

# Incorporating Built Environment “Smart-Growth” Effects into Travel Demand Models

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## Abstract

Local details of land use density and mix, the pedestrian environment, and others, have been shown to affect mode choice and/or trip length, but these effects, commonly expressed as elasticities, apply only to aggregations of travel and can only adjust aggregate forecasts from a travel demand model post-hoc, rather than adjust trips within the model. Conventional models already account for some of these details, such as density and land-use mix, to some extent, so that post-hoc adjustments double-count some effects. Aggregate elasticities also do not specify substitutions of travel to other modes or destinations, nor do they respond to the availability or not of such alternatives. This study pursues an alternative approach of estimating incremental logit models of mode and trip length choice changes with respect to a good-practice base model, using a cross-sectional household travel survey, and local environment measures, finding statistically significant parameters for those measures. This parameter estimation investigates interactions and combinations of variables as well as additive effects, at both ends of trips. The incremental model is applied as a trip matrix adjustment stage that shifts person-trips to available alternative modes and/or local destinations, prior to assignment on the network, within a model stream that equilibrates demand, loading, and travel time.

## Introduction

“Smart Growth” analysis by “4 Ds” in large part comes from Ewing and Cervero *Travel and the Built Environment – A Synthesis* (2001, Transportation Research Record 1780), and application of its results in the US EPA’s Smart Growth INDEX planning tool. It synthesized numerous studies examining relationships between travel and built environment measures, and summarized them into elasticities of vehicle trip generation and vehicle-miles of travel with respect to numerically formulated values representing density, local land use mix, design, and regional accessibility (density, diversity, design, and destinations).

Ewing and Cervero asserted that conventional travel demand models do not respond to density, diversity, or design. So in efforts to quantify the benefits of “smart growth” development strategies, many planners have turned to post-process supplemental methods (4Ds), applying after-model adjustments to aggregations of vehicle trips (VT) and vehicle-miles traveled (VMT)

according to elasticities from Ewing and Cervero and other studies. However, post-process methods have their own limitations too:

- Elasticities apply to aggregate VMT and VT, rather than to particular actual trips in the model. While economists often use elasticities to quantify aggregate rates of effect, aggregate elasticities do not translate into any particular adjustments to auto and transit trips in the model, or their assignments, and system equilibrium. Instead, they can only adjust aggregations of VMT and VT resulting from travel models.
- Post-process methods double-count some sensitivity already in models (unless specially adjusted to compensate for local model's sensitivity). Elasticities are relative to averages, not to model responses.
- Adjustments upon aggregate auto travel (VT and VMT) assume that non-auto or closer travel alternatives are available to which people shift, enabling fewer or shorter vehicle trips. For some places, and some trips, they are not, so such shifts are not possible. For example, if a good walking environment is provided to a neighborhood, but no transit service to employment centers, then its commuters cannot shift from auto to transit.
- Modern “complete” travel models solve for system equilibrium, a state of consistency among demand, network loading, and travel times. But a post-process analysis with elasticities does not “feed back” into system equilibrium, so it cannot account for the adaptive and absorptive effects of equilibration.

However, travel models actually are partly sensitive to some smart-growth strategies:

- Density and diversity provide opportunities to satisfy travel needs with shorter vehicle trips and non-motorized travel. Trip distribution models naturally place more trips between neighboring zone pairs with productions in one and attractions in the other, and intrazonal trips into mixed zones. Conversely, in models as in the real world, persons in rural and homogenous areas must travel far to reach activities, and use auto modes for lack of alternatives.
- Some models use income and auto availability variables, which may correlate to smart-growth variables, and possible self-selection effects.
- Models with transit networks and mode choice are sensitive to transit service, although transit and mode choice modeling is often hampered by zone size.
- SACOG’s trip-based model of the Sacramento region includes an adaptation of the “pedestrian environment factor” originated in Portland, Oregon.

Travel models can and have been improved in these sensitivities. Simpler models might only have auto modes, meant for highway capacity planning. But modern “complete” models in widespread use include transit networks and mode choice, with walk and bike as one or two mode alternatives. Also, increasing computer capacity permits smaller zones for better representation of the choices for walking and transit travel.

