# Homes, autos, and travel: Household decision chains

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# ABSTRACT

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(Under the direction of Asad J. Khattak)

Transportation planners have long recognized a role for the environment in travel behavior, although the most effective techniques for incorporating the environment into travel research remain an open and active area of inquiry. A clearer understanding of the link between the physical environment and travel may inform planning and policy that has the potential to influence household travel behavior and reap tangible benefits in air quality, congestion management, fuel conservation, and other areas.

The objectives of this research are

1) Understand how auto ownership and travel behavior vary across physical environments
2) Understand direct and indirect associations between environment and travel behavior, mediated by auto ownership
3) Model and describe differences in environmental representations in travel models

This work models household decisions relating to auto ownership and travel, specifically auto ownership, trip generation, and mode choice. Three different representations of the environment inform the models. These include 1) a neighborhood typology (transect) describing a range of development types from the intensely urban city center to rural

greenfields; 2) factors used to generate clusters in the transect: walkability, access, agglomeration, industry, and property values; and 3) direct environmental measures: residential density, and distance to transit, commerce, and central business district.

Auto ownership relates primarily to household factors. Trips are more sensitive than is the number of autos to the environment, and less sensitive to some household measures. Mode choice is sensitive to environmental measures; specifically, choice of the walk mode is associated with walkable and accessible environments, and with clusters on the more urban end of the transect. Trips differ by purpose, with home-based work trips sensitive to the environment but not socio-demographic variables, but the more discretionary other home-based trips showing the reverse.

Comparing across environmental representations, factors prove to be more informative than clusters about autos and travel. The four direct measures generally are not statistically significant. Walk trips differ from drive trips in being sensitive to walkability and accessibility but not to socio-demographic variables.

Path analysis shows that indirect effects mediated through autos are swamped by much larger direct associations of the environment with trips and mode choice.

Dedicated to my mother, Mary, and to the memory of my father, Edward

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| | |
|---|---|
| CBD | Central business district |
| HBO | Home-based other (trips) |
| HBW | Home-based work (trips) |
| IVTT | In-vehicle travel time |
| NHB | Non-home-based (trips) |
| NHTS | National Household Travel Survey |
| OVTT | Out-of-vehicle travel time |
| VMT | Vehicle miles traveled |

Clusters

| | |
|---|---|
| CITYCENTER | City center |
| URBAN | Urban |
| INNERSUB | Inner suburban ring |
| MIDDELSUB | Middle suburban ring |
| OUTERSUB | Outer suburban ring |
| RURALMIX | Rural mixed zone |
| GREEN | Rural greenfields |

Factors

| | |
|---|---|
| ACCESS | Accessibility |
| AGGLOM | Agglomeration |
| INDUSTRY | Industrial acreage |
| PROPERTY | Property value |
| WALKABLE | Walkability |

Direct measures

| | |
|---|---|
| BUS | Distance to nearest bus stop |
| CBDDIST | Distance to central business district |
| COMM | Distance to nearest commercial use |
| RESDENSITY | Residential density, single-family homes/acre |

# 1. Research Context and Research Questions

Household decisions relating to residential location, auto ownership, and travel are made within the context of physical environments, themselves the subject of extensive study in the planning and policy fields. Renewed interest in urban planning as a creative design process as well as a technical discipline, along with growing concerns about low-density single-purpose land uses and the implications of travel patterns in such environments for individuals as well as society, have produced a steady stream of research in the last two decades relating to land use, transportation, and the interactions between them. The study of environment and travel necessarily must cross temporal and geographic scales, from daily travel to long-term household decisions such as auto ownership and residential location, and from the individual home and neighborhood to the community and region.

Heavy use of private autos has implications for public funds devoted to infrastructure and services; for the environment in terms of resource depletion, air and water pollution and other impacts (e.g., noise, habitat loss); and for public health because of declining physical activity and rising environmentally linked ailments. Increasingly, researchers and practitioners view the environment as an intervention opportunity, where land use and transportation policy and design can shape individual choices that, in the aggregate, may be important for society and the environment. Because the physical landscape, both natural and built, generally changes slowly (barring major natural or human disasters), understanding how behavior may vary within the environment becomes an important area of potential research and policy relevance.

