Impacts of Mixed Use and Density on Utilization of Three Modes of Travel: Single-Occupant Vehicle, Transit, and Walking

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Findings from an empirical analysis to test the impacts of land-use mix, population density, and employment density on the use of the single-occupant vehicle (SOV), transit, and walking for both work trips and shopping trips are presented. The hypothetical relationships tested focused on whether there is a relationship between urban form and modal choice, whether this relationship exists when controlling for non-urban form factors, whether this relationship is linear or nonlinear, and whether a stronger relationship exists between modal choice and urban form when they are measured at both trip ends as opposed to either the origin or the destination. A review of the literature and experiences suggested that a fair amount of information is known about the impacts of density on mode choice. However, considerable debate exists over whether density itself is actually the causal stimulus or a surrogate for other factors. To address this issue a data base was developed with a comprehensive set of variables for which density may be a proxy, for example, demographics and level of service. This analysis employed a correlational research design in which mode choice was compared among census tracts with differing levels of density and mix. Findings from this research indicate that density and mix are both related to mode choice, even when controlling for non-urban form factors for both work trips and shopping trips. Furthermore, the relationship between population and employment density and mode choice for SOV, transit, and walking is nonlinear for both work and shopping trips. Transit usage and walking increase as density and land-use mix increase, whereas SOV usage declines. The findings from this research suggest that measuring urban form at both trip ends provides a greater ability to predict travel choices than looking at trip ends separately. The findings also suggest that increasing the level of land-use mix at the trip origins and destinations is also related to a reduction in SOV travel and an increase in transit and walking.

This project is part of a research agenda developed by the University of Washington for the Washington State Department of Transportation (WSDOT). The goal of the agenda is to discover ways to plan and implement urban forms that promote increased accessibility. At the crux of this agenda are the intentions to decrease the need to travel, reduce dependence on the single-occupant vehicle (SOV), and enhance the competitiveness of other travel modes. More specifically, this paper documents empirical relationships between urban form (land-use mix and density) and trip making by individuals who use SOVs, transit, and walking as modes of travel. This analysis focuses on two trip purposes: working and shopping.

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This research is important because of recent policy initiatives at the federal, state, and local levels that state that it is no longer feasible to maintain access to opportunities in urban areas by increasing the mobility of SOVs. Among the commonly cited reasons are economics, new environmental legislation (e.g., the Clean Air Act Amendments of 1990), public opposition, changing demographics, and political pressure to reduce fuel consumption. Several urban-form strategies have been recommended to reduce dependence on driving alone. These strategies include increasing residential and employment densities and intermixing a variety of land uses (residential, employment, and commercial). Although these strategies would seem to enhance the viabilities of alternatives to SOVs, relatively little work has been conducted to test these relationships empirically.

STRUCTURE OF ANALYSIS

The findings presented in this paper are based on a three-phase research approach. In Phase I information was gathered from other sources resulting in the identification of hypothetical relationships between urban form and travel behavior on the basis of theory, past research findings, and current policies. In Phase II the project data base was developed to test these hypothetical relationships. Statistical techniques were used to conduct hypothesis testing (e.g., multiple regression or correlation) in Phase III.

POLICY PERSPECTIVE

Over the past 3 years several policies that are intended to reduce the rate of growth in travel demand through the manipulation of urban-form and a variety of other factors have been enacted at the federal, state, and local levels. These policies are based on a variety of hypotheses that characterize the nature of the relationship between travel demand and both urban-form and non-urban-form factors. Although the intent of this research was to provide insight regarding urban form, it also tested and evaluated the relative impacts of non-urban-form factors. Selected policies that target both urban-form and non-urban-form factors and that affect travel demand include

- The Intermodal Surface Transportation Efficiency Act of 1991, which provides new funding opportunities for non-SOV improvements;

• The Clean Air Act Amendments of 1990, which designate vehicle miles traveled as a form of mitigation to meet air quality attainment;

• Washington State Growth Management Act, which encourages densification and concurrency between development and transportation infrastructure;

• Washington State Commute Trip Reduction Law, which requires major employers to implement transportation demand management (TDM); it also requires the review of parking requirements in local zoning ordinances;

• Washington State Transportation Policy Plan, which encourages mobility options for the public, including those individuals without access to automobiles; and

• Central Puget Sound Vision 2020, which promotes the clustering of development into a hierarchy of mixed-use transit-oriented centers.