This paper reports the beginning of an investigation to:

- Disentangle the response an existing modern complete four-step travel demand model already has to quantified land development characteristics, from response it lacks,
- Quantify this incremental response in terms of adjustments that can be made directly to the trip tables in a model, instead of aggregate elasticities,
- Run the model with these incremental effects applied to the trip tables, in full system equilibrium, and compare this model's vehicle trip loadings to those without the adjustments.

The next sections describe the method of investigation and the data and models used, the estimated models of incremental response, application within a regional model, and its results, conclusions, and directions for further research.

Other types of travel demand modeling responds to land use detail in other ways, most notably activity-based demand models. The activity based model of Sacramento (among others) applies its activity location choices to pseudo-parcels rather than just TAZs, uses measures of local street connectivity, and other details not in typical four-step models (Bowman and Bradley 2006). But many planning agencies don't have the resources to create and use their own such models, so they seek improvements to four-step models as a pragmatic alternative. This study aims to contribute to satisfying that need, although there is much more work to be done.

## **Methodology**

Two aspects of travel behavior were chosen as the focus of this investigation: mode choice, and short-distance trip distribution. These are deemed appropriate since many "smart growth" development characteristics aim to encourage pedestrian and bicycle travel instead of automobile travel, by providing opportunities for work, shopping, and other activities within a short distance of each other and home, along with connectivity and safety by non-motorized modes among nearby activities, and transit stops. Person-trip generation warrants study too, but was not investigated here.

Mode choice is commonly modeled using multinomial or nested logit models. Trip distribution commonly uses gravity models, which can also be represented as multinomial logit models. Logit models (and other *discrete choice* models) predict probabilities of each of a set of qualitative set of alternatives. Gross amounts of flow, consumption, etc. result from applying the discrete choice models to all the distinct units or quantities of demand (persons, trips, etc.), and aggregating amounts of demand x probability.

**Incremental logit** models are a variation of multinomial logit, used to adjust a base logit model's predicted probabilities due to any number of added or changed independent variables, without having to use all the independent variables of the base model. Details are in Ben-Akiva and Lerman (1985).

This study estimates and applies incremental logit models using built-environment indices as independent variables, with travel modes and destinations in the choice sets as in the base models. Incremental logit models are here examined that are structured to:

- Adjust mode shares of zone-to-zone movements.
- Adjust trip distribution between long and short distance.
- Conserve trips (inasmuch as zonal total person trips are held constant).
- Provide logically consequential effects upon auto travel choice and length. Travel shifts to non-auto modes and/or shorter trips have the consequence, within the model stream, of reducing VMT and VT. An increase in one mode has a consequential decrease in others; adjustments favoring shorter trips take away from longer trips.
- No travelers are forced onto alternatives they don't have. Where no short-distance or non-auto travel opportunity provided, no adjustment occurs. E.g. better walking environment diverts from auto to transit only those commuters who are served by transit.
- All parameters estimated simultaneously, rather than in isolation, so correlations among variables do not cause double-counting of their effects.
- All parameters are estimated with the base model shares present as independent variables, avoiding double-counting effects captured by the model. Effects are relative to base model, not to averages.

### **Data for Model Estimation**

Data for incremental logit model estimations was prepared using observed travel from a survey containing over 30,000 usable trips from over 3,300 households in the Sacramento region (NuStats 2000) commissioned by the Sacramento Area Council of Governments (SACOG). Origins and destinations of trips were geocoded to mapped locations at fine resolution, as well as travel model zones (TAZs). Trip details were included such as the mode of travel and the type of activity on each end of the trip.

The travel model furnishing the base choice probabilities was a Sacmet model, also developed for SACOG (DKS 2002). It was run with its Pedestrian Environment Factor variable set to an average constant in place of the given values, so they wouldn't mask or correlate with the new parcel-based pedestrian-related variables.

Land development characteristics were derived from pseudo-parcel data prepared by SACOG for input to their newer activity-based travel demand model SacSim (Bowman and Bradley 2006). The land development characteristics developed for this study measured land use mix, density, pedestrian accessibility and connectivity, and bus and light rail access. Tables 2 through 6 below describe the measures of these characteristics in detail.

