles of all streets per square mile of gross land area within the MXD

INTDEN - Number of intersections per square mile of gross land area within the MXD

SIDEWALK – Mileage of sidewalks per centerline mile of streets within the MXD

Sidewalk mileage is available for Portland and Atlanta.

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[2] JOBMIX = -[retail share*LN (retail share) + service share*LN (service share) + FIRE share*LN (FIRE share) + TCPU share*LN (TCPU share)]/ LN (4), where LN is the natural logarithm of the value in parentheses

[3] The employment categories were as follows: for Atlanta, retail, service, FIRE, transportation/communication/utilities, and government; for Boston, retail, service, finance, transportation, and government; and for Seattle, retail, FIRE, wholesale/transportation/communications/utilities, and civic.

[4] 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 of the value in parentheses.

[5] For Houston, the land uses were: residential, commercial, industrial, and institutional; a “mixed residential and commercial” class of land uses was included with commercial. For Boston, the land uses were: residential, commercial, industrial, and recreational. For Seattle, detailed land uses were aggregated into four categories: residential, commercial, industrial, and institutional. For Atlanta, detailed land uses were aggregated into four categories: residential, commercial, industrial, and institutional. For Sacramento, detailed land uses were aggregated into four categories: residential, commercial, industrial, and institutional; a mixed class of land uses was included with commercial.

Destination Accessibility Variables

EMPMILE – Total employment within one mile of the MXD

Weighted average for all 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).

EMP10A – Total employment accessible within 10-minutes travel time of the MXD using an automobile at midday

Computed in same manner as EMPMILE.

EMP20A – Total employment accessible within 20-minutes travel time of the MXD using an automobile at midday

Computed in same manner as EMPMILE.

EMP30A – Total employment accessible within 30-minutes travel time of the MXD using an automobile at midday

Computed in same manner as EMPMILE.

EMP30T– Total employment accessible within 30-minute travel time of the MXD using transit

Computed in the same manner as EMPMILE.

Distance to Transit Variables

STOPDEN – 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.

The number of MXDs for which we have values of different explanatory values varies greatly from variable to variable, as shown in Table 5.

Table 5. Sample Sizes and Descriptive Statistics for Level 2 Variables

	N	Mean	S.D.
POP	239	2271.0	3261.4

EMP	239	2696.3	5572.2
ACTIVITY	239	4967.2	6945.6
POPDEN	205	21600.3	35147.5
EMPDEN	204	30269.4	51360.9
ACTDEN	239	19780.9	30669.4
FAR	121	0.400	0.538
DEVLAND	239	0.825	0.218
JOBPOP	239	0.558	0.297
JOBMIX	180	0.702	0.166
BUILDMIX	64	0.554	0.325
LANDMIX	239	0.518	0.199
STRDEN	239	25.4	10.5
INTDEN	239	257.5	203.0
SIDEWALK	74	0.915	0.673
EMPMILE	239	30.5	50.9
EMP10A	239	69.8	111.2
EMP20A	239	276.1	377.1
EMP30A	239	505.0	630.6
EMP30T	239	86.1	147.9
STOPDEN	239	70.5	83.9
RAILSTOP	239	0.084	0.277

Modeled Results

Internal Capture

For internal capture, the dependent variable is the natural log of the odds of an individual making a trip with both ends within an MXD. Explanatory variables, their coefficients, and their significance levels (p-values) are shown in Table 6.

Models were estimated sequentially, starting with the full set of MXDs and the limited set of Level 2 variables for which all MXDs have values. The resulting base model includes only those explanatory variables with values for all 239 MXDs. Level 2 variables were sequentially added to the base model, resulting in a loss of cases and degrees of freedom. The last variables to be added were the sidewalk and building mix variables, each available for only two regions.

In the base model, four Level 1 variables have the expected signs and are significant. Home-based other and non-home based trips are more likely to be internal trips than are home-based work trips. While characterized as controls, these trip purpose variables are a function of the employment mix within the MXD. Office-oriented developments generate a disproportionate number of home-based work trips, while retail-oriented developments generate a disproportionate number of home-based nonwork trips. These variables could be treated as inputs to traffic impact analyses.