REVIEW OF LITERATURE AND EXPERIENCES

A literature review was conducted to identify methods that had been used and findings from empirical research efforts. These methods and findings were then used to test the impacts of urban form on travel behavior. Several areas in which research documenting empirical relationships between urban form and travel behavior was limited were found to exist. There areas include the impact of land-use mix on travel behavior, the relationship between non-work-related travel and urban form, and the collective impacts of urban form at both origins and destinations on travel choices.

In relation to land-use mix, Cervero (7) concluded that a significant reduction in midday travel and overall automobile dependence could be achieved through the integration of services into office parks. If further research establishes that an increased mixing of uses at both the household and employment trip ends reduces travel demand, the policy implications may be vast. Much of the existing zoning in urban and suburban areas is based on the principle of separation of land uses. In addition limited research has tested the collective impacts of urban form at both trip ends.

Findings from this review suggest the existence of two conflicting camps of believers regarding the effect of urban form on travel behavior and associated energy consumption. In the first camp are individuals who have concluded that the intensity of development and land-use mix seem to have a measurable impact on travel behavior. Their work is summarized as follows:

• Per-capita energy consumption increases as density decreases *(2-4)*.

• Population and employment density are the aspects of urban form (studied to date) that have the greatest impacts on travel behavior *(1,5-7)*. Previous research suggests that density has a significant impact on mode choice *(1,7-9)*.

• As density increases households with one or more vehicles produce fewer trips, whereas zero-car households experience an increase in trip production *(10)*.

• Job-housing policies may not provide the relief from congestion and air pollution that is needed *(11,12)*.

• Mixing of uses at the employment trip end has been found to reduce travel demand *(1)*.

The second group is more skeptical of the strength of this relationship. Researchers in this camp suggest that the intensity of development may appear to affect travel behavior; however, the underlying causes of this relationship are based on costs and demographics. These researchers most commonly cite the example that higher densities are associated with higher levels of transit service, higher parking costs, and lower automobile ownership rates. Findings from work on non-urban-form factors suggest that density may not be a causal factor itself, but rather a proxy for a host of other economic-related factors that do affect travel behavior *(13,14)*.

RESEARCH APPROACH

The conceptual model in Figure 1 illustrates the significance that both urban-form factors (i.e., density and land-use mix) and non-urban-form factors (i.e., income, gender, age, and level of service) have on travel behavior. In this research urban-form factors were the focus, and non-urban-form factors were used as control variables in recognition of their significance. For example, when the impacts of density on mode choice were tested, it was critical to account for the socioeconomic characteristics of the trip maker. This enabled comparisons to be made between trip makers with similar socioeconomic characteristics. This process canceled the impacts of these factors on travel choices, allowing the impacts of urban-form factors to emerge. This project used a correlational research design in which the relationships between urban form as the independent phenomenon and modal choice as the dependent phenomenon were analyzed *(15)*. This research design was cross-sectional and did not offer the ability to identify whether variations in the dependent phenomenon (e.g., mode choice) were a direct reaction to variation in the independent phenomenon (e.g., population density). Therefore, there was no ability to truly document causality. The primary constraint preventing the documentation of causality was temporal. In a cross-sectional research design there is no ability to conduct a pretest; therefore, the impact of the stimuli (e.g., urban form) cannot be longitudinally isolated in an experimental design. The relationship between travel behavior and urban form was cross-sectionally isolated through the control of other variables that affect travel behavior (non-urban-form factors).