**Table 2**

**Mixed-Use Index MUI**

**Range: 0 (low) to 10 (high)**

**Source: SacSim input data from SACOG**

$$Mui = \sum_{i=1}^4 \left[ \left( \frac{\min(hh_i * \beta_i, x_i)}{\max(hh_i * \beta_i, x_i)} \right) * 2.5 \right]$$

where:

*hh*<sub>1</sub> = households within a half-mile      *x*<sub>1</sub> = K-12 jobs within a half-mile  
*hh*<sub>2</sub> = households within a one-mile      *x*<sub>2</sub> = retail jobs within a one-mile  
*hh*<sub>3</sub> = households within a two-miles      *x*<sub>3</sub> = service jobs within a two-miles  
*hh*<sub>4</sub> = households within a two-miles      *x*<sub>4</sub> = total jobs within a two-mile  
*β*<sub>1</sub> = regional K-12 enrollment per household  
*β*<sub>2</sub> = regional retail jobs per household  
*β*<sub>3</sub> = regional service jobs per household  
*β*<sub>4</sub> = regional jobs per household

<p><b>Table 3</b>  <b>Entropy Index ENT</b>  <b>Range 0 (low) to 10 (high)</b>  Measures local land use mix within 1/2 mile</p>	<p><b>Table 4</b>  <b>Density Index DEI</b>  <b>Range 0 (low) to 10 (high)</b></p>
$Ent = (-1) * \sum_{i=1}^4 \frac{p_i * \ln(p_i)}{\ln(4)}$ <p>where:</p> <p><i>p</i><sub>1</sub> = weighted proportion of households  <i>p</i><sub>2</sub> = weighted proportion of K-12 enrollment  <i>p</i><sub>3</sub> = weighted proportion of retail jobs  <i>p</i><sub>4</sub> = weighted proportion of nonretail jobs</p>	$Dei = \frac{hh_{1/4mile} + jobs_{1/4mile}}{188.5}$ <p>where:</p> <p><i>hh</i><sub>1/4mile</sub> = households within a quarter-mile  <i>jobs</i><sub>1/4mile</sub> = jobs within a quarter-mile</p> <p>Groups:  if (Dei &gt; 8), then Dei=9  if (Dei &gt; 14), then Dei=10</p>

**Table 5**  
**Pedestrian Access PAI**  
**Range 0 (low) to 4 (high)**

$Pai = -0.696x_1 + 0.235x_2 + 0.853x_3$ <p>where:</p> <p><math>x_1</math> = number of 1 link nodes within a half-mile</p> <p><math>x_2</math> = number of 3 link nodes within a half-mile</p> <p><math>x_3</math> = number of 4 link nodes within a half-mile</p> <p>Groups:</p> <p>if (Pai &gt;0), then Pai=1</p> <p>if (Pai &lt;10), then Pai=2</p> <p>if (Pai &lt;20), then Pai=3</p> <p>if (Pai &gt;70), then Pai=4</p>
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**Table 6**  
**Transit Access Index**  
**Range 0 (low) to 6 (high)**

Index	Definition
0	No bus lines within ½ mile
1	1 bus line within ½ mile
2	2 bus lines within ½ mile
3	3 bus lines within ½ mile
4	4 bus lines within ½ mile
5	5 bus lines within ½ mile
6	At least 1 light rail stop within ½ mile

### **Incremental Choice Model Estimations**

Adjustments to mode choice were estimated in incremental multinomial logit, using ALogit (availability and further information now through [www.alogit.com](http://www.alogit.com)). The mode choice set of Sacmet is 7 alternatives: drive-alone, auto 2 persons, auto 3 or more person, transit walk-access, transit drive-access, walk, and bike. For this incremental model, the choice set combined the three auto modes into one, and the walk and bike modes into one. Combined modes share the same incremental adjustment parameters.

Several experiments were made with all or a reduced set of variables (due to statistical insignificance), and various ways to separate or combine land use attributes at the production and/or attraction end of the trip, before narrowing them down to the model in Table 7. Auto is the “reference” alternative with zero coefficients except for the base probability, to avoid redundancy.

**Table 7**  
**An Estimated Incremental Logit Mode Choice Model**

Variable	Transit		Walk & Bike	
	Coef	t-stat	Coef	t-stat
Ln(base model probability)	1	(fixed)	1	(fixed)
Mui(attr)	0.00673	1.1	0.00929	4.2
Tai(min)				
Pai(min)	0.328	3	0.208	7
Dei(min)	0.000394	0.1	0.105	8.1
Ent(attr)				
constant	-0.876	-2.1	-1.125	-9.1

The transit and entropy variables are here omitted after previous tests found them not statistically significant.

