Traffic Generated by Mixed-Use Developments—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 exactions and development fees than necessary and discouraging otherwise desirable developments. The purpose of this study is to create new methodology for more accurately predicting the traffic impacts of MXDs. Standard protocols were used to identify and generate data sets for MXDs in six large and diverse metropolitan regions. Data from household travel surveys and geographic information system (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. **DOI:** 10.1061/(ASCE)UP.1943-5444.0000068. *© 2011 American Society of Civil Engineers.*

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Introduction

Mixed-use development (MXD) is a signature feature of smart growth, New Urbanism, and other contemporary land-use movements aimed at reducing the private automobile's dominance in suburban America. By putting offices, shops, restaurants, residences, and other codependent activities in close proximity to each other, MXD shortens trips and thus allows what might otherwise be external car trips to become internal walk, bike, or transit trips. This in turn can reduce the vehicle miles generated by an MXD relative to what it would be if the same activities were separated in single-use developments. Fewer vehicle miles traveled (VMT) not only relieves traffic congestion but also reduces greenhouse gas (GHG) emissions, air pollution, and fuel consumption. MXDs are also promoted for their supply side benefits, such as possibilities for shared parking and economizing on roadway and related infrastructure expenditures (because peak travel periods often differ between offices, retail, and other uses, enabling investments to be descaled) (Cervero 1988).

A diverse group of stakeholders has a vested interest in the traffic impacts of MXDs. The replacement of off-site car trips with on-site walking or cycling or (for larger mixed-use sites) on-site transit or driving matters to developers who want smooth-flowing traffic conditions to help market their projects, to communities that want to keep existing residents safe from traffic impacts, and to traffic engineers whose very profession is devoted to facilitating traffic flows but often harbor some skepticism about the traffic benefits of MXDs.

Accurately estimating the proportion of trips captured internally by MXDs is vitally important if communities are to accurately assess their traffic impacts and reward such projects through lower exactions and development fees or expedited project approvals. However, lacking a reliable methodology for adjusting trip generation estimates, communities face a dilemma when assessing MXD proposals: do they err on the conservative side by downplaying internal capture and thereby potentially discourage worthwhile projects, or err on the liberal side and risk unmitigated traffic

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impacts? Often, the "do no harm" sentiment prevails: when in doubt, go with conventional practices, which, with MXD proposals, typically means only a small downward adjustment in estimated trips, if any adjustment at all.

In addition to getting internal capture estimates right, accurate assessments of MXD projects also depend on estimating the share of external trips served by alternative modes (e.g., transit and walking). These must also be subtracted from nominal trip generation rates to estimate the net impacts of MXDs on traffic and VMT.

Community acceptance depends on whether a proposed MXD is perceived as a good neighbor. Exaggerated estimates of a project's traffic generation can heighten concerns about congestion, community image and character, and even public health and safety. A nimby backlash can add substantially to the time and expense of securing project approval, and can result in the project being scaled back to a level at which elected officials feel that the trip generation is more acceptable. However, the market demand for the development that is disallowed does not vanish and more often than not ends up in another location, often at a lower density and in a less mixed-use configuration. The end result can be more traffic and higher overall VMT than if the original MXD proposal had been approved.

Traffic generation estimates have supply-side impacts, affecting project design and cost. This includes the most obvious components, such as street widths, parking supply, and access point design, and secondary effects on the design and cost of ancillary infrastructure like storm water drainage systems. Within constrained sites, overdesign of traffic elements can limit the space available for revenue-producing land uses and increase other development costs; forcing, for example, the rerouting of utilities to accommodate traffic-handling infrastructure.

Statutory laws also place pressure on getting the traffic estimates for MXDs right. The formal National Environmental Policy Act (NEPA) process and state-level environmental reviews rely on traffic generation estimates to assess impacts and dictate a project's mitigation measures. Estimates that exaggerate negative impacts increase the likelihood a project will be judged as a significant threat to environmental quality. This leads to more rigorous analysis and reporting of a wide array of potential secondary impacts, such as the growth inducing effects of the additional required traffic capacity. It also prompts a more protracted discussion of community concerns through formal public involvement, document review, comment/response periods, and certification protocols. In addition, it can incorrectly trigger a review of other impacts such as noise, air quality, energy use, and greenhouse gas emissions.

Development fee programs rely heavily on traffic generation estimates. As the most comprehensive and widely used reference on the subject, the *Trip Generation* report of the Institute of Transportation Engineers (ITE) (2008) has become the principal data source for setting transportation development fee rates. Most cities, counties, and regional agencies opt for uniformity rather than accuracy in this regard. In the interest of standardization of assumptions and approach, many jurisdictions rely on the numbers in *Trip Generation* to quantify traffic impacts and mitigation fee schedules. The unquestioning use of the ITE report can unreasonably jeopardize a MXD project's approval, financial feasibility, and design quality.

Conventional Traffic Impact Analysis

Virtually all traffic impact analyses rely on the ITE *Trip Generation* report (2008). 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. Quoting the report: "Data were primarily collected at suburban localities with little or no transit service, nearby pedestrian amenities, or travel demand management (TDM) programs." Recognizing but not resolving this limitation, *Trip Generation* advises: "At specific sites, the user may want to modify the trip generation rates presented in this document to reflect the presence of public transportation service, ridesharing or other TDM measures, enhanced pedestrian and bicycle trip-making opportunities, or other special characteristics of the site or surrounding area." Unfortunately, the desire among traffic engineers for standardization and substantial documented evidence prevents them from taking this advice in the vast majority of cases.

Even setting aside the variety and complexity of mixed-use developments, the reliability of *Trip Generation* for evaluating simple single-use developments is less than one might assume. For example, for the most widely studied land-use category within the report, single-family residential, the average ITE *Trip Generation* daily rate is 9.6 vehicle trips per dwelling unit, but the standard deviation is 3.7, almost 40% of the mean. Even for this most uniform of land-use types, when described in terms of a single descriptive variable (number of dwelling units), the 9.6 ITE trip generation figure used in impact study guidelines and fee ordinances throughout the United States is just a midpoint in a standard deviation range of 5.9 to 13.3 vehicle trips per dwelling. The standard deviations for other common and well-studied land-use types (e.g., office buildings and shopping centers) are at least 50% of the mean values. Clearly, trip generation estimation is far from a precise science.

Professor Donald Shoup of UCLA has been particularly critical of *Trip Generation* for the following reasons: the false precision with which average trip generation rates are presented, the small samples upon which average rates and regression equations are based, the insignificance of regression coefficients and constants, the implicit assumption that trip generation increases with building size, and the disregard of factors other than building size in the regression analyses. Pointing to the need to represent land-use interactions more carefully, Shoup remarks, "Floor area is only one among many factors that influence vehicle trips at a site, and we should not expect floor area or any other single variable to accurately predict the number of vehicle trips at any site or land-use" (Shoup 2003).

As an indication of just how far off the mark ITE rates may land, the Transit Cooperative Research Program (TCRP) recently funded a study of the trip generating characteristics of transit-oriented developments (TODs) (Cervero and Arrington 2008). The aim was to seed the ITE *Trip Generation* report with original and reliable trip generation data for one important TOD land-use—housing—with the expectation that other TOD land uses will be added later. For all TOD housing projects studied, weekday vehicle trip rates were considerably below the ITE average rate for similar uses. Taking the weighted average across the 17 case-study projects, TOD housing projects, which included both multifamily and single-family residential units, generated approximately 44% fewer vehicle trips than predicted by the ITE report (3.8 trips per dwelling unit for TOD housing versus 6.7 trips per dwelling unit by ITE estimates for the site-specific mixes of multi- and single-family residences).