Development of a Data Base for Hypothesis Testing

The data used for this project were obtained from a variety of sources. Table 1 presents the data sources that supported each of the

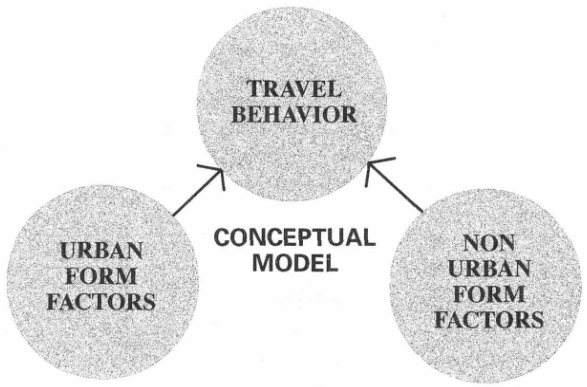

FIGURE 1 Relationship between travel behavior and factors that affect it.

TABLE 1 Data Base Structure

SOURCE Puget	VARIABLE TYPE
Puget Sound Transportation Panel (PSTP)	Travel Behavior, Level of Service for Transit (non-urban form), Demographic Factors (non-urban form)
U.S. Census Bureau	District Population (urban form)
Washington State Department of Economic Security (DBS)	District Employment (urban form)
Puget Sound Regional Council (PSRC)	Area of Census Tracts in Acres (Urban Form)
King County BALD file	District Mix (urban form) - using parcel level data

variables in this study. These variables are defined in greater detail below.

This project used data on household travel behavior and demographics (control variables) from the Puget Sound Transportation Panel (PSTP). The PSTP is a 5-year longitudinal cohort study that was conducted between 1989 and 1994. This project was based on the 1989 survey, with approximately 28,955 valid trips made by 1,680 households. The sampling technique that was used for the data collection process in the PSTP is known as "choice based." Transit and carpooling were the infrequent travel choices that were oversampled in the PSTP. To perform meaningful research that would be generalizable to the study population, a weighting system was developed to apply to the 1989 survey of the PSTP *(16).* Another complication associated with coding the trips in the PSTP was associated with trip chaining. The effects of trip chaining on mode choice were not accounted for because each trip was coded independently, making it difficult to identify where a trip chain began or ended.

Data on travel behavior, land-use density, and land-use mix were all coded to the census tract to allow use of a correlational research approach. The percentage of SOY, transit, and walking trips that originated or ended in a census tract were calculated for each census tract. These modal proportions were used as continuous dependent variables in regression analysis. More specifically, the census tract was the unit of analysis. Census tracts with different levels of land-use densities and mix could be compared to test for differences in the proportions of SOV, transit, and walking trips that originated and ended in those tracts.

Variables in Study

The variables used in this project fell into three categories: mode choice, urban form, and non-urban form. Descriptive statistics for and definitions of the variables by trip purpose that were found to be most significant in the statistical analysis are presented later in this paper.

Mode Choice: Dependent Variables

Three alternative travel mode choices are presented in this paper. They are SOV, transit, and walking. Each of these modes was a dependent variable in this study and is defined in Table 2 in association with some basic descriptive statistics.

The mean proportion of work trip origins per census tract was clearly dominated by the SOV (74.76 percent), with a small proportion of transit (5.16 percent) and walking (3.69 percent). Even smaller proportions of work trip destinations were reached by transit (1.68 percent) and walking (3.37 percent). This was due to an increase in the mean proportion of SOV trips at destinations over origins of 5.33 percent.

Urban Form: Independent Variables

The variables representing various measures of population density, employment density, and land-use mix that were found to be most highly related to mode choice for SOV, transit, and walking are presented in Table 3. In some cases there were two variables with the same definition (e.g., popdenA) that differed only in their relationship with trip origin or destination data. If the same variable appears twice (popdenA), it indicates that the variable was significantly related to the proportion of trip origins and destinations for SOV, transit, or walking.

Gross Population Density Gross population density measured the entire population or number of residents within a designated geographic area divided by the size of the designated area, which was the census tract. Variables representing measures of gross population density are presented and defined in association with descriptive statistics for both work trips and shopping trips in Table 3. The average gross population density at trip origins and destinations We found to be the population density variable most significantly related to mode choice. The maximum value for gross population density at the tract level ranged from 40.5 to 47 residents per acre. Between 345 and 443 tracts in which work or shopping trips original or ended had valid data for population density.