Adjustments to trip length are expressed in terms of a choice set of four strata of trip length: 0 to 0.5 mile as measured in the model network, 0.5 to 1 mile, 1 to 2 miles, or anything longer. In the base model's zone-to-zone person-trip matrix (for the trip's purpose), trips in each row, corresponding to the demand side of each trip (usually the home), are aggregated into the four strata. Division by total trips in the table row yields the base model's probabilities. Table 8 presents a trip-length adjustment model estimation. Lengths longer than 2 miles are the "reference" alternative to avoid redundancy.

**Table 8**  
**Trip Length Adjustment Model**  
**Incremental Logit**

<b>Home-Based Work</b>						
Variable	0 - 0.5 mi		0.5 - 1.0 mi		1 - 2 mi	
	Coef	t-stat	Coef	t-stat	Coef	t-stat
Ln(base model probability)	1	(fixed)	1	(fixed)	1	(fixed)
mui(prod)	0.203	4.4	0.19665	(cnst'd*)	0.1903	5.8
tai(prod)						
pai(prod)	0.00947	1.6	0.004455	(cnst'd*)	-0.00056	-0.1
dei(prod)						
ent(prod)						
mui*dei/40(prod)	-0.7264	-3.5	-0.78895	(cnst'd*)	-0.8515	-5
constant	-0.8674	-3.3	-0.9432	-5.8	-0.6239	-3.7

\* Middle stratum constrained to average of preceding and next strata.

Table 8, Continued

<b>Home-Based Non-Work</b>						
Variable	0 - 0.5 mi		0.5 - 1.0 mi		1 - 2 mi	
	Coef	t-stat	Coef	t-stat	Coef	t-stat
Ln(base model probability)	1	(fixed)	1	(fixed)	1	(fixed)
mui(prod)	0		0.00409	1.7	0.1012	5.6
tai(prod)						
pai(prod)	0.152	5.1	0.1264	4.4	0.00921	3.9
dei(prod)	0.00239	1.6				
ent(prod)			0.00871	4.6	0.00472	3.5
mui*dei/40(prod)					-0.3357	-4
constant	-0.472	-6.2	-1.39	-10.1	-1.051	-12.1
<b>Non Home-Based</b>						
Variable	0 - 0.5 mi		0.5 - 1.0 mi		1 - 2 mi	
	Coef	t-stat	Coef	t-stat	Coef	t-stat
Ln(base model probability)	1	(fixed)	1	(fixed)	1	(fixed)
mui(prod)	0.00002	0	0.003575	(cnst'd*)	0.00713	4.7
tai(prod)						
pai(prod)	0.1288	3.7	0.0683	(cnst'd*)	0.0078	2.6
dei(prod)	0.00675	5.7	0.00404	(cnst'd*)	0.00133	1.3
ent(prod)						
mui*dei/40(prod)						
constant	-0.5708	-6.6	-0.8612	-12.9	-0.63	-8.7
* Middle stratum constrained to average of preceding and next strata.						