Despite a recent trend toward neo-traditional development with mixed land uses and higher density, conventional neighborhood design remains the norm in the U.S. Auto-oriented developments, often lacking a commercial center or human scale, dominate the landscape and dilute the focus and character of cities. Automobile use has risen as spatial separation of destinations increasingly discourages non-motorized and mass transit travel modes. Between 1982 and 1997, the urbanized land area in the U.S. rose 47% while the population grew only 17%, for a net decrease of over 20% in urban density. During this same period, vehicle miles traveled (VMT) increased 55% (Fulton et al., 2001). Between 1983 and 1995, average commute length increased 36%, from 8.5 to 11.6 miles (National Household Travel Survey), with a more modest rise to 12.2 by 2001. Meanwhile, auto ownership, measured as autos per driver, rose from 0.98 in 1983 to saturation at 1.00 in 1995, reaching 1.07 autos per driver by 2001 (Polzin and Chu, 2005). This trend has not gone unnoticed by planners and developers, who have been experimenting with alternative development strategies, while intense research has examined how various urban environments differ in terms of human activity and travel patterns.

In recent years, the discussion of travel behavior and physical environment has ranged from descriptive work at the macro level (Kenworthy et al., 1999; Newman and Kenworthy, 1989, 1999) to more quantitative and disaggregate attempts to account for urban development history and socio-demographic factors (e.g., van de Coevering and Schwanen, 2006). Vuchic (1999) casts the discussion in terms of livable and sustainable cities, where economically efficient, socially equitable, and environmentally healthy cities include integrated transportation systems serving public and private modes—both motorized and non-motorized.

There is ample evidence of impending broad changes in the urban landscape, as well as uncertainty over whether these changes can be guided to achieve social objectives. The still-dominant suburban model, which reflects policies and pressures in the first half of the 20th century to address public health, housing, and urban congestion concerns (Nelson, 2006), will not serve in a future of smaller households (many with only one person, no children, or older members), scarcer resources (with attendant higher costs for energy and materials), and shifting work and residential locations. Nelson (2006) cites evidence of superior performance, on balance, of higher-density, mixed-use models compared to suburban developments in terms of health, economic efficiency, and other measures. Demographic shifts—including migration of affluent and immigrant households back toward urban centers, coupled with extensive new construction and redevelopment anticipated in the coming decades, offer an opportunity for planners to shape the built environment to achieve multiple public goals, given solid knowledge about the demand for land and services and the implications of various strategies. Understanding how people travel in various environments may serve this goal.

Within the constraints of policy and physical environment, households express their needs and preferences through decisions at various temporal scales—from choosing a residence, to acquiring or shedding vehicles, to daily travel choices. Relevant factors include traits of the household and its members, as well as features of the physical environment. Established theory and earlier empirical work suggest relationships to be modeled and new measurement techniques to be tested. Research into what factors are relevant to the travel-related decisions households face may illuminate where urban design and planning tools could lead to environments more responsive to household needs and preferences and able to shape travel choices to benefit society.

The relation of the built environment with residential location and auto ownership merits deeper exploration (Eliasson and Martinez, 2001; Waddell, 2001). Although planners know from experience that urban form affects location decisions, housing prices, auto ownership, and travel behavior, rigorous empirical treatment of these interactions is not yet mature. This dissertation looks at household decisions—given residential location in neighborhoods with quantitatively described physical attributes—relating to auto ownership and travel behavior, using a single dataset containing a core set of independent variables that theory and prior research suggest as relevant, as well as additional variables important for particular temporal scales of household decisions.