Gross Employment Density Gross employment density measured the number of employees within a designated geographic area divided by the size of the designated area, the census tract. Variables representing measures of gross employment density are presented and defined in association with descriptive statistics for b work trips and shopping trips in Table 3. Employment density was found to be related to both work trips and shopping trips at origins, destinations, and an average of the two. The maximum

TABLE 2 Mode Choice Variables

Variable Name	Trip Purpose	Mean	Std Dev	Minimum	Maximum	Valid cases
sovpctO	percent of trips originating in census tracts made by SOV					
	WORK	74.76	26.66	0	100	509
	SHOP	58.61	30.39	0	100	497
sovpctD	percent of trips ending in census tracts made by SOV					
	WORK	80.09	25.94	0	100	446
	SHOP	58.94	33.07	0	100	393
buspctO	percent of trips originating in census tracts made by transit					
	WORK	5.16	13.34	0	100	509
	SHOP	1.23	6.35	0	100	497
buspctD	percent of trips ending in census tracts made by carpool					
	WORK	1.68	5.48	0	51.81	446
	SHOP	1.45	8.45	0	100	393
wallkpctO	percent of trips originating in census tracts made by walking					
	WORK	3.69	12.52	0	100	509
	SHOP	3.16	10.03	0	100	497
walkpctD	percent of trips originating in census tracts made by walking					
	WORK	3.37	12.44	0	16.67	446
	SHOP	4.165	14.53	0	100	393

TABLE 3 Urban-Form Variables

Variable Name	Trip Purpose	Mean	Std Dev	Minimum	Maximum	Valid Cases
popdenA	average gross population density per acre at trip origins and destinations (based on trip destination data)					
	WORK	6.158	4.361	0.028	40.503	382
	SHOP	6.44	4.767	0.01	46.97	345
popdenA	average gross population density per acre at trip origins and destinations (based on trip origin data)					
	WORK	6.495	4.888	0.006	44.52	443
empdenO	gross employment density per acre at trip origins (based on trip origin data)					
	WORK	9.93	25.94	0.002	225.16	370
empdenD	gross employment density per acre at trip destinations (based on trip destination data)					
	SHOP	7.9	30.02	0.002	401.43	256
empdenA	average gross employment density per acre at trip origins and destinations (based on trip destination data)					
	WORK	9.465	22.26	0.002	232.58	274
	SHOP	12.46	32.7	0.002	287.49	252
mixentO	mixing of uses at trip origin census tracts (based on trip origin data)					
	WORK	0.443	0.185	0.002	0.794	267
mixentO	mixing of uses at trip origin census tracts (based on trip destination data)					
	WORK	0.471	0.128	0.048	0.794	273
mixentD	mixing of uses at trip destination census tracts (based on trip destination data)					
	WORK	0.471	0.178	0.006	0.794	223
	SHOP	0.478	0.166	0.006	0.794	204

employment density value for a census tract in the study area was 401.43 employees per acre, which was in downtown Seattle. Very few tracts in the study area had an employment density of greater than 200 employees per acre. Between 252 and 274 tracts in which work or shopping trips originated or ended had valid data for employment density.

Land-Use Mix Land-use mix is the composition of uses within a given geographic area. According to Cervero (7): "Mixed-use developments are those with a variety of offices, shops, restaurants, banks, and other activities intermingled amongst one another." A descriptive statistic known as an entropy index was developed to describe the evenness of the distribution of built square footage among seven land-use categories. The entropy index was based on the following equation:

Level of land use mix (entropy value) =

$$
\begin{aligned}
&- [\text{single family} \cdot \log_{10}(\text{single family})] \\
&+ [\text{multifamily} \cdot \log_{10}(\text{multifamily})] \\
&+ [\text{retail and services} \cdot \log_{10}(\text{retail and services})] \\
&+ [\text{office} \cdot \log_{10}(\text{office})] \\
&+ [\text{entertainment} \cdot \log_{10}(\text{entertainment})] \\
&+ [\text{institutional} \cdot \log_{10}(\text{institutional})] \\
&+ [\text{industrial/manufacturing} \cdot \log_{10}(\text{industrial/manufacturing})]
\end{aligned}
$$

This equation resulted in the development of a normalized value between a minimum of 0 and a maximum of 0.845 (the log of *K* or the number of categories, which was seven) assigned to each census tract. Definitions and descriptive statistics are presented in Table 3 for the land-use mix variables most highly correlated with mode choice.