The other two controls, household size and vehicle ownership per capita, are inversely related to the likelihood of internal trips. These two variables represent the sixth D, *demographics* (actually *sociodemographics*). While characterized as controls, these sociodemographic variables depend on the housing mix within the development and its surroundings. As noted earlier, their inclusion can help control for potential self-selection biasing effects. Thus, demographic variables should aso be used as inputs to traffic impact studies. The least variation in vehicle trip estimates will occur when the residential component of a MXD appeals to a fairly homogenous household market.

In the base model, internalization of trips is significantly related to three Level 2 variables, resident population, employment, and the job-population balance within the MXD. The first two are measures of *development scale*, the third a measure of *diversity*. All three are positively related to the likelihood of internal trips. Larger MXDs are more likely to capture trips internally, as are MXDs with a balance of employment and resident population. A high job-housing balance index suggests relatively high trip internalization for not only work trips but also retail shopping since employment counts include individuals working in the retail and service sectors.

Two additional Level 2 variables proved significant in subsequent model estimations, floor area ratio (FAR) in the model with 121 MXDs from three regions, and land use mix (BUILDMIX) in the model with 64 MXDs from two regions. FAR is a measure of the first D, *density*, while BUILDMIX is a measure of *diversity*. Both have the expected signs, being positively related to internal capture. The inclusion of land use mix, and the smaller sample it begets, causes job-population balance and floor area ratio to fall below the conventional 0.05 level of statistical significance. Yet, for theoretical reasons, we prefer the fully specified model, with all seven D variables, and propose to use it in the internal capture methodology.

None of the Level 3 variables proved significant. While there is significant variance of internal capture from region to region, it is not explained by the variables in our data set. It is, however, captured in the random effects term of the Level 3 equation.

Added to Table 6 are the elasticities of internal capture with respect to the significant explanatory variables. These are percentage changes in the probability of internal capture with respect to a one percent change in each explanatory variable. They are computed with the formula:

> *elasticity = coefficient of explanatory variable * mean value of explanatory variable * (1 - mean probability of internal capture)*

Among built environmental variables, the elasticity of internal capture is highest for job-population balance. The elasticity value, 0.35, suggests that the probability of internal capture increases by 0.35 percent for every one percent increase in the value of this variable. Other elasticity values can be interpreted in the same way. Internal capture is relatively inelastic with respect to all explanatory variables.

These elasticity values will be used to develop adjustment factors for ITE trip generation rates.

Probabilities are just expected internal capture rates, so it will be easy to adjust ITE's vehicle trip rates downward by expected internal capture rates, pivoting off ITE values.
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Table 6. Log Odds of Internal Capture

	239 MXDs				64 MXDs			
	coeff	t-ratio	p-value	elast	coeff	t-ratio	p-value	elast
constant	-3.375				-4.145			
POP	0.00009	4.39	< 0.001	0.17	0.0001	2.21	0.031	0.19
EMP	2.8E-05	2.15	0.033	0.06	0.00008	3.34	0.002	0.29
JOBPOP	0.78	2.82	0.006	0.36	0.61	1.15	0.26	0.22
FAR					0.21	0.98	0.33	0.09
BUILDMIX					1.15	2.36	0.022	0.52
HBO	1.021	13.6	< 0.001	NA	1.052	9.95	< 0.001	NA
NHB	1.919	25.9	< 0.001	NA	2.131	20.5	< 0.001	NA
HHSIZE	-0.19	-14.4	< 0.001	-0.41	-0.274	-15.6	< 0.001	-0.58
VEHCAP	-0.467	-12.4	< 0.001	-0.31	-0.732	-14.9	< 0.001	-0.49
Pseudo-R^2	0.067				0.45			

Walk and Transit Use for External Trips

For external trips, walking and transit use have been modeled independently because they depend on different environmental factors (as described below). For walk mode choice, the dependent variable is the natural log of the odds of an external trip being made by walking. For transit mode choice, the dependent variable is the natural log of the odds of an external trip being made by transit. The significant independent variables, their coefficients, and their significance levels (p-values) are shown in Tables 7 and 8.