ITE Method for MXDs

For mixed-use development projects, Chapter 7 of *Trip Generation Handbook* (2004) outlines a procedure for estimating the proportion of trips that remain within the development (i.e., the internal capture rate), and hence place no strain on the external street network. An ITE member survey found that nearly two-thirds of practitioners estimate internal capture rates using this procedure. The procedure works as follows:

1. The analyst determines the amounts of different land-use types (residential, retail, and office) contained within the development.
2. 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.
3. The generated trips are then reduced by a certain percentage to account for internal-capture of trips within MXDs. The reductions are based on lookup tables. The share of internal trips from the appropriate lookup table is multiplied by total numbers of trips generated by a given use to obtain an initial estimate of internal trips for each producing use and attracting use.
4. For each pair of land uses, productions and attractions are reconciled such that the number of internal trips produced by one use just equals the number attracted by the other use. The lesser of the two estimates of internal trips constrains the number of internal trips generated by the other use.

Strengths of the Current ITE Method

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

1. 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 therefore no reason to pressure the analyst into skewing the results in a predetermined direction).
2. 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.
3. It is fast. With a spreadsheet template, an analyst can input the data and have an answer in a matter of minutes.

Viewed 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 major shortcomings:

1. The two lookup tables are based on data for a "limited number of multiuse sites in Florida" (specifically, three sites analyzed by the Florida Department of Transportation, ITE 2004). The accuracy of forecasts is thus dependent on how closely the site being analyzed matches the sites used in the tables' creation. The fact that the data are drawn from the suburbs of Florida casts doubt on the applicability to other parts of the country. The handbook acknowledges this problem and instructs the analyst to find analogous sites locally and collect his own data to produce locally valid lookup tables.
2. The land-use types and adjustments embodied in the lookup tables are limited to the three uses: residential, retail, and offices. The traffic impacts of other mixed uses cannot be assessed.
3. The scale of development is disregarded. Clearly, a large site with many productions and attractions is more likely to produce matches than a small site, and the lookup 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).
4. 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 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.
5. The possibility of mode shifts for well-integrated, 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.
6. The length of external private vehicle trips is not considered. The ITE methodology deals with trip generation, not traffic generation. Clearly, in terms of roadway congestion, emissions, and other impacts, a 10-mile trip has a greater impact than a 5-mile trip. Trip distribution is an ad hoc process under the ITE methodology.

Parallel Efforts

There would seem to be two ways to refine ITE trip generation estimates of MXDs. One, a bottom-up approach, would add to the paltry set of development projects that currently constitute the ITE database on MXDs, analyze in detail this larger sample's trip-making characteristics, and then derive a set of more complete adjustments to ITE trip rates. In an effort parallel to our own, the National Cooperative Highway Research Program (NCHRP) is taking this approach in NCHRP Project 8-51, "Enhancing Internal Trip Capture Estimation for Mixed-Use Developments." Adding four sites to the three that currently form the basis for internal capture calculations in ITE's *Trip Generation Handbook* (2004), the project has developed an estimation procedure that includes a proximity adjustment to account for project size and layout.

A second approach, more top down in nature, would assemble enough data on MXDs to estimate statistical models of traffic generation in terms of standard built environmental variables, the so-called "D" variables of density, diversity, design, destination accessibility, distance to transit, and development scale. Taking this approach, Ewing et al. (2001) modeled internal capture rates for 20 mixed-use communities in South Florida. For the 20 communities, internal capture rates ranged from 0 to 57% of all trip ends generated by the community.

To explain this variation, internal capture rates were modeled in terms of land-use and accessibility measures. The variable that proved most strongly related to internal capture was neither land-use mix nor density, but the size of the community itself. The two communities with the highest internal capture rates, Wellington and Weston, also are the largest, each having more than 30,000 residents and 5,000 jobs. Indeed, these two communities are large enough to have incorporated as their own small cities. The second most important variable was regional accessibility, which was inversely related to internal capture rates. Both of these communities are on the western edge of development in Southeast Florida, far from other population centers.

Owing to size and inaccessibility, these communities capture a much higher percentage of trips internally than, for example, the higher density and better-mixed Miami Lakes. However, Miami

Lakes doubtless generates shorter auto trips and many more walk, bicycle, and transit trips than the other two. Its overall impact on the regional road network is almost certainly less.

The validity and reliability of Ewing et al.'s results are limited by the small sample, limited geography coverage, and small number of built environmental variables. The present study improves on the earlier study by, in this order: (1) pooling travel and built environmental data for 239 MXDs in six diverse regions; (2) consistently defining travel outcomes and built environmental variables for these MXDs and regions; (3) estimating models of internal capture, external walk and transit choice, and external private vehicle trip length using hierarchical modeling methods; and (4) validating the results through comparison to traffic counts at an independent set of mixed-use sites in various parts of the United States.

Conceptual Framework

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. Additional Ds have been labeled since then: destination accessibility, distance to transit, and demographics (Ewing and Cervero 2001, 2010). An additional D variable is relevant to this analysis: development scale.

The theory of rational consumer choice underlies this study. It is well articulated elsewhere (for example, Crane 1996; Boarnet and Crane 2001; Cervero 2002; Zhang 2004; Cao et al. 2009). Travel to/from MXDs is conceived as a series of choices that depend on the D variables (see conceptual framework in Fig. 1). The choices relate directly to the methodology this paper is 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% deductions 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. For external trips, a traveler may choose to walk or not. Likewise, the traveler may choose to use transit or not. Walking and transit use may be treated as 100% deductions from ITE trip generation rates, or may be treated as partial offsets. It is reasonable to assume that transit trips substitute for automobile trips, but walk trips may supplement or substitute for automobile trips. The study team plans to propose substitution rates based on a review of literature.

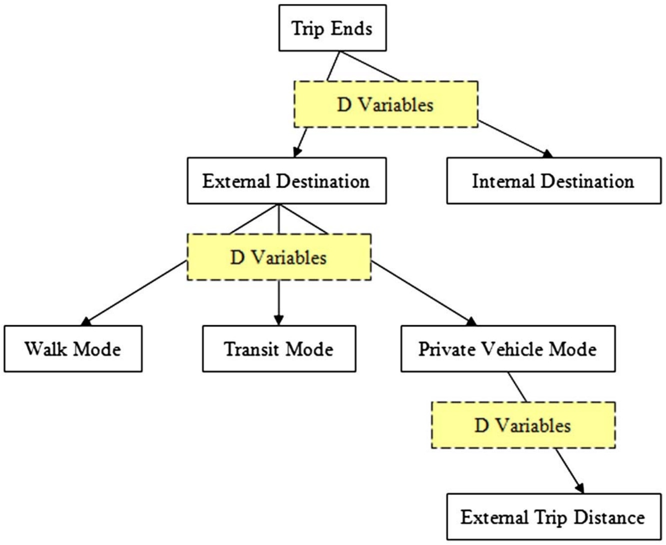

Fig. 1. Traffic impact adjustments

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

Sample Selection

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

1. Regional household travel surveys with XY coordinates for trip ends, so we could distinguish trips to, from, and within small MXDs; and
2. 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. Although 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, although 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 experience of planning researchers who had worked with these data sets.