Land-use mix at trip origins (mixentO) was found to be significantly related to mode choice for work trips when modal proportions for SOV, carpool, transit, and walking were calculated at both trip origins and destinations. Land-use mix at the trip destination (mixentD) was found to be significantly related to mode choice for work trips and shopping trips when modal proportions were calculated at trip destinations. The maximum value for each of the census tract-level land-use mix variables was 0.794. Between 204 and 273 tracts in which work or shopping trips originated or ended had valid data for land-use mix.

Non-Urban-Form: Control Variables

The non-urban-form factors that were found to be significantly related to mode choice are presented in Table 4. An examination of non-urban-form factors allows the researcher to place urban form in context relative to the myriad of variables that affect travel behavior.

Household-type variables were measures of life-cycle stage. The household types most highly related to mode choice for shopping trips were households with single adults under age 35 (hhtype3) and households with single adults between the ages of 35 and 64 (hhtype4), with mean values of 3.13 and 5.97 percent, respectively. These values indicated that the mean proportion of shopping trips that ended in census tracts and that were made by individuals who lived alone and who were under 35 years of age was 3.13 percent. Hhtype5 (single adults over age 65) was the group most highly related (negatively) with the work trip subset. Overall, households with individuals who lived alone had the strongest relationships to mode choice for work and shopping.

Based on destination data, more than 90 percent of the work trips and shopping trips were made by individuals who had a driver's license. As would be expected, a significantly larger proportion of each census tract's work trip destinations (93.49 percent) than shopping trips destinations (57.86 percent) were reached by individuals who worked outside the home. A small proportion of each census tract's shopping trips were made by individuals who had a bus pass, as indicated by the mean value for all census tracts of 4.3 percent. Roughly 10 percent of all census tract's work trip and shopping trip destinations were reached by individuals who had less than one vehicle available to them. The mean age of the individuals who made shopping trips to all census tracts was 47.28 years.

TESTING OF HYPOTHETICAL RELATIONSHIPS

An analysis of four hypothetical relationships is presented in this analysis. These relationships are global enough to address the published criticisms of similar research efforts. These four hypothetical relationships were as follows:

- Population density, employment density, and land-use mix are related to mode choice.
- Population density, employment density, and land-use mix are related to mode choice when non-urban-form factors are controlled.
- A stronger relationship exists between mode choice and urban-form characteristics at both trip ends than at one trip end.
- The relationship between population density, employment density, land-use mix, and mode choice is nonlinear.

Findings from the analysis of hypothetical relationships between urban form and mode choice are presented below. The statistical methods used to test these hypotheses were selected on the basis of the nature of the hypothetical relationship being tested. Tests of the presence, strength, and nature (+, —) of the linear relationship between various urban-form and mode choice variables were conducted with the Pearson correlation. Multivariate regression was used to test the presence of a relationship between urban-form and mode choice while controlling for non-urban-form factors. Nonlinear relationships between urban-form and mode choice variables were simulated by cross-tabulation. The findings are presented according to the four research questions presented previously.

Hypothesis 1

Hypothesis 1 states: a statistically significant relationship exists between urban form and travel behavior. Empirical relationships between urban form and travel behavior variables for work and shopping trips are presented in Table 5. These findings were the result of simple linear correlation.