### *Research questions*

This work considers household decisions of different temporal scales, with less common decisions impacting subsequent—and more frequent—decisions by altering the choice set. For example, mode choice for routine travel is constrained, in part, by the number of autos held by a household, as well as by residential location and the transportation alternatives at that site. Thus, location may affect travel choices directly, as well as indirectly through auto ownership. This dissertation uses, as an exogenous input, a newly developed typology (a "transect") of neighborhood types to characterize residential location, with extremes of rural and intensely urban neighborhoods, and five intermediate types characterized by particular mixes of features likely to influence travel behavior. A general depiction of the relationships of interest follows:

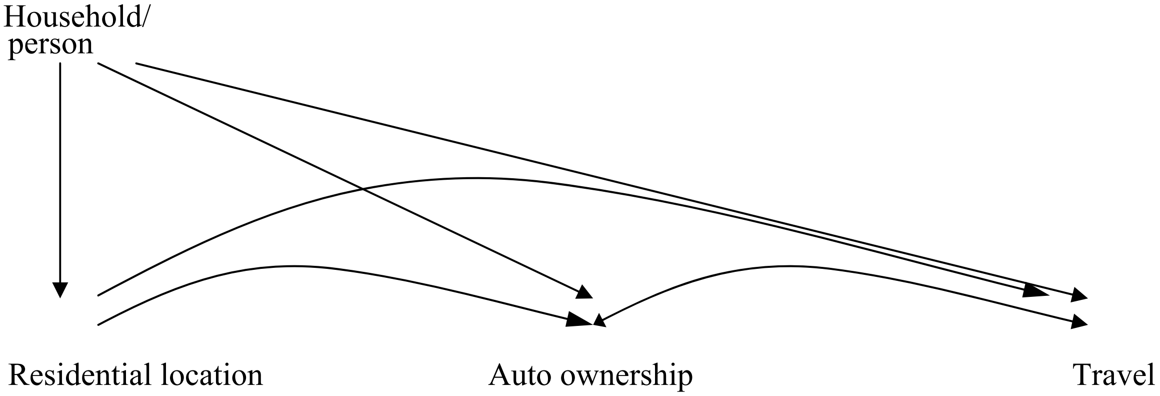


**Figure 1. Direct and indirect relationships among household decisions relating to residential location, auto ownership, and travel**

Research questions include:

- How do neighborhood type or environmental characteristics relate to auto ownership, expressed as number of vehicles held by a household?
- How do neighborhood type or environmental characteristics relate to travel behavior, expressed as numbers of trips and mode choice?

And, more generally:

- What socioeconomic and environmental factors are associated with long-term choices (auto ownership) versus short-term decisions (trips, mode choice)?
- How are long- and short-term decisions related, through direct and indirect associations among common model variables?

Extensive research already has been done on many of these relationships. However, most such studies focus on one of these temporal scales of decision-making, while suggesting likely links with other decisions made at other (more or less frequent) levels. Thus, subsequent studies may pick up the challenge of tying certain household decisions into other research on decisions made in shorter or longer time frames, but typically use data collected from other locations and times, surrendering some of the comparability and generalizability of findings. This dissertation uses a single data set to examine household decisions that represent different temporal scales, and identify a set of common household variables that may be useful in understanding auto ownership and travel in other spatial and temporal contexts. Path analysis is used to examine the relationship of environment with travel—both directly, and indirectly through auto ownership. In addition, environmental measures describing residential location and trip origins and destinations are considered in relation to auto ownership and travel, and incorporated into statistical models in three different environmental representations, then evaluated and compared, to show how different approaches to quantifying the environment relate to the modeled decisions.

This work contributes to land use and travel research by considering decisions representing multiple temporal scales with an extensive set of data collected in a single time and place. In addition, this research advances travel modeling approaches by comparing results using a select set of frequently used environmental measures with a complex representation of residential neighborhood type generated by factor and cluster analysis, which characterizes neighborhoods in terms of features commonly used to distinguish, for example, traditional and neo-traditional from conventional suburban neighborhoods. This makes it possible to tell a more complete and compelling story about household decisions in the long and short terms and how they are related for the study area, and contribute to a body of research that may inform research and practice in urban form and travel behavior.