All six travel databases were derived from large-scale household travel diary surveys. All allowed the writers 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. Although the specific variables differed somewhat from database to database, it was possible to reconcile differences and specify equivalent models. Also, although the years of the surveys differed, it was possible to control for these and other fixed effects at the regional level in a three-level hierarchical model.

Identifying MXDs

The ITE definition of multiuse 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 localities were queried about MXDs within their boundaries. Using this approach, a definition of an MXD was read to local planners over the phone, and they were asked to name, identify the boundaries, and list the uses contained within such areas. In two of the six regions, local traffic engineers and ITE members were asked to review the selected sites to confirm that they met the criteria normally applied by practitioners to identify mixed-use developments.

Final Samples

A total of 239 MXDs were identified, ranging from a low of 24 in Atlanta to a high of 59 in Boston. Site characteristics ranged from compact infill sites near the region's core to low-rise freeway oriented developments. The 239 survey sites varied in population and employment densities, mix of jobs and housing, presence or absence of transit, and location within the region. The sites ranged in size from less than five acres to over 2,000 acres, and over 15,000 residents and employees.

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.

RiverPlace, a classic MXD just south of downtown Portland, is one of the 239 MXDs in our sample (Fig. 2). Its internal capture rate is a surprisingly high 36%. Of the external trips, 14% are made by walking and 9% by transit. Its external auto trips average 7.7 miles. According to the National Household Travel Survey of 2009, 14% of Portland's trips are by walking, and 2% are by transit. The average vehicle trip length in the Portland Consolidated Metropolitan Statistical Area is 8.9 miles. On balance, the traffic impact of RiverPlace is a fraction of the regional average.

Table 1. Sample Statistics

	Survey year	MXDs	Mean acreage per MXD	Total trip ends	Mean trip ends per MXD
Atlanta	2001	24	287	6,167	257
Boston	1991	59	175	3,578	61
Houston	1995	34	401	1,584	47
Portland	1994	53	116	6,146	116
Sacramento	2000	25	179	2,487	99
Seattle	1999	44	207	15,915	362
Total		239	211	35,877	150

Fig. 2. (Color) RiverPlace at eye level

Variables

In this study, all seven types of D variables were measured and used to predict the travel characteristics of MXDs (Tables 2 and 3). The richness of the data sets varies from region to region. Portland and Atlanta have the most complete data sets. Houston and Sacramento have the least complete data sets. Sidewalk data, for example, are only available for Atlanta and Portland. Floor area ratios are only available for Atlanta, Portland, and Seattle. Measures of job mix are only available for Atlanta, Boston, Portland, and Seattle.

To maximize the sample of MXDs, the writers decided to limit our analysis to built environmental variables available for all six regions. This also simplifies the use of the resulting models by practitioners, who may have incomplete data on their projects or their surroundings.

There is great variation in internal capture rates from MXD to MXD and region to region. Across regions, average internal capture rates vary from a low of 15.9% in Portland to a high of 31.1% for Houston (Table 4). 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. Many are standalone master-planned communities.

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. 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 an automobile, or to take transit or use an automobile. For external trips, average mode shares by walking and transit combined vary from a low of 3.3% for Sacramento to a high of 28.4% for Boston (Table 4).

Of the 35,877 trip ends generated by these MXDs, 6,378 (17.8%) involved trips within the mixed-use site, another 2,099 (5.9%) 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 trip ends generated by mixed-use developments put no strain on the external street network and should be deducted from ITE trip rates for standalone suburban developments.

Trip distances are also variable across regions. For external auto trips, average distances range from 4.6 miles for MXDs in Boston to 13.9 miles for MXDs in Houston (Table 4). Again, this reflects the size and remoteness of Houston's MXDs.

Table 5 provides comparable data for trips internal to MXDs. In four of the six regions, approximately half of the internal trips are walk trips, and auto trips are short. For these regions, it may be reasonable to ignore the contribution of internal trips to regional VMT and emissions, particularly since internal trips are only approximately 16% of all trips produced by or attracted to these MXDs. For the remaining two regions, with their large master-planned communities, the share of walk trips is low, and auto trips are relatively long. For these regions, the contribution of internal trips to regional VMT and emissions is significant. Although these trips may not contribute to area-wide congestion, they should be considered in VMT and emissions calculations.

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).
WALK	Dummy variable indicating that the travel mode on an external trip is walking (1 = walk, 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.
Explanatory variables	
	Level 1 traveler/household level
CHILD	Variable indicating that the traveler is under 16 years of age (1 = child, 0 = adult).
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 1/4 mile of a bus stop (1 = yes, 0 = no)
	Level 2 MXD explanatory variables
AREA	Gross land area of the MXD in square miles.
POP	Resident population within the MXD; prorated sum of the population for the census block groups that 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 traffic analysis zone (TAZ) level were prorated.
EMP	Employment within the MXD; weighted sum of the employment within the MXD for all Standard Industrial Classification (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.
ACTDEN	Activity density per square mile within the MXD. Sum of population and employment within the MXD, divided by gross land area.
DEVLAND	Proportion of developed land within the MXD.
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.[a]
LANDMIX	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. For Portland, the land uses were: residential, commercial, industrial, and public or semipublic.[b] For other regions, the categories were slightly different.[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.
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.
EMPMILE	Total employment outside the MXD within one mile of the boundary. 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).
EMP30T	Share of total regional employment accessible within 30-min travel time of the MXD using transit.
EMP10A, EMP20A, EMP30A	Share of total regional employment accessible within 10, 20, and 30-min travel time of the MXD using an automobile at midday.
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.
	Level 3 regional explanatory variables
REGPOP	Population within the region.
REGEMP	Employment within the region.
REGACT	Activity within the region (population + employment).
SPRAWL	Measure of regional sprawl developed by Ewing et al. (2002, 2003). Index derived by extracting the common variance from multiple measures through principal components analysis.

[a] 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.

[b] 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.

[c] 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.

Table 3. Sample Sizes and Descriptive Statistics for Levels 1 and 2 Variables

	N	Mean	SD
INTERNAL	35,877	0.18	0.38
WALK	29,499	0.07	0.26
TRANSIT	29,499	0.07	0.25
TDIST	23,921	6.48	7.79
CHILD	35,877	0.10	0.30
HHSIZE	35,877	2.66	1.32
VEHCAP	35,877	0.80	0.47
BUSSTOP	35,877	0.43	0.50
AREA	239	0.33	0.32
POP	239	2,271	3,261
EMP	239	2,696	5,572
ACTIVITY	239	4,967	6,945
ACTDEN	239	19,780	30,669
DEVLAND	239	0.83	0.22
JOBPOP	239	0.46	0.31
LANDMIX	239	0.52	0.20
STRDEN	239	25.4	10.5
INTDEN	239	257	203
EMPMILE	239	30,510	50,914
EMP30T	239	0.058	0.095
EMP10A	239	0.048	0.073
EMP20A	239	0.185	0.230
EMP30A	239	0.336	0.391
STOPDEN	239	70.8	83.6
RAILSTOP	239	0.08	0.28