## Application Test

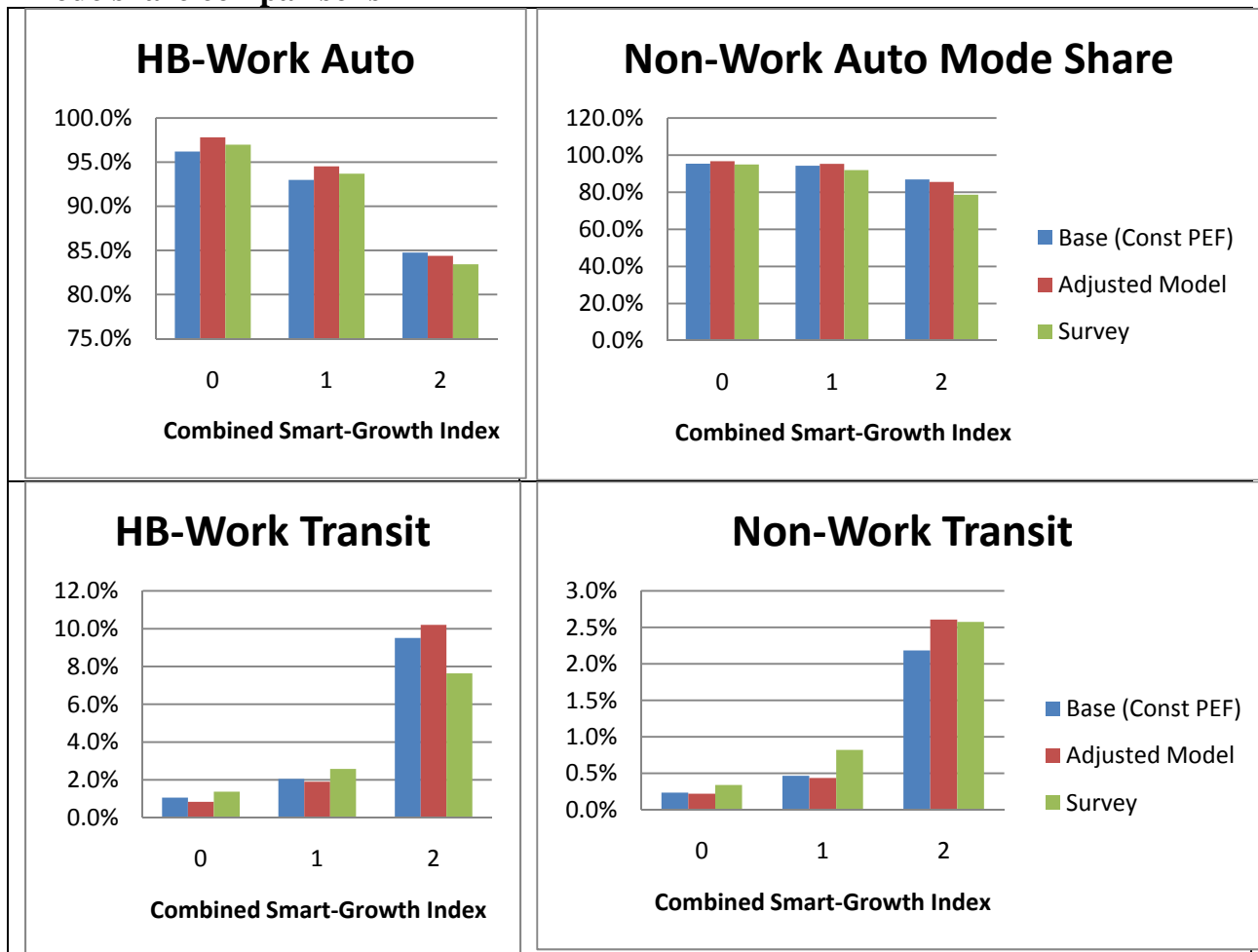
Application of the estimated incremental models was made to a copy of the Sacmet base model. In this copy, the script incorporated the incremental logit mode choice model applied to each i-j pair of each of the five person-trip purposes in the Sacmet, after its regular mode choice processes. Total person trips in each i-j pair by purpose were preserved; only the split among the modes was changed. Incremental application of the trip length adjustment model followed these steps:

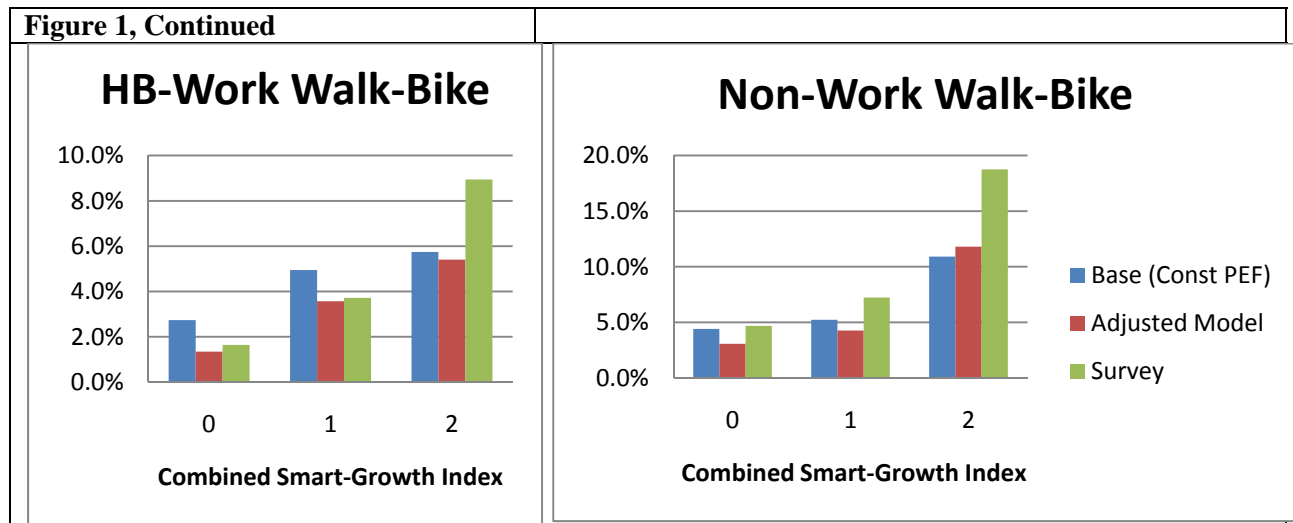
- 1) After the trip distributions of all trip purposes, factor the person trips (not distinguished by mode) in cells whose skimmed walk distance is in strata of the model, by the exponential of utility.
- 2) Using a Fratar process, factor each matrix's rows and columns iteratively to restore the row and column totals each had before adjustment. For HB-Work, which in Sacmet is a