The objectives of this research are to

1) Understand how auto ownership and travel behavior vary across physical environments
2) Understand direct and indirect associations between environment and travel behavior, mediated by auto ownership
3) Model and describe differences in environmental representations in travel models

Chapter 2 reviews the theoretical foundations for this work, drawing on microeconomics and decision behavior, as well as the literature relating to physical environment, residential location, auto ownership, and travel behavior. Chapter 3 offers a conceptual framework and states the hypotheses to be tested, while Chapter 4 details the research design, study site, data collection and preparation, and model specification. Results of modeling are presented in Chapters 5 (autos and trips) and 6 (mode choice); these chapters include path analysis of two different decision chains, ending in trips and modes. Chapter 7 includes a summary of findings and a comparison of the three different representations as they performed in the models, and further discusses the path analysis as well as policy and research relevance of all models presented here. A conclusion follows in Chapter 8, including implications of this work for future travel behavior research.

# 2. Empirical and Theoretical Literature

The chains of decisions households make regarding residential location, auto ownership, and travel are embedded in the physical and social systems that support travel and other human activity. The literature relevant to this work includes residential location and auto ownership, environment and travel behavior, and quantitative measurement of the environment. The underlying theoretical base draws from microeconomics and decision behavior.

The evolving consensus that land use and transportation are complex and interwoven systems both motivates and complicates research into the interaction of travel behavior and the environment. While research has been intense, unambiguous findings and concrete practical guidance for practitioners remain elusive. Several recent reviews summarize research to date, pointing out conflicting findings and gaps in the research (Badoe and Miller, 2000; Boarnet and Crane, 2001a; Ewing and Cervero, 2001; Krizek, 2003a), and highlighting the need for an integrated approach to studying travel behavior within the environment.

Beyond the established literature on urban form and transportation, theory and research in microeconomics and decision are relevant to decisions linking residential location and auto ownership to routine travel behavior. Decision behavior theory offers grounding in individual and group decision-making, and provides tools to investigate such questions as short- vs. long-term decisions, decision-making under uncertainty, multi-attribute utility estimates, and risk assessment. The effort devoted to specific decisions may depend in part on the complexity of the decision and possible outcomes, and on the stakes involved (commitment of time or money, or other possible consequences such as implications for other people). Long-term decisions, such as residential location and type of home, as well as the number and type of vehicles a household owns, interact (in both directions) with short-term decisions of daily travel behavior, including the initial decision to travel, as well as destination, mode, time and route. Daily travel is in part a routine, which may be altered more or less easily depending on the habits and characteristics of the traveler, openness or resistance to change, and personal circumstances, as well as external factors such as traffic or weather conditions.

### a. Microeconomics and decision behavior

Decision behavior has a more central place in current travel modeling, compared to early efforts using aggregate models of volume flows (Hartgen, 1981) that ignored the individual traveler. As the need to include decision behavior in travel forecasting became accepted as axiomatic, the challenge lay in reconciling such disparate disciplines as neoclassical economics and cognitive psychology, each of which offers useful concepts (McFadden, 1999). These two fields take different views of decision-making, with psychology focused on the nature of decision elements, values, and the human experience, while economics assumes that the cognitive process maximizes personal utility and maps information inputs directly to choices. That is, pure economics is outcome-focused, and does not concern itself with human motivations and values. Consumers are assumed to seek to maximize innate and stable pre-determined preferences, i.e., the preference precedes the availability (McFadden, 2001); this is not always relevant to travel behavior, where travelers may be forced to adjust preferences to limited or dynamic options.

This dissertation focuses on two sets of inputs to travel models—socio-demographic measures of households and travelers, and environmental measures—while acknowledging the relevance of factors not measured here, such as preferences and social obligations, or detailed representation of the transportation system. Microeconomics and decision behavior provide two key theoretical frameworks to support this research into auto ownership and travel decisions.

### *Microeconomic theory*

Microeconomic theory posits that independent decision-makers identify alternatives, evaluate the economic consequences, and maximize utility through their discrete choices. Thus, assuming economic rationality as well as perfect knowledge of alternatives and consequences, behavior can be predicted, given information about risks and constraints. Utility maximization suggests that higher costs (or generalized disutility) would encourage mode switching, substitution of destinations, or foregone trips. Extreme increases in cost may have upstream effects on more fundamental decisions such as location or auto ownership.