Table 4. Average Internal Capture Rates, Walk and Transit Mode Shares for External Trips, and Auto Trip Distances for External Trips to/from MXDs

Region	Internal capture (percentage of all trips)	Mode share percentages for external trips: Walk share	Transit share	Sum of walk and transit	Auto distance for external trips (miles)
Atlanta	16.7%	5.0%	3.1%	8.1%	6.3
Boston	16.9%	20.6%	7.8%	28.4%	4.6
Houston	31.1%	3.1%	6.1%	9.3%	13.9
Portland	15.9%	7.3%	4.6%	11.9%	4.8
Sacramento	16.4%	2.9%	0.4%	3.3%	6.8
Seattle	18.0%	5.8%	9.9%	15.7%	6.9
Overall	17.8%	7.1%	6.8%	13.9%	6.5

Table 5. Walk and Transit Mode Shares and Auto Trip Distances for Trips Internal to MXDs

	Walk share of internal trips	Transit share of internal trips	Sum of walk and transit internal trips	Auto distance of internal trips (miles)
Atlanta	53.7%	0.8%	54.5%	0.45
Boston	54.3%	1.0%	55.3%	0.51
Houston	15.0%	4.5%	19.5%	3.29
Portland	43.4%	0.8%	44.2%	0.57
Sacramento	7.4%	0%	7.4%	0.64
Seattle	57.1%	1.1%	58.2%	0.36
Overall	47.7%	1.2%	48.9%	0.81

Models

As indicated, four outcomes are modeled in this study: choice of internal destination, choice of walking on external trips, choice of transit on external trips, and distance of external trips by private vehicle. Models apply to both trips produced by and trips attracted to MXDs. Models are estimated separately by trip purpose: home-based work, home-based other, and non-home-based. The writers presume that different factors might be at play, or that the same factors might be more or less important when people travel for different purposes. Modeling by trip purpose also gives us some ability to distinguish peak hour travel (disproportionately home-based work) from off-peak travel (disproportionately home-based other and non-home-based).

The writers took an exploratory approach in modeling factors that could explain outcome variables, seeking to include at least one variable from each of the six Ds. To keep the results parsimonious and avoid possible multicollinearity problems, the threshold for inclusion of variables in models was a significance level of 0.10. A majority of variables included in our models have much higher significance levels than this threshold value.

For internal capture, our dependent variable is the natural log of the odds of an individual making a trip with both ends within an MXD. For external walk and transit trips, the dependent variable is the natural log of the odds of an individual making a trip by these modes. For external private vehicle trips, the dependent variable is the distance from origin to destination in miles.

For these outcomes, models have been estimated with both linear and logarithmic (natural log) values of the independent variables. The logarithmic models, which express the odds as a power function of the independent variables, outperform the linear models in terms of their pseudo-R^2s, sensitivity to changes in values of independent variables, and validation results (described in the following). Thus, only the logarithmic models are presented in this article. Coefficient values are arc elasticities of odds with respect to the independent variables.

For estimating the trip distance by automobile, models took three forms: linear, semilogarithmic (linear-log), and log-log forms. The semilogarithmic models, which express trip distance as a linear sum of logged variables, outperform the other models in terms of their pseudo-R^2s and sensitivity to changes in values of independent variables. Only the semilogarithmic models are presented in this article.

This study's data and model structure are hierarchical. Thus, hierarchical modeling is the best methodology to account for dependence among observations, in this case the dependence of trips to and from a given MXD and dependence of MXDs within a given region. 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 (multilevel) modeling overcomes these limitations, accounting for the dependence among observations and producing more accurate coefficient and standard error estimates (Raudenbush and Bryk 2002).

The writers 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 data set, 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.

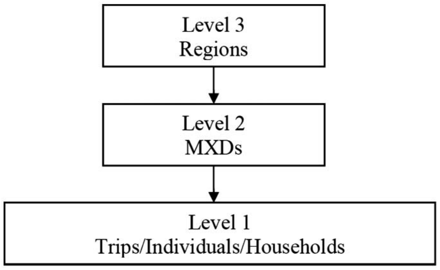

Fig. 3. Data and model structure

This has implications for modeling methodology. Rather than a five-level hierarchy, the choices facing travelers have been modeled in a three-level framework. Individual trip ends are uniquely identified with MXDs. Therefore, 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 (Fig. 3). Within a hierarchical model, each level in the data structure is formally represented by its own submodel. The submodels are statistically linked.

Models were estimated with hierarchical linear and nonlinear modeling (HLM) 6 software. Hierarchical linear models were estimated for the continuous outcome (trip distance), and hierarchical nonlinear models were estimated for the dichotomous outcomes (internal versus external, walk versus other, and transit versus other). Hierarchical linear modeling is analogous to linear regression analysis, although models are estimated by using maximum likelihood estimation rather than OLS. Hierarchical nonlinear modeling is analogous to logistic regression. Like logistic regression, hierarchical nonlinear modeling uses maximum likelihood estimation.

In the 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 (Raudenbush and Bryk 2002). As the sample of MXDs expanded, we also tested for cross-level variable interactions with random coefficient models. It is certainly possible that the relationship between, for example, walking and vehicle availability varies with size of the MXD, or the relationship between internal capture and MXD density varies from region to region. As the cross-level interaction terms seldom proved significant, only the random intercept models are presented in the following section.

Results

Internal Capture

For internal capture of trips, coefficients and their significance levels (*p*-values) are shown in Table 6. The coefficients are elasticities of the odds of internal capture with respect to the various independent variables, that is, measures of effect size. In the case of home-based work trips, the odds of an internal trip decline with household size and vehicle ownership per capita, and increase with an MXD's job-population balance. Internal capture is thus related to two D variables, diversity and demographics. Larger households have more complex activity patterns that are more likely to take them beyond the bounds of an MXD. Households with higher vehicle ownership have fewer constraints on the use of household vehicles for long trips. A high job-population balance value translates into more opportunities to live and work on-site. The pseudo-R^2 of this model is quite low, at 0.01, indicating a considerable amount of unexplained influence on the odds of a home-based work trip being internally captured.

For home-based other trips, the odds of internal capture decline with household size and vehicle ownership per capita and increase with an MXD's land area, job-population balance, and intersection density. Internal capture for trips from home to nonwork destinations is thus related to development scale, diversity, design, and demographics. Relationships to household size and vehicle ownership are as explained previously. As for the other significant variables, job-population balance spawns on-site travel because jobs include those in the retail sector, suggesting the presence of shops and restaurants encourages some residents to substitute walk trips for out-of-neighborhood car trips. Also, a large land area increases the likelihood that nonwork destinations will be on-site while high intersection density increases routing options, makes routes more direct, creates frequent street crossing opportunities, and makes trips seem more eventful. Among the built environment variables analyzed, the most statistically significant predictor of internal capture for home-based other trips is job-population balance followed by an MXD's land area and then by its intersection density. The pseudo-R^2 of this model is a more respectable 0.20, but still indicates that there is a considerable amount of unexplained influence on the odds of a trip being internally captured

For non-home-based trips, the odds of internal capture decline with household size and vehicle ownership, and increase with land area, employment, and intersection density of the MXD. Internal capture is thus related to design, development scale, and demographics. Relationships to land area and intersection density were explained previously. The relationship to employment is likely attributable to the greater likelihood of matching employees'