The findings in Table 5 indicate that employment density and land-use mix were both significantly related to percent SOV use, percent transit use, and percent walking. Population density was not significantly related to percent SOV use. Percent SOV use had a negative relationship and transit use and walking had a positive relationship with density and mix, which is intuitively correct. Overall, these findings confirm the hypothesis that urban form and mode choice are significantly related. The strongest linear relationships for work trips were between employment density and transit and

TABLE 4 Non-Urban-Form Variables

Variable Name	Trip Purpose	Mean	Std Dev	Minimum	Maximum	Valid Cases
hhtype3	proportion of survey households per census tract with one adult less than 35 years old					
	SHOP	3.13	12.99	0	100	393
hhtype4	proportion of survey households per census tract with one adult between 35 and 64 years old					
	SHOP	5.97	16.4	0	100	393
hhtype5	proportion of survey households per census tract with one adult over 65 years of age or older					
	WORK	0.456	5.113	0	100	446
licensel	proportion of survey participants per census tract that have a driver's license					
	WORK	98.07	8.31	0	100	446
	SHOP	90.98	18.58	0	100	393
employl	proportion of trip ends per census tract made by survey participants that are employed outside the home					
	WORK	93.49	19.11	0	100	446
	SHOP	57.86	31.3	0	100	393
buspassl	proportion of trip ends per census tracts made by survey participants with a buspass (based on trip destination data)					
	SHOP	4.3	19.05	0	100	116
vehavail	proportion of trip ends per census tract made by survey participants that have access to less than one vehicle					
	WORK	9.41	21.64	0	100	446
	SHOP	11.07	20.98	0	100	392
numveh	mean number of vehicles available for survey participants ending trips in each census tract					
	SHOP	2.23	0.725	0	6	393
age	mean age of survey participants ending trips in each census tract					
	SHOP	47.28	12.44	6	8	393

walking; however, significant associations were found between percent walking and population density and land-use mix. These findings suggest that the census tract can be a meaningful geographic unit of analysis for use in measuring the relationship between land-use mix and mode choice for work trips.

The findings in Table 5 indicate that the percentage of walking and transit trips had the highest linear relationship to density for shopping trips. Percent SOV use was negatively associated with density, whereas percent transit and percent walking had a positive association with density. These results were consistent with the findings from the work trip subset. Land-use mix was not found to be significantly correlated with these three mode choice variables for shopping trips. Overall the hypothesis that mode choice for SOV use, transit use, and walking is significantly related to urban form (for shopping trips) was confirmed for population and employment density.

TABLE 5 Correlation Coefficients between Urban-Form and Mode Choice Variables

WORK TRIPS			
TRAVEL BEHAVIOR VARIABLES	**EMPLOYMENT DENSITY**	**POPULATION DENSITY**	**MIXING OF USES**
% SOV	-0.26	-	-0.13
% TRANSIT	0.59	0.19	0.15
% WALK	0.43	0.34	0.21
SHOPPING TRIPS			
% SOV	-0.15	-	-
% TRANSIT	0.44	0.16	-
% WALK	0.24	0.31	-

Hypothesis 2

Hypothesis 2 states: a statistically significant relationship exists between urban form and modal choice while controlling for non-urban-form factors. Multivariate regression models were developed for each of the mode choice variables (percent SOV, percent transit, and percent walking) to determine whether urban-form variables were significantly related to mode choice when non-urban-form factors were controlled. These models are presented in Table 6 for both work trips and shopping trips. Non-urban-form factors were entered into the regression analysis before the stepwise selection of urban-form variables. Therefore, only those urban-form variables that were still significantly related to the dependent variable (after non-urban-form variables were entered) are presented below. Beta values are presented in association with the variables in each of these models. The slopes (b-values or coefficients) of each urban-form variable were interpreted but are not presented in this paper. More detailed information about these models is available through the Office of Urban Mobility, WSDOT.

The hypothesis that urban form is significantly related to mode choice for SOV use, transit use, and walking when non-urban-form factors are controlled was confirmed by the significance of both urban-form and non-urban-form variables. The findings presented in Table 6 suggest that the percentage of transit and walking (for both work trips and shopping trips) had the highest relationships with the urban-form variables. Urban-form factors were consistently negatively associated with percent SOV use and were positively associated with percent transit use and walking. Percent transit use appeared to be highly related to employment density for both work and shopping. Percent walking (in addition to employment density) was also significantly related to other urban form variables such as population density (for both work and shopping) and land-use mix (work trips). Percent SOV use was also related to employment density. Employment density at trip origins and destinations for work trips and percent transit use was found to be the strongest relationship between an urban-form and mode choice variable. Population density had the greatest effect on walking trips for both work and shopping. Employment density was found to be significantly related to SOV use, transit use, and walking trips for both work and shopping. Mixing of uses had the weakest relationship with mode choice, having the greatest effect on walking for work trips.