Research design based on well-substantiated methodology is essential to inferring relationships or laws that describe, explain, and predict processes and events. Based on theory dating back to the 19th century (de Palma, 1998), the discrete choice modeling first used in transportation research in the mid-20th century saw major advances with McFadden's econometric multinomial logistic estimations. Microeconomic theory may be further refined in travel modeling through addition of more dimensions in choice sets, including activity, mode and destination—refinements that may be hampered by budgetary, information and other constraints.

Some adaptations to microeconomic theory accommodate Simon's bounded rationality. For example, Payne (1993) assumes that tradeoffs depend on several mediating factors: characteristics of the decision task (number and attributes of alternatives), presentation of information, the time available to decide, personal traits such as prior knowledge or expertise, and the social context of expectations and accountability. As related to this research, travel decisions such as mode choice may be constrained by real or perceived alternatives (e.g., transit service), household characteristics, costs to travel as well as obtain more information, and other factors.

Location research, including residential choice, draws heavily on micro-economics, often treating the choice from among available homes and neighborhoods as a classic problem of economic rationality. Models that assume residential location to be a function of transportation and housing tradeoffs remain in active development, including recent elaborations that extend the chain of associations from land use to travel behavior and on to air quality. For example, Lam and Niemier (2005) used policy scenarios to investigate the combined effects of land use and land market measures on vehicle emissions, mediated through residential mobility. Waddell and Nourzad (2002) used a spatially disaggregated model to test the influence of local and regional accessibility on residential location, as well as the role of auto ownership, finding significant relationships for all of these.

### *Decision behavior theory*

While microeconomic theory often is used to predict *outcomes* from rational choices, decision behavior theory more often focuses on the *process*. Decision behavior research is an empirical approach to describing and understanding human decisions; good decisions are those where the action or outcome matches the decision-maker's objective. Understanding decision-making is relevant to the study of travel choices, as human behavior often is a confounding force in both research and practice. Beyond travel-specific decision-making, 20th-century decision theory has included both a descriptive focus on how people actually make decisions, and a normative vision of how decisions *should* be made (Svenson, 1998).

The capacity to make qualitative predictions makes behavioral modeling particularly relevant to travel choice, which to date has relied more on quantitative modeling and forecasting. Inclusion of qualitative measures is consistent with the theoretical tradition of Simon, who valued laws of qualitative structure as well as quantitative relationships (Garling et al., 1998).

Decision behavior theory includes many approaches that may be useful in studying travel behavior, such as subjective utility theory, the related multi-attribute utility theory (with weighted utilities and estimated probabilities related to risk or uncertainty), and Simon's satisficing concept of adjusting goals and values to the environment.

Sequential decision-making, commonly conceptualized in structural models (Svenson, 1998), is relevant to the chains that link residential location and auto ownership to short-term travel decisions made in dynamic environments. Sequential linking occurs through 1) formation of strategy or routine; 2) similar problems that appear in sequence; or 3) early decisions that dictate conditions for later decisions and help form choice sets.

### *Travel behavior modeling*

Travel modeling in recent decades has drawn on a blend of consumer theory from economics and choice theory from psychology (Levin and Louviere, 1981). Mental accounting (Thaler,

2000) may explain some travel decisions. Applying mental accounting to pay-as-you-drive insurance products, which convert fixed insurance fees to per-mile charges as an incentive to reduce driving, Greenberg (2006) found that framing of economic choices affects decisions.

Early models of travel choices, which considered single-worker households in terms of access to a regional center, transportation level of service, autos, and socio-demographic factors (Lerman, 1976; Ben-Akiva and Lerman, 1976), have been extended. Looking at dual-income households, Plaut (2006) found that owners commute farther than renters, and men farther than women, although commute trips by household partners seem to be complements rather than substitutes, suggesting a household location decision process that accounts for both commuters in addition to house and neighborhood attributes. Commuting by women appears to be more sensitive to house value and more elastic in pursuit of better housing. Clark et al. (2003) used longitudinal data to model household location and commuting distance for a multimodal city (rather than monocentric) for 1- and 2-worker households.