Table 6. Log Odds of Internal Capture (Log-Log Form)

	Home-based work			Home-based other			Non-home-based		
	Coefficient	*t*-ratio	*p*-value	Coefficient	*t*-ratio	*p*-value	Coefficient	*t*-ratio	*p*-value
Constant	1.75			2.43			5.32		
EMP	—	—	—	—	—	—	0.208	3.28	0.002
AREA	—	—	—	0.486	3.61	0.001	0.468	4.58	< 0.001
JOBPOP	0.389	2.62	0.010	0.399	4.55	< 0.001	—	—	—
INTDEN	—	—	—	0.385	1.92	0.055	0.638	4.95	< 0.001
HHSIZE	1.33	6.03	< 0.001	0.867	13.0	< 0.001	0.237	4.54	< 0.001
VEHCAP	0.990	4.15	< 0.001	0.590	8.19	< 0.001	0.163	3.00	0.003
Pseudo-R^2		0.01			0.20			0.30	

desired trips to on-site destinations when there are more attractions nearby. The most statistically significant relationship is to intersection density, followed by land area, and then by employment. The pseudo-R^2 of this model is highest of the three trip purposes, 0.30.

Although there is significant variance of internal capture from region to region, it is not explained by the variables in our data set. None of the Level 3 variables proved significant. This is not too surprising, given the small sample (six) of Level 3 units. Nonetheless, regional variance is captured in the random effects term of the Level 3 equation, just not explained by any of the regional variables.

Mode Choice for External Trips

Table 7 shows the coefficients and significance levels (*p*-values) of estimated models for predicting walk mode choice on external trips. The coefficients are elasticities of the odds of walking with respect to the various independent variables, that is, measures of effect size. For external home-based work trips, the odds of walking decline with household size and vehicle ownership per capita, and increase with job-population balance within the MXD and number of jobs outside the MXD within a mile of the boundaries. Walking on external trips is thus related to three types of D variables: diversity, destination accessibility, and demographics. Large households achieve economies through car pooling and trip chaining, and thus are less likely to walk. Households with more cars have a lower generalized cost of auto use, making them less likely to walk. Reasons for the positive association between internal job-population balance and walking for external work trips are less obvious. One possibility is that on-site balance creates opportunities for trip chaining. Another possibility is that on-site balance is associated with off-site, nearby balance as well, thus further inducing walk commutes. This is buttressed by the fact that the coefficient of EMPMILE is positive, indicating that when off-site job opportunities are nearby, MXD residents will walk to work. The pseudo-R^2 of this model is 0.19.

For external home-based other trips, the odds of walking decline with household size and vehicle ownership per capita, decline with the land area of the MXD, and increase with the activity density of the MXD, the job-population balance within the MXD, and number of jobs outside the MXD within a mile of the boundaries. Walking on external trips is thus related to measures of development scale, density, diversity, destination accessibility, and demographics. The larger the area of the MXD, the longer the external trips and the less likely they will be made by walking. The higher the activity density, the better the pedestrian environment and the more accessible attractions will be to those traveling into the community. Relationships to job-population balance and employment within a mile have already been discussed. The pseudo-R^2 of this model is a high 0.51.

For external non-home-based trips, the odds of walking decline with household size and vehicle ownership per capita, and increase with the activity density of the MXD, the intersection density of the MXD, and the number of jobs outside the MXD within a mile of the boundaries. Walking on external trips is thus related to measures of density, design, destination accessibility, and demographics. High intersection density within the MXD makes walking to/from activities outside the MXD that much more direct. The other independent variables have already been discussed. The pseudo-R^2 of this model is a very high 0.64. Overall, the external walk models have the greatest explanatory power of all models estimated.

Table 8 shows the coefficients and significance levels (*p*-values) of estimated models for predicting transit mode choice on external trips. For external home-based work trips, the odds of transit use decline with household size and vehicle ownership per capita, and

Table 7. Log Odds of Walking on External Trips (Log-Log Form)

	Home-based work			Home-based other			Non-home-based		
	Coefficient	*t*-ratio	*p*-value	Coefficient	*t*-ratio	*p*-value	Coefficient	*t*-ratio	*p*-value
Constant	5.55			10.96			15.09		
AREA				0.415	4.27	< 0.001			
ACTDEN				0.370	2.74	0.007	0.377	3.12	0.003
JOBPOP	0.226	2.46	0.015	0.219	3.83	< 0.001			
INTDEN							0.803	5.05	< 0.001
EMPMILE	0.385	3.12	0.002	0.450	5.05	< 0.001	0.440	5.09	< 0.001
HHSIZE	1.57	6.29	< 0.001	0.486	5.05	< 0.001	0.281	2.59	0.010
VEHCAP	1.84	7.00	< 0.001	0.768	7.62	< 0.001	0.242	2.13	0.033
Pseudo-R^2		0.19			0.51			0.64	

Table 8. Log Odds of Using Transit on External Trips (Log-Log Form)

	Home-based work			Home-based other			Non-home-based		
	Coefficient	*t*-ratio	*p*-value	Coefficient	*t*-ratio	*p*-value	Coefficient	*t*-ratio	*p*-value
Constant	8.05			6.08			2.69		
ACTDEN				0.324	2.89	0.005			
INTDEN	1.12	4.44	< 0.001						
EMP30T	0.209	2.98	0.004				0.134	3.29	0.002
HHSIZE	1.14	6.31	< 0.001	0.958	8.48	< 0.001			
VEHCAP	1.68	8.56	< 0.001	1.09	8.91	< 0.001	0.340	3.74	< 0.001
BUSSTOP	0.357	2.08	0.037	0.467	4.04	< 0.001			
Pseudo-R^2		0.47			NA			NA	

increase with the intersection density of the MXD and the number of jobs within a 30-min trip by transit. The odds of transit use are significantly higher for households living within 1/4 mile of a bus stop than those farther away. Transit use on external trips is thus related to measures of design, destination accessibility, distance to transit, and demographics. A higher intersection density translates into a more direct walk trips to and from transit stops, and also possibly more efficient routing of transit vehicles. More jobs within 30 min by transit increase the likelihood a particular job being within easy commuting distance for residents. Residence within the standard quarter mile walking distance of a bus stop shortens access trips. The pseudo-R^2 of this model is 0.48.

For external home-based other trips, the odds of transit use decline with household size and vehicle ownership per capita and increase with the activity density within the MXD. The odds are significantly higher for households living within 1/4 mile of a bus stop than those further away. The higher the activity density, the better the pedestrian environment and the more accessible attractions will be to those traveling into the community. The other independent variables have already been discussed. This is a weak model. The pseudo-R^2 of this model is a negative number because the combined variance at Levels 1 through 3 is greater for the estimated model than the null model with only an intercept and no explanatory variables.

For external non-home-based trips, the odds of transit use decline with household size and vehicle ownership per capita, and increase with the number of jobs within a 30 min trip by transit. These independent variables have already been discussed. The pseudo-R^2 of this model also is a negative number.