nested combination mode and destination choice model, factor each cell of the mode-specific matrices by the same ratio by which the total person trips changed. For other trip purposes, mode choice follows, using the adjusted person trip matrices instead of the originals. (All computations are in small fractions of trips, to minimize random errors.)

Figures 1, 2, and 3 compare mode shares of the base model (with its original zonal pedestrian environment factor removed), that model with adjustments applied and fully equilibrated, and the household travel survey. The summarizing index variable (horizontal axis) is a composite of the three strongest development variables (MUI, PAI, DEI).

**Figure 1**  
**Mode share comparisons**

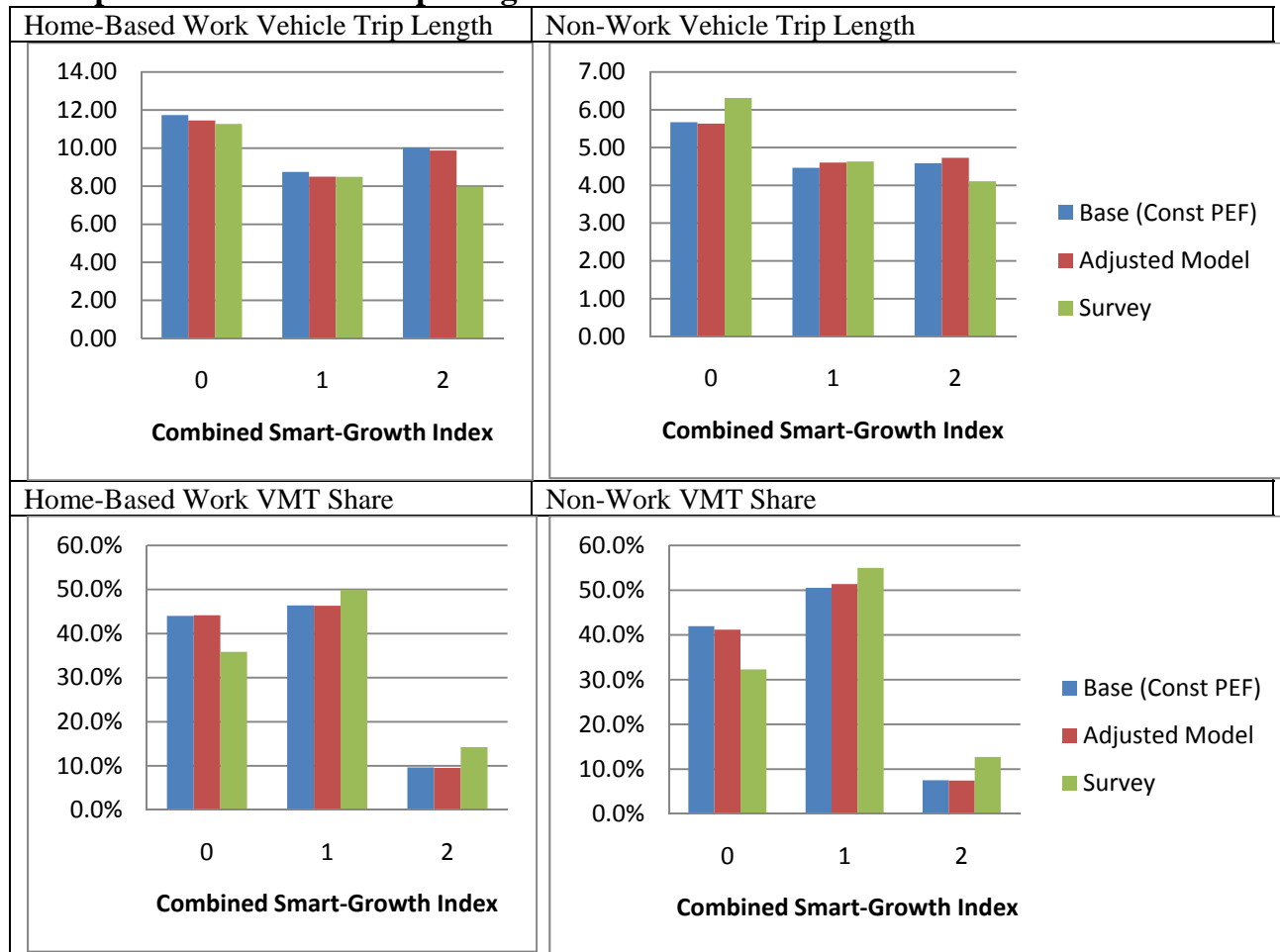




The base and adjusted models both follow the general trend of the survey, indicating the model is sensitive to the factors comprising the combined “smart-growth index”, and/or its zonal and network data are correlated with them. The applied adjustments move most mode shares in the expected direction, down for index 0 and up for index 2. However, the adjustments are quite spotty at moving summarized quantities toward the survey, with many moving away from it or not significantly closer. It is difficult to conclude a definite improvement in the mode choice model compared to the survey on this basis.

Figure 2 compares vehicle trip length and VMT shares. VMT shares instead of absolute VMT are presented due to absolute VMT in the survey totaling much lower due to scaling issues.

**Figure 2**  
**Comparison of Vehicle Trip Length and Miles Traveled Shares**



Both the base and adjusted models generally conform to most overall trends of the survey. But the adjustments relative to the base model do not show any clear trend, either by index or in moving closer to the survey. The Sacmet model's approximately solves for system equilibrium, a state of consistency among the interrelated causalities of network travel times and travel choices. It is suspected that in a model with system equilibrium, behavioral shifts are absorbed and accommodated much more than by a simpler sequential model lacking congestion effects in most travel choices. For example, if vehicle trips from one area are reduced, congestion lessens some, but others shift their routes and destinations into the opportunities, replacing some of the reduction.