The recent move toward activity-based modeling requires more detailed data and greater sophistication in model structure; at the same time, such approaches offer the promise of more nuanced and realistic model output. For example, Dong et al. (2006) propose an activity-based accessibility measure that builds on random utility theory, but incorporates socioeconomic traits, trip chaining and activity scheduling to describe the impact on travelers of various transportation and land use policies. Davidson et al. (2007) cite three key elements of emerging regional travel demand models, including a framework derived from daily activities, tours as the modeling unit rather than trips, and disaggregate (individual or household) micro-simulation modeling to convert activity and travel choices into probabilities-based discrete choices.

### *Travel behavior and habit formation*

Among the many schools of decision theory, Fishbein and Ajzen's (1975) seminal theory of planned behavior holds that three types of beliefs guide behavior: behavioral (concerned with consequences), normative (expectations), and control (factors that encourage or impede certain behaviors). At odds with this theory of reasoned, planned behavior is the notion that habits can take over decision-making and bypass the deliberative process. Habit formation is relevant to travel research because of the potential for repeated action to develop into habits—automated cognitive processes triggered by situational factors (Aarts et al., 1997).

Recent work on travel choices has built on decision behavior theory, with a particular focus on habit and inertia in travel mode choice. Verplanken et al. (1997) found that subjects with a strong habit for a particular travel mode used less information and displayed a less complex choice process than others who engaged in a more elaborate deliberative process. Testing the power of habits to endure even when the context shifts, Garling et al. (2001) found that subjects continued to drive to distant destinations even after attractive destinations moved closer. Other studies (Fujii and Kitamura, 2003; Rose and Marfurt; 2007) have found that temporary changes in infrastructure or policy may induce behavioral changes in the case of social dilemmas such as excessive auto use—which benefits individual drivers while imposing costs on society. Bamberg et al. (2003) question the role of habit in travel choices, finding evidence of openness of certain populations to changing behavior.

Svenson (1998) describes multi-level decisions, starting with first-level habit-based responses that do not consider values or utility. The 2nd level may weight attractiveness of attributes, but relies on stereotypical and static mental maps of alternatives, while 3rd-level decisions may trade off attractiveness of various attributes. At the 4th level, new or unfamiliar problems or other circumstances prompt the decision-maker to identify or create new alternatives in an active form of decision-making that may confer greater perceived control and produce less regret. Travel choices often fall near the habitual end of series of linked decisions, where prior decisions dictate the choice set (Svenson, 1998).

### b. Residential location and auto ownership

The residential location process is relevant to this dissertation as an input into models for auto ownership and travel behavior. Residential location decisions, like auto ownership, are entangled in relationships with socioeconomic household traits, attitudes and preferences, and exogenous factors such as physical environment (built and natural) and regional accessibility, as well as attributes of homes in the choice set. Both auto ownership and residential location are appropriate areas for probing qualitative research (Clifton and Handy, 2003), despite an earlier tradition of treating residential location as a classically rational economic decision where buyers weigh bundles of attributes of a residence and its immediate surroundings, including travel costs and options, and the distribution of goods and services, to maximize household utility (McFadden, 1978; Jara-Diaz and Martinez, 1999). This assumes that property is freely traded and buyers have perfect knowledge of the market (Alonso, 1964), a condition that—while unrealistic—may be closer today than earlier, given the penetration of electronic media and ready information retrieval.

The association between residential location and travel is bi-directional. Residential location decisions may respond to and influence transportation infrastructure and travel alternatives. Although the Bay Area Rapid Transit (BART) in the San Francisco Bay Area had largely localized and uneven effects, falling short of projections for strong and uniform subcenters (Cervero and Landis, 1997), positive outcomes of BART were realized. These include retention of downtown San Francisco as the regional anchor, and moderately focused development around several stations with strong BART ridership. Levine (1992) examined how different patterns of suburbanization affect commuting; where multi-family housing doesn't keep pace with suburban employment, lower-income households commute farther, suggesting a positive effect from the availability of multi-family housing on residential location decisions of low- and moderate-income households.