Regarding these negative pseudo-R^2s, a pseudo-R^2 is not entirely analogous to R^2 in linear regression, which can only assume positive values. One standard text on multilevel modeling notes that the variance can increase when variables are added to the null model. It goes on to say: "This is counterintuitive, because we have learned to expect that adding a variable will decrease the error variance, or at least keep it at its current level… In general, we suggest not setting too much store by the calculation of [pseudo-R2s]" (Kreft and de Leeuw 1998). For more discussion of negative pseudo-R^2s, also see Snijders and Bosker (1999).

Activity density has the expected positive sign in all three regressions. It reaches statistical significance in only one regression. This is consistent with a finding from a recent meta-analysis of the built environment-travel literature that density is the least important of the D variables (Ewing and Cervero 2010). Having a rail stop within a development also has a positive sign in all three regressions but never reaches statistical significance.

Although there is significant variance of walking and transit use from region to region, it is not explained by the variables in our data set. Again, none of the Level 3 variables proved significant. Regional variance is, however, captured in the random effects term of the Level 3 equation.

Trip Distance for External Automobile Trips

Table 9 shows the coefficients and significance levels (p-values) of estimated models for predicting auto trip distances on external trips. For external home-based work trips by private vehicle, trip distance increases with household size, vehicle ownership per capita, and land area of the MXD, and declines with a project's job-population balance and the share of regional jobs reachable within 30 min by automobile. External trip length is thus related to four types of D variables, development scale, diversity, destination accessibility, and demographics. Larger MXDs produce and attract longer external trips simply because the shortest trips are internalized. MXDs with good job-population balance apparently reduce the need for very long external trips; e.g., on-site residents patronizing on-site retail outlets. They may also facilitate trip chaining. MXDs with good auto accessibility to regional jobs generate shorter trips because more trip attractions are nearby. On the other hand, larger households have more complex activity patterns, which lengthen trips. More vehicles per household frees up family cars for trips to more distant destinations. These relationships match expectations. The pseudo-R^2 is 0.11.

For external home-based other trips, trip distance increases with household size and vehicle ownership per capita, and declines with the job-population balance within the MXD and the share of regional jobs reachable within 20 min by automobile. External trip length is thus related to measures of diversity, destination accessibility, and demographics. Relationships to job-population balance, accessibility to regional employment, household size, and vehicle ownership follow the same explanations provided above. The destination accessibility measure with the greatest explanatory power is the number of jobs reachable within 20 min by automobile, not 30 min as with home-based work trips. This makes sense, because home-based other trips are shorter than home-based work trips. The pseudo-R^2 of this model is 0.03.

For external non-home-based trips, trip distance increases with household size and vehicle ownership per capita, and declines with the job-population balance within the MXD, intersection density within the MXD, and the share of regional jobs reachable within 20 min by automobile. External trip length is thus related to measures of diversity, design, destination accessibility, and demographics. As for the one new variable, higher intersection density within an MXD (and perhaps its surroundings as well) makes for

Table 9. Trip Distance for External Automobile Trips (Semilog Form)

	Home-based work			Home-based other			Non-home-based		
	Coefficient	t-ratio	p-value	Coefficient	t-ratio	p-value	Coefficient	t-ratio	p-value
Constant	6.54			4.33			8.99		
AREA	1.07	2.92	0.004						
JOBPOP	0.298	1.88	0.061	0.356	2.38	0.018	0.282	2.05	0.041
INTDEN							0.832	2.06	0.041
EMP20A				0.697	4.79	< 0.001	0.823	5.69	< 0.001
EMP30A	1.19	6.05	< 0.001						
HHSIZE	2.76	8.08	< 0.001	0.772	5.06	< 0.001	0.520	2.58	0.010
VEHCAP	2.76	7.26	< 0.001	1.48	9.22	< 0.001	1.06	5.12	< 0.001
Pseudo-R^2		0.11			0.03			0.05	

more direct connections to external trip attractions. The pseudo-R^2 of this model is 0.05.

The VMT calculations made possible with the models presented in Tables 6–9 represent only the mileage generated by travel external to the development site. For large MXDs where internal vehicle travel is likely, users of the MXD method are advised to perform an independent estimate of internal vehicle trip generation and VMT. In these cases, internal and external VMT should be combined for complete estimates of impacts such as fuel consumption, greenhouse gases, and other emissions.

Model Validation

For this method to gain credibility, it is important that the results be validated by comparing estimates to in-field traffic counts. The preceding models were applied to 22 MXDs for which traffic counts of external vehicle trips were available. Six of those 22 sites are located in South Florida. Their traffic counts are presented in Appendix C of the *Trip Generation Handbook* (2004). Four additional sites are located in Central Florida, Atlanta, and Texas, of which three are nationally known examples of smart growth or transit-oriented development: Celebration Florida, Atlantic Station, and Mockingbird Station. Six sites are located in San Diego County and were designated by local planners and traffic engineers in 2009 as representing a wide range of examples of smart growth trip generators. The six remaining sites are conventional development projects located elsewhere in California. The sites represent a wide range of densities, land-use mixes, and development scales. Populations of the validation MXDs range from zero (Crocker Center in Boca Raton, FL and Hazard Center in San Diego, containing a mix of commercial and office uses only) to nearly 17,000 (the entire town of Moraga, CA). Employment levels range from near-zero (The Villages in Irvine, CA, which is predominantly residential, with only a small amount of restaurant and service retail) to more than 5,500 (Park Place, also in Irvine, CA). Some sites are well served by transit, including three built around rail stations, whereas others are suburban and poorly served by transit. With such a diverse validation sample, one can begin to build confidence that these MXD models have external validity.

Data were collected for all model variables at each of the 22 sites. The variables EMPMILE and EMP30T were estimated from regional travel models for the MXD traffic analysis zones and visually verified from aerials, and in some cases, from websites of the MXDs. For those sites for which household data were not available, the household size and vehicle ownership variables for trips produced and attracted to the MXD were taken from 2000 census data for the census tracts most closely matching the locations of the MXDs.

The probabilities estimated with these models and the resulting predicted external vehicle traffic counts are shown in Table 10. The results demonstrate that the models are capable of predicting a wide range of internal capture rates and mode shares for external trips, taking into account development scale, site design, and regional context. The models predict total vehicle counts within 20% of the actual number of trips observed for 15 of the 22 validation sites, within 30% for four sites, and within 40% for another one. Only two sites were off by more than 40%. When compared with the best available published methods for estimating trip generation, the models improved the prediction of vehicle counts at 16 of the 22 validation sites.