Among Level 2 environmental variables, the strongest influences on walking are intersection density and jobs within one mile of the MXD boundary. The former is a measure of *design*, and the latter is a measure of *destination accessibility*. High intersection density within the MXD makes walking to/from activities outside the MXD that much faster and easier. High employment totals within a mile of the MXD affords trip attractions within walking distance. Activity *density* within the MXD is also positively related to walking on external trips. Perhaps this is due to better walking conditions or trip chaining opportunities.

The significant environmental influences on transit use are the density of bus stops within the MXD, the presence of a rail station within the MXD, and the regional transit accessibility of the MXD, measured in terms of jobs reachable within 30 minutes by transit. These variables measure *distance to transit* and *destination accessibility*. They suggest, consistent with other

literature, that mixed-use transit oriented developments (TODs) that concentrate residents, workers, and retail shops in close proximity to major transit stops can "de-generate" trips (Cervero and Arrington, 2008).

The results in Tables 7 and 8 are shown for control variables as well as environmental variables. Walking is more likely on home-based other trips than on home-based work trips. Transit use is less likely on trips for purposes other than work. Larger household size and greater vehicle availability reduce the likelihood of both walk and transit trips. In fact, transit use is highly elastic with respect to vehicle availability. Children are more likely to walk, and are less likely to use transit. Finally, the likelihood of walking declines, the likelihood of transit use increases, with the length of trips (a proxy for the relative cost of one mode versus another).

One of the Level 3 variables proved marginally significant as a predictor of walking for all MXDs. Controlling for other influences, the likelihood of walking increases as the population of the metropolitan area increases.

Table 7. Log Odds of Walking on External Trips

	239 MXDs				75 MXDs			
	coeff	t-ratio	p-value	elast	coeff	t-ratio	p-value	elast
constant	-4.549				-4.298			
METPOP	0.00025	2.09	0.102	0.67				
EMPMILE	0.00653	5.32	< 0.001	0.19	0.00754	1.79	0.077	0.14
ACTDEN	6E-06	2.57	0.011	0.11	5E-06	1.18	0.244	0.11
INTDEN	0.00204	4.99	< 0.001	0.49	0.0018	2.37	0.021	0.45
SIDEWALK					0.358	1.85	0.068	0.31
HBO	0.123	2.29	0.022	NA	0.167	1.79	0.073	NA
TDIST	-0.428	-25.8	< 0.001	NA	-0.461	-14.7	< 0.001	NA
CHILD	0.262	3.01	0.003	NA	0.526	3.7	< 0.001	NA
HHSIZE	-0.203	-8.77	< 0.001	-0.51	-0.302	-6.85	< 0.001	-0.74
VEHCAP	-0.795	-11.5	< 0.001	-0.60	-0.966	-7.84	< 0.001	-0.77
pseudo-R^2	0.631				0.624			

Table 8. Likelihood of Using Transit on External Trips

	239 MXDs			
	coeff	t-ratio	p-value	elast
constant	-3.765			
EMP30T	0.00116	2.79	0.006	0.09
STOPDEN	0.00297	3.5	0.001	0.24

RAILSTOP	0.502	2.17	0.031	NA
HBO	-0.481	-6.36	< 0.001	NA
NHB	-0.404	-5.28	< 0.001	NA
TDIST	0.0392	12	< 0.001	0.23
CHILD	-0.627	-5.41	< 0.001	NA
HHSIZE	-0.373	-16.3	< 0.001	-0.93
VEHCAP	-2.249	-30	< 0.001	-1.69
BUSSTOP	0.404	5.94	< 0.001	NA
pseudo-R^2	0.406			

Trip Distance for External Automobile Trips

The length of external automobile (private vehicle) trips is related to the regional accessibility of the MXD, measured in terms of employment that can be reached within 20 minutes by automobile (see Table 9). The better the regional accessibility to employment (and hence to shopping, services, etc.), the shorter the length of vehicle trips. Job-population balance is also significant and negatively related to external automobile trip length. This may be due to trip chaining behavior.