Although much of the research on urban form and travel behavior focuses on short-term—generally daily—travel decisions, the need to account for longer-term decisions by households with regard to location and type of home and number and types of automobiles is reflected, for example, in auto ownership components in integrated models (Bhat and Pulugurta, 1998; Bunch, 2000). McFadden (1974) noted over 30 years ago that, in order to estimate urban travel demand, disaggregate travel behavior must be analyzed in the context of auto ownership and residential location. While the prevailing trend in current travel modeling is toward fully disaggregate modeling of individual behavior, the interactive decision-making process in households is important to take into account (Daly, 1981). Auto ownership is of particular interest, given the accepted link between auto ownership and use; that is, once purchased, cars tend to be driven.

Auto ownership may be lower in mixed-use neighborhoods; Hess and Ong, (2002) found, in particular, that inner-ring suburbs with traditional design offer alternatives to car ownership. Auto ownership and use may be sensitive to both neighborhood features such as commerce (Cervero, 1996a), density, or transit access, and to socioeconomic traits such as income and household size (Holtzclaw et al., 2002; Messenger and Ewing, 1996; Voith, 1991), with rising income linked to increased auto ownership and use, and attendant decreases in public modes (Paulley et al., 2006). Ownership and acquisition may differ across urban and rural areas (Dargay, 2002), and socioeconomic groups (Gardenhire and Sermons, 1999), as poorer households convert income into autos at a higher rate, and additional adults into autos at a lower rate, than non-poor households. Comparative modeling (Giuliano and Dargay, 2006) of U.S. and British auto ownership and use found differences in travel to be related to demographic differences, lower income levels in Great Britain, and other country-specific differences in travel costs and transport supply, with a much stronger inverse relationship between daily travel distance and local population density in the U.S.

Both number and type of vehicles held by a household relate to socio-demographic factors and features of the residential environment (Bhat and Sen, 2006), as well as vehicle attributes such as cost of operation. Cao et al. (2006a) found vehicle type to be sensitive to not only socio-demographic characteristics and attitudes, but also environmental factors like commute distance, parking, and residential lot size; light-duty vehicles (minivans and sport utility vehicles) were more strongly associated with suburban neighborhoods, and passenger vehicles with traditional designs. Plaut (2004) found associations between vehicle type and socioeconomic traits such as income and education, as did Choo and Mokhtarian (2004), who also identified attitudes, personality, lifestyle, and mobility measures as significant.

Recent developments in auto availability blur the link between auto ownership and use. A recent model to emerge, first in Europe and more recently in the U.S., is car-sharing—a type of collective ownership that offers short-term vehicle use. Members typically pay an annual fee, as well as mileage- or time-based charges, and may access a wide variety of vehicle types at multiple depots. Car shares are operating in several dozen U.S. cities (Shaheen et al., 2006), as well as several university campuses. Schuster et al. (2005) modeled the economic decision to own or share a vehicle, concluding that policies to promote car-sharing are likely to bring increasing marginal social benefits even as individuals engage in the behavior for their own economic gain.

Any influence of the built environment (both hard design features, and performance or policy constraints such as congestion or parking costs) should be manifest more slowly in car ownership than in routine travel behavior. Although the influence of auto and home ownership is largely one-way (i.e., once the home is purchased and the cars in the driveway, auto travel will follow), there may be some influence in the other direction for residents who find their neighborhoods support lower car ownership and use, or home buyers who discover new options for exercise, shopping or other activities within the neighborhood.

Table 1 summarizes key empirical research findings relating to the association between physical environment and auto ownership.

**TABLE 1 Key findings in the literature relating to environment and auto ownership**

| Author | Type of study | Key findings |
|---|---|---|
| Bhat and Sen, 2006 | Models of vehicle holdings and use with San Francisco survey data | Vehicle holdings and use shaped by household factors, residential location, vehicle attributes |
| Cao et al., 2006a | Vehicle type relative to urban form, household, attitudes, No. California | Neighborhood design associated with vehicle type; light-duty trucks associated with suburbs |
| Hess and Ong, 2002 | Number of household autos relative to urban form, household factors, Portland | Traditional neighborhoods support alternatives to private auto; inner-ring suburbs offer travel choices |
| Holtzclaw et al., 2002 | Auto ownership/VMT relative to household factors, density, transit, shopping | Average auto ownership a function of residential density, income, family size, and transit access |