Hypothesis 3

Hypothesis 3 states: a stronger relationship exists between mode choice and urban-form characteristics when they are measured at both trip ends than at one trip end. This hypothesis was confirmed only in certain instances. Employment density at trip origins and destinations had the greatest degree of explanatory power over variation in mode choice for transit use for both work trips and shopping trips and for SOV use for work trips. Employment density at trip origins and destinations had the greatest degree of explanatory power over variation in mode choice for walking for both work trips and shopping trips. Land-use mix at trip origins and destinations had the greatest degree of explanatory power over variation in mode choice for walking for work trips. Although they are not universal, the findings from this analysis suggest that average urban-form

TABLE 6 Variables Related to Each Mode by Trip Purpose

	%SOV (regression variables & betas)	%TRANSIT (regression variables & betas)	%WALK (regression variables & betas)
WORK TRIPS	average employment density at trip origins and destinations (-0.29), has a driver's license (0.37)	employment density at trip origins and destinations (0.65)	employment density at trip origins (0.38), population density at trip origins and destinations (0.29), mixing of uses at trip origins and destinations (0.15)
adj. r-sq.	0.2	0.42	0.31
SHOP TRIPS	employment density at trip destinations (-0.18), has a driver's license (0.23), single adult households between 35-64 (0.21), household income (0.16)	employment density at trip origins and destinations (0.32), population density at trip origins and destinations (0.19), distance for carpool trips (0.51)	employment density at trip destinations (0.19), population density at trip origins and destinations (0.26), less than 1 vehicle available (0.15), age (-0.13), has a driver's license (-0.4)
adj. r-sq.	0.14	0.43	0.35

measures rather than measures taken at the origin or destination have the strongest ability to predict variations in mode choice for SOV use, transit use, and walking.

Hypothesis 4

Hypothesis 4 states: the relationship between population density, employment density, and mode choice is non-linear. The purpose of this analysis was to identify the thresholds where shifts from one mode (SOV) to another (transit or walking) occur as a function of population or employment density. (A similar analysis was conducted between land-use mix and the proportion of trips by mode for both work trips and shopping trips. That analysis determined that no detectable nonlinear relationship exists.) The focus of this analysis was to identify the linearity or nonlinearity of the relationship between urban-form variables and SOV use, transit use, and walking. Cross-tabulation was used to separate employment density and population density into intervals to allow changes in the relationship between mode choice for SOV use, transit use, and walking to be detected at different levels of density.

The proportions of trips by SOV, transit, and walking at different levels of density are presented in Figures 2 and 3 for employment density and population density by trip purpose, respectively. The findings from this research indicate that population density has a more significant relationship with mode choice when it is measured at the trip origin, as does employment density when it is measured at the trip destination. Employment density is presented in Figure 2 in association with work trips, whereas population density is presented in Figure 3 in association with shopping trips.

Figure 2 indicates that there is a nonlinear relationship between employment density and mode choice for SOV use, transit use, and walking for work trips. The nature of these nonlinear relationships between employment density and mode choice has significant policy implications. Policies that call for an increase in employment density to encourage transit use and walking and to discourage SOV use for work trips will not be cost-effective unless certain density thresholds are reached. Two thresholds are indicated by Figure 2. Significant modal shifts from SOV use to transit use and walking occur with between 20 and 75 employees per acre and again with more than 125 employees per acre. This analysis suggests that policies that encourage employment densities to increase from 75 to 125 employees per acre will have little effect on mode choice.