Table 11 compares model performance to current methods, specifically:

1. ITE *Trip Generation* or *SANDAG Traffic Generators* (2004) without any adjustments (Gross trips); and
2. Current internalization methods from the ITE *Trip Generation Handbook* or from SANDAG's current method of deducting 5% for mixed-use and 10% for proximity to transit (Net trips)

Table 10. Predicted Probabilities from Application of the Model to Validation Sites

Site name and location	Internal capture rate	External walk mode share	External transit mode share	Predicted external vehicle counts	Observed external vehicle counts
Atlantic Station, Atlanta, GA	11%	7%	4%	31,377	28,787
Boca Del Mar, Boca Raton, FL	10%	3%	2%	20,890	22,846
Town of Celebration, Celebration, FL	26%	2%	0%	35,775	40,912
Country Isles, Weston, FL	9%	0%	0%	14,891	22,419
Crocker Center, Boca Raton, FL	3%	4%	3%	17,077	9,791
Galleria, Ft. Lauderdale, FL	9%	3%	3%	29,505	22,971
Gateway Oaks, Sacramento, CA	11%	4%	3%	16,320	23,280
Jamboree Center, Irvine, CA	9%	5%	4%	36,039	36,569
Legacy Town Center, Plano, TX	14%	12%	4%	24,903	20,082
Mizner Park, Boca Raton, FL	8%	9%	5%	11,559	12,086
Mockingbird Station, Dallas, TX	6%	19%	6%	11,153	20,677
Town of Moraga, Moraga, CA	28%	1%	1%	55,816	49,689
Park Place, Irvine, CA	7%	7%	4%	17,417	19,064
South Davis, Davis, CA	25%	2%	2%	66,752	74,648
The Villages, Irvine, CA	2%	7%	4%	7,680	7,128
Village Commons, West Palm Beach, FL	6%	4%	0%	22,793	18,075
Rio Vista, San Diego, CA	4%	15%	7%	5,024	5,307
Village Plaza, La Mesa, CA	7%	17%	8%	3,920	4,280
Uptown Center, San Diego, CA	6%	17%	6%	14,734	16,886
Morena Linda Vista, San Diego, CA	6%	16%	7%	4,132	4,712
Hazard Center, San Diego, CA	5%	10%	8%	11,685	11,644
Otay Ranch, Chula Vista, CA	5%	3%	4%	9,279	7,935

Table 11. Comparison of Percent Differences between Predicted and Observed External Vehicle Counts by Gross, Net, and MXD Modeling Methods

Site name and location	Gross trips[a]	Net trips[b]	MXD method
Atlantic Station, Atlanta, GA	37%	25%	9%
Boca Del Mar, Boca Raton, FL	7%	4%	9%
Town of Celebration, Celebration, FL	21%	17%	13%
Country Isles, Weston, FL	27%	38%	34%
Crocker Center, Boca Raton, FL	94%	82%	74%
Galleria, Ft. Lauderdale, FL	50%	35%	28%
Gateway Oaks, Sacramento, CA	15%	19%	30%
Jamboree Center, Irvine, CA	20%	8%	1%
Legacy Town Center, Plano, TX	74%	50%	24%
Mizner Park, Boca Raton, FL	20%	20%	4%
Mockingbird Station, Dallas, TX	24%	26%	46%
Town of Moraga, Moraga, CA	59%	49%	12%
Park Place, Irvine, CA	10%	4%	9%
South Davis, Davis, CA	24%	3%	11%
The Villages, Irvine, CA	22%	17%	8%
Village Commons, West Palm Beach, FL	40%	31%	26%
Rio Vista, San Diego, CA	26%	8%	5%
Village Plaza, La Mesa, CA	33%	13%	8%
Uptown Center, San Diego, CA	20%	8%	13%
Morena Linda Vista, San Diego, CA	35%	16%	12%
Hazard Center, San Diego, CA	29%	11%	0%
Otay Ranch, Chula Vista, CA	32%	19%	17%
RMSE	44%	32%	22%
R^2	0.65	0.81	0.92

[a] Gross trips estimates are computed from the trip generation rates contained in the ITE *Trip Generation* report (sites 1–16) or the *SANDAG Traffic Generators* report (sites 17–22) for each of the individual land uses within the mixed-use site, without discounting for internalization, walking or transit use.

[b] Net trips estimates apply internalization reductions for multiuse sites as prescribed in the ITE *Trip Generation Handbook* (sites 1–16) or the *SANDAG Traffic Generators* report (sites 17–22) and represent the best estimates that one could obtain relying on currently published material alone.

Percentages reported in Table 11 indicate errors in trip estimates using gross, net, and MXD modeling methods, respectively, for each testing site. The percent root mean squared error (%RMSE), used in the transportation field to evaluate model accuracy, penalizes proportionally more for large errors and normalizes the error across different values of the quantity one is trying predict. A % RMSE of less than 40% is generally considered good. Table 11 shows that the proposed models improve the %RMSE over the gross and net methods. The MXD models improve the %RMSE from 32%, produced by the best of the previously available trip generation estimation methods, to a figure of 22%.

R^2 in this table measures the squared difference between the observed and predicted external vehicle counts as a percentage of the squared variation of the observed external vehicle counts about the mean over the 22 sites. Table 11 shows that the proposed models also improve the R^2 significantly compared to the gross and net methods. The R^2 for the MXD model is 0.92, markedly better than the 0.81 value for the net method, the best estimates that one could obtain relying on previously published material alone.

Finally, Figs. 4 and 5 show the strong association between predicted and observed external vehicle counts using the models developed herein, and a comparison of daily observed external vehicle counts across the three methods.

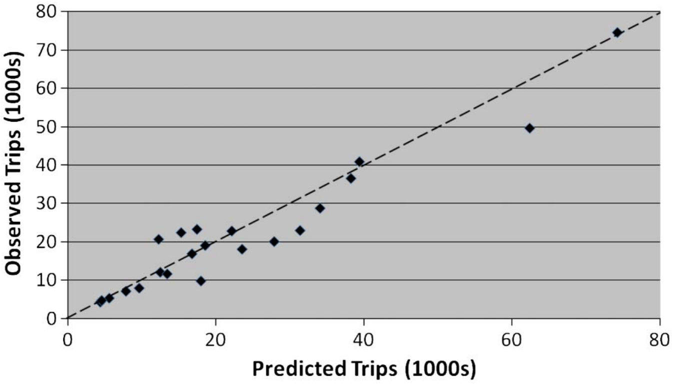

Fig. 4. Scatterplot of predicted versus observed external vehicle counts

Applications

The previously derived models can be used to predict trip productions plus attractions for three separate trip purposes. Having the models for three trip purposes allows the practitioner to predict external private vehicle trips on either a daily basis or a morning or afternoon peak hour basis. The likelihood that a trip during any of these times of day is home-based-work or home-based-other or non-home-based is determined based on purpose-specific trip generation rates in NCHRP Report 365, *Travel Estimation Techniques for Urban Planning* (1998). The log odds estimates of internal capture or walk or transit, as obtained from Tables 6–8, are first exponentiated, then converted into probabilities using the formula: $\text{probability} = \text{odds}/(1 + \text{odds})$. They are then applied to each estimate of total trips generated for the three trip purposes. The remaining trips are combined across all three trip purposes to get total net external private vehicle trips.

The models are applied in sequential fashion for each trip purpose. The probability of trips for a given trip purpose traveling external to the site is computed first, using the equations in Table 6. These resulting probabilities are used to discount the total site trip generation as estimated by the trip rates contained in the ITE *Trip Generation* report. The resulting external trips are then further reduced to account for those external trips that would probabilistically travel by walking or transit, using the equations provided in Tables 7 and 8. The three trip purposes are then combined. This leaves the estimate of external vehicle trips, or in ITE terms, site traffic generation. For those who want to compute the VMT generated by the site, one would apply the Table 9 equations to compute the average external trip lengths, and for large sites, would add an estimate of VMT generated by trips remaining entirely within the site.

Most of the information required to apply these equations is readily available from project site plans and programmatic data developed as part of a project planning process or submitted as part of a development application. Certain data items may require the traffic engineer to obtain information via GIS mapping of the site area or a request to the jurisdiction or metropolitan planning organization for information easily extracted from the regional travel model. These data, when incorporated into equations that estimate MXD internal capture and walking and transit use, produce trip generation reductions to be applied to estimates based on the ITE *Trip Generation* report.