Home-based other and non-home based trips are shorter than home-based work trips (the reference case), on average about 2.5 miles shorter. The length of external trips increases to a significant extent with household size, perhaps due to multi-purpose trip making. The length of external trips also increases with vehicle availability, which may due to higher income or less competition for the family car.

Table 9. Trip Distance for External Automobile Trips

	239 MXDs			
	coeff	t-ratio	p-value	elast
constant	10.17			
EMP20A	-0.0016	-2.35	0.02	-0.07
JOBPOP	-3.036	-3.38	0.001	-0.26
HBO	-2.581	-17.7	< 0.001	NA
NHB	-2.391	-16.1	< 0.001	NA
CHILD	-0.896	-5.67	< 0.001	NA
HHSIZE	0.305	7.23	< 0.001	0.13
VEHCAP	1.27	10.5	< 0.001	0.17
pseudo-	0.12			

R^2	

Conclusion

The "bibles" of traffic impact analysis, the Institute of Transportation Engineers' *Trip Generation* manual and *Trip Generation Handbook*, are woefully lacking when it comes to MXDs, an increasingly common development form. Except for a handful of master-planned projects in Florida, actual numbers on internal capture rates are few and far between. Traffic engineers are thus largely left to their own devices to quantify the trip reductions that might accrue from this often varied and complex development type. Often times, no adjustment is made. This ends up over-stating the traffic impacts of MXD proposals, leading to high impact fees, exactions, and negotiated payments than should be the case and adding fodder to those who oppose any and all land-use changes. Unavoidably, then, failure to account for internal capture ends up penalizing MXDs by forcing developers of these projects to, in effect, cross-subsidize single-use projects through their bloated impact-fee payments. Besides adjustments in impact fee schedules, the trip-reducing benefits of MXDs call for other actions that reward this inherently efficient form of development, like flexible parking codes, market-responsive zoning, streamlining the project review and permitting process, and investments in supportive public infrastructure.

This research sought to advance the state of knowledge on the relationships that govern travel to and within mixed used development projects and to enumerate tangible and verifiable traffic reductions relative to the rates in the ITE *Trip Generation* manual. Travel research published over the last few years convincingly shows that changes by several percentage points in any or several of the 7D variables used in this study slightly reduces the number of vehicle trips and vehicle miles traveled. Our study extends and focuses that research on the particular characteristics of MXDs. It represents the first national study of the travel generation by mixed-use development, making use of household travel survey data from six metropolitan areas. We found an average of three out of 10 trips produced by and attracted to MXDs put no strain on the external street network and generated very few vehicle miles traveled. Statistical equations derived from the data reveal that the primary factors affecting this reduction in automobile travel are:

- The total and the relative amounts of population and employment on the site
- The site density (floor area ratio)
- The size of households and their auto ownership
- The amount of employment within walking distance of the site
- The pedestrian-friendliness (small blocks and sidewalks) of the site
- The density of bus stops, presence or absence a rail station, and the access to employment within a 30 minute transit ride of the site

For traffic impact, greenhouse gas, and energy analyses, the number of vehicle miles of travel (VMT) generated by a mixed-use site depends, in addition to the factors above, upon the site's placement within the region, specifically, the number of jobs located within a 20-minute drive of

the site. Greater destination accessibility translates into shorter auto trips external to the site. This effect is as significant as the effects associated with internal capture of trips with mixed-use developments, and conversion of some external trips from auto to alternate modes.

The findings on mixed-use trip generation reported here will be refined and validated through field surveys at representative sites in locations such as Southern California, Salt Lake City, Denver, Dallas, Florida, Atlanta and Washington D.C. When the study is completed, it will help guide planners and developers of mixed-use projects on design features likely to minimize traffic generation and greenhouse gas and energy impacts, and it will produce new analysis techniques for traffic engineers to more realistically quantify impacts and size infrastructure for mixed-use development proposals. Only through smart calculations informed by studies like ours can planners and engineers begin to put in place strategies that reward smart growth.

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