Figure 3 indicates that a nonlinear relationship exists between population density and mode choice for SOV use, transit use, and walking for shopping trips. The authors note that few shopping trips in the panel survey were to or from higher-density census tracts, limiting the ability to separate out intervals at higher densities. This analysis suggests that population densities need to exceed approximately 13 persons or residents per acre before a significant modal shift occurs from SOV use to transit use and walking for shopping trips. This analysis suggests that policies that encourage population densities to increase to levels below 13 persons per acre will have little effect on mode choice. Thirteen persons per acre roughly corresponds to approximately seven to nine dwelling units per gross acre, which is similar to findings from previous research *(8)*.

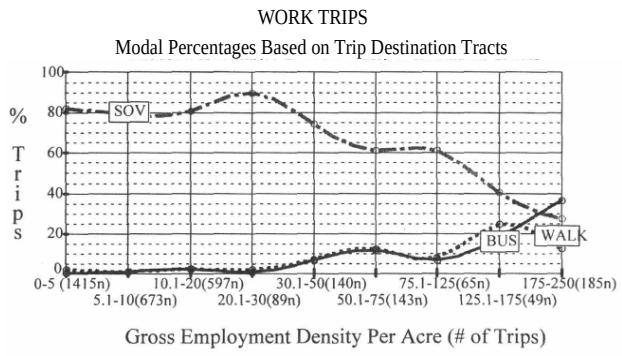

FIGURE 2 Average employment density of trip origins and destinations and mode choice.

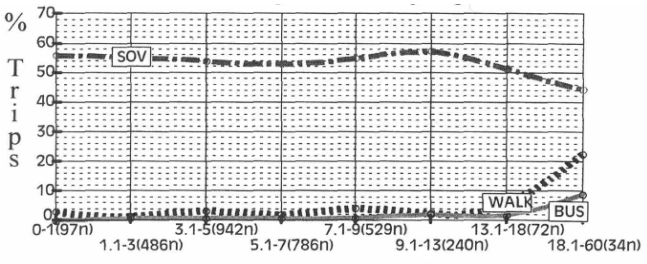

FIGURE 3 Average population densities of trip origins and destinations and mode choice.

SUMMARY

This paper presents findings from research conducted to test the presence and nature of the relationship between urban form and mode choice at the census tract level. The proportions of trip origins or destinations for SOV use, transit use, and walking were the dependent continuous variables. Relationships between employment density, population density, land-use mix, and SOV usage were found to be consistently negative for both work and shopping trips. The relationships between employment density, population density, land-use mix, and transit and walking were consistently positive for both work trips and shopping trips. General findings identified in the analysis of mode choice were documented through the analysis of descriptive statistics, correlation, regression, and cross-tabulation.

Past research and findings from this analysis suggest that the relationship between mode choice and employment density is nonlinear. The findings presented here indicate that there are two thresholds along a continuum of employment density at which a modal shift occurs from SOV use to transit use and walking. The most compelling of the findings is the dramatic increase in the proportion of transit trips that occur as employment density increases to more than 75 employees per acre. In addition, a significant decrease in SOV travel occurs at relatively low densities (between 20 and 50 employees per acre). This finding could have significant implications for the reduction of SOV travel and the associated vehicle miles traveled required to meet federal Clean Air Act requirements.

The measure of population density that was found to have the strongest relationship with mode choice in correlation and regression analyses was average gross population density at trip origins and destinations for shopping trips. A nonlinear relationship was identified between all three modes analyzed and population density

for shopping trips. Walking trips were the most sensitive to increases in population density. Findings suggest that population densities need to exceed 13 residents per acre for changes in mode choice to be detected. The reduction in SOV travel was not as significantly associated with increases in population density as it was with employment density.

The findings presented in this paper indicate that the relationship between mode choice and land-use mix can be measured at the census tract scale; however, the relationships are relatively weak. Only the relationship between average land-use mix at origins and destinations and percent walking for work trips was significant enough to remain in a regression model when non-urban-form factors were controlled. This indicates that further research that focuses on measures of land-use mix at a smaller geographic unit of analysis (e.g., block groups) may be more able to detect relationships with mode choice.

The findings presented in this paper support the use of urban form policies to reduce dependence on the SOV. They also identify a variety of non-urban-form factors that affect mode choice. Furthermore, this research indicates that a comprehensive approach to policy development would be most successful in reducing dependence on SOVs.

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