The pattern that index-0 areas (more suburban, rural, or homogeneous) have low trip lengths but high VMT shares (whether adjusted or not), despite relatively conforming auto mode shares, suggests that land development characteristics affect trip generation more affected than originally suspected. Sacmet was developed on the expectation that home-based person-trip generation including walk and bike is mainly determined by household characteristics (numbers

of person and workers), unlike trip generation of motorized or vehicle trips only. It includes moderate accessibility effects based on attractions within 5 or 10 minutes drive time, but none on the localized scale of the development characteristics of this study.

## **Conclusions and Directions for Further Research**

It might have been hoped that a set of adjustments to trip distribution and mode choice applied to the model would roughly (not exactly) duplicate the changes predicted by aggregate elasticity methods, and significantly improve its conformity to the household survey. Instead, net effects of the applied model were significantly less. This is partly due to significant sensitivities already in the model, partly due to effects evident in trip generation for which no incremental is yet estimated, equilibration, and unknown relationships.

The results indicate that the Sacmet model already responds either to land development characteristics examined, or to variables correlated to them. The incremental models exerted a significant adjustment to particular travel movements, but after full system application and equilibration, this effect did not translate into changes in vehicle trip numbers or VMT with discernable trend. Meanwhile, land development effects upon person-trip generation are evident but their analysis remains unexplored.

This study does not conclude with a new set of adjustment factors for travel demand model forecasts due to land development details. But it identifies a means to identify adjustments from detailed land and travel observation data that can be directly applied to travel demands within a model application system without double-counting the model's own response, and with full equilibration of adjusted demand and network performance. Further study is needed to find more effective incremental formulations, and determine the extent of absorption of effects in equilibrium.

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