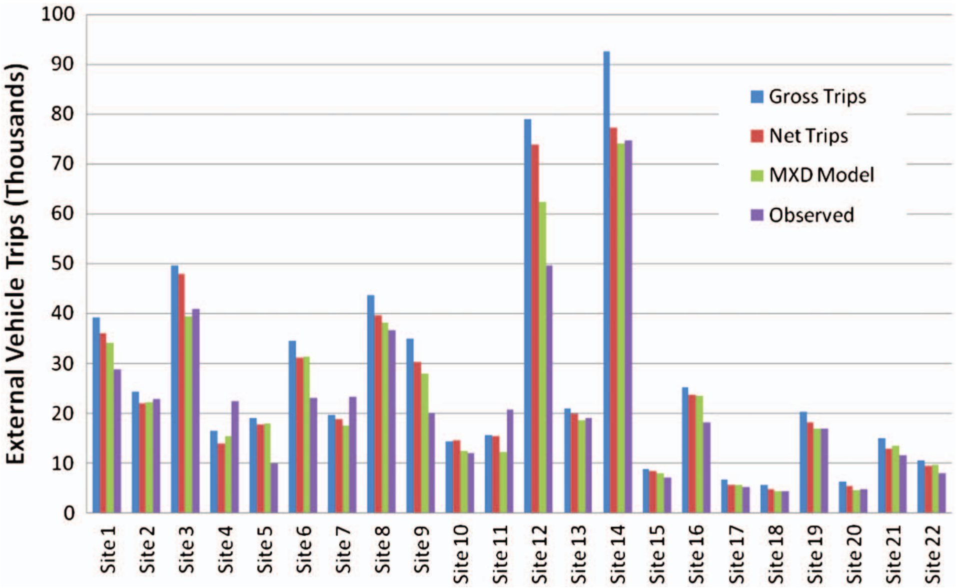

Fig. 5. (Color) Comparison of external vehicle trips across methods

As is the case with many of the guidelines presented in *Trip Generation*, expert judgment is advised on case-by-case basis. This might be necessary if, for example, in the judgment of a qualified traffic engineer or planner, the development proposal under study is unique in its relative composition of restaurant, theater, or other commercial uses.

Conclusion

The bibles of traffic impact analysis, the Institute of Transportation Engineers' *Trip Generation* report (2008) and *Trip Generation Handbook* (2004), are sorely lacking when it comes to MXDs. Except for a handful of master-planned projects in Florida, actual studies of internal capture rates are few and far between. Traffic engineers are thus largely left to their own devices when quantifying the trip reductions that might result from mixing land uses. Therefore, to err on the conservative side and avoid possible liability charges from underdesigning road capacity, often no adjustment is made at all. This results in overestimates of the traffic impacts of MXD proposals, leading to higher development fees than necessary and raising opposition among those who fear potential adverse impacts. Failure to account for internal capture and external walk and transit trips ends up penalizing MXDs and can force MXD developers to, in effect, cross-subsidize single-use projects through disproportionate exactions. In addition, lack of accounting for the trip-reducing benefits of MXDs can result in an oversupply of parking.

This research sought to advance the state of knowledge on the relationships that govern travel to, from, and within mixed-use development projects and to enumerate tangible and verifiable traffic reductions relative to the rates in the ITE *Trip Generation* report. Travel research published over the last few years convincingly shows that changes by several percentage points in any or several of the D variables used in this study reduces the number of vehicle trips and vehicle miles traveled (Ewing and Cervero 2001, 2010). This study extends and focuses that research on the particular characteristics of MXDs. It represents the first national study of the traffic generation by mixed-use developments, making use of household travel survey data from six metropolitan regions. The writers found that an average of three out of 10 trips generated by MXDs put no strain on the external street network and generate relatively few vehicle miles traveled. Statistical equations derived from the data reveal that the primary factors affecting this reduction in automobile travel are:

1. The total and the relative amounts of population and employment on the site;
2. The site size and activity density;
3. The size of households and their auto ownership;
4. The amount of employment within walking distance of the site;
5. The block size on the site; and
6. The access to employment within a 30 min transit ride of the site.

For traffic impact, greenhouse gas, and energy analyses, the VMT generated by a mixed-use site depends, in addition to the previously described factors, on the site's placement within the region, specifically, on the share of jobs located within a 20- to 30-min 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 within mixed-use developments, and conversion of some external trips from auto to alternate modes.

This study's findings regarding the factors that influence mixed-use trip generation have been validated through field surveys at illustrative sites in California, Florida, Georgia, and Texas. The results will help guide planners and developers of mixed-use projects on design features likely to minimize traffic generation, greenhouse gas emissions, and energy impacts, and will produce new analysis techniques for traffic engineers to more realistically quantify infrastructure impacts of mixed-use development proposals.

There are five caveats for practitioners. First, although MXDs offer the option of walking, not all internally captured trips are walk trips. This study focuses on MXD effects on external trip generation. Microscale built environmental features and their influence on short-distance driving and nonmotorized trip-making in MXDs warrant further investigation.

Second, when applying these models, internal capture rates computed with the formulas are presumptive rates. They still need to be adjusted to balance productions and attractions within the site, as with the ITE *Trip Generation Handbook* method.

Third, owing to limitations of the hierarchical modeling software the writers used (HLM), we specified two binomial mode choice models (walk or not, transit or not) rather than one multinomial mode choice model (walk, transit, or auto). As a suggestion for future research, it might be possible to estimate a multinomial model with different software. As it is, the "not" alternative in each case ("not walking," "not transit") is quite heterogeneous, including all other alternatives. It would be more behaviorally sound (and therefore may well increase the goodness-of-fit of the models) to explicitly divide the "not" alternative into its constituent modes: a traveler probably does not usually say, "should I take transit or not?" but rather, "should I drive, walk, or take transit?"

Fourth, while acknowledging that walk trips may supplement rather than substitute for private vehicle trips, we have in our validation exercise treated walking and transit use as one-for-one, trip-for-trip substitutes for private vehicle trips. Our data set prevents us from estimating trip generation rates by mode because we have only a sample of trips to, from, and within MXDs to work with, not the full set of trip ends for nonresidential trip generators. This, in turn, forces us to estimate mode choice equations, and keeps us from drawing any inference about trip substitution. Because some of the walk trips may supplement automobile trips, our walk mode choice models represent an upper bound on actual rates of substitution.

Finally, the MXD methods presented here do not explicitly account for the effects of parking supply and price. Although several of the variables included in the analysis, such as development density and proximity to regional job centers, may be partial proxies for parking supply and price, site-specific parking data were not available and were, therefore, not included in the MXD models. If parking supply and price data were available they might significantly improve the ability to predict trip generation. It would also inform the discussion of how MXDs can reduce trip generation by pricing, supply constraint and unbundling the cost of parking from the cost of real estate.

In closing, smart growth requires smart calculations. Unless developers are rewarded for the trip-reducing impacts of MXDs, the market incentive to build projects with relatively small environmental footprints is substantially reduced. Although the technical aspects of this work might not be accessible to city planning commissioners and lay citizens, the basic premise that good development should be rewarded can be understood by all.

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