### c. Environment and travel behavior

Interest in assessing the performance of neo-traditional development (here referring to a suite of popular approaches, including smart growth, new urbanism, transit-oriented design, and others) has grown as the trend has taken hold; Berke et al. (2003) estimated 1.4 million people already living in new urbanist communities in 2003—half established on greenfield sites, with the number of such projects growing steadily. Researchers have employed various approaches to studying the multiple levels of relationships among land use, transportation systems, and human behavior. Acceptance of the centrality of human behavior is evident in the trend toward behavior-oriented inquiry, such as activity-based modeling (Krizek, 2000; Krizek and Waddell, 2002; Waddell, 2001) and decision behavior analysis.

Handy (1996a) suggests that research into urban form and travel behavior should shift the focus away from changing behavior to identifying strategies that provide choices. Current urban design philosophies tend to emphasize accessibility (the ability to reach desired destinations easily) over mobility (the ability to travel fast and far), by altering the environment to offer choices and alternatives (Levine, 1999). A combination of urban design, land use zoning, and transportation systems intended to promote non-motorized travel may create healthier and more livable communities (Handy et al., 2002), but refined modeling approaches will be necessary to assess this, including better measures of the environment, more complete data on non-motorized travel, and spatial matching of travel data.

### *Environment and travel—Empirical evidence*

Extensive research has demonstrated an association between physical environment and travel behavior. Rodriguez and Joo (2004) found environmental attributes such as sidewalks and gentle topography to be associated with attractiveness of non-motorized modes. Commercial services within neighborhoods may better predict non-motorized trips than does residential density (Cervero, 1996a). In addition, within-neighborhood distances are important; Cervero (1996a) found consumer services within 300 feet of residences to encourage non-auto commuting, while services between 300 feet and 1 mile were associated with more auto commuting, likely because of linked work and shop trips. Shay et al. (2006) found differences between the walk and drive modes in the number of internal utilitarian trips within a neo-traditional neighborhood, where walk trips drop off sharply as the distances between residences and the commercial center increase, and drive trips increase, albeit more slowly. Frank and Pivo (1994), testing environmental influence on commute and shopping trips, found both density and diversity of land uses to have a significant and nonlinear relationship with mode choice. Trips of different types (e.g., the journey to work versus non-commute) may respond differently to environmental factors (Meurs and Haaijer, 2001).

The complexity of travel behavior and its multiple measures make it difficult to say unequivocally how the environment affects trip generation and travel distance. Several studies suggest local trips substituting for some regional trips in neo-traditional developments (Cervero and Radisch, 1995; Handy, 1996b; Handy and Clifton, 2001; Krizek, 2003a, 2003b; Khattak and Stone, 2004).

Crane (1996a, b) and Berman (1996) found that alternatives to conventional low-density, single-use development offer potential benefits in reduced auto use, but that the net effects from open grids of short blocks, mixed uses, and higher densities are an empirical question, and that such designs may have been oversold without full knowledge of the critical thresholds and combinations of design features. The increased proximity afforded by mixing residential, retail, and office land uses appears to support walking trips; however, it is less clear whether such trips complement or substitute for existing trips that rely on motorized modes (Ewing and Cervero, 2001; Handy, 2006). Likewise, higher density may shorten travel distances, but its impact on travel speeds is less certain; in addition, trip generation may increase (Boarnet and Crane, 2001a; Crane and Crepeau, 1998). The success of neo-traditional development may be limited by a lack of regional planning and policy initiatives (Cervero, 1996b), or ineffective street design and lack of spatial legibility (Crane and Crepeau, 1998), as well as limited knowledge on the part of developers and consumers.

Evidence of the link between land use and travel behavior is mixed (Boarnet and Sarmiento, 1998; Ewing et al., 1996). In reviewing dozens of studies on the environment and travel behavior, Ewing and Cervero (2001) concluded that trip generation relates more to household socioeconomic traits than urban form, although mode choice is more sensitive to local land use. Regional and local accessibility appear to influence distances, but not frequency, of shopping trips (Handy, 1993). Ewing (1995) determined total travel to be a function of regional access, and thus largely beyond the power of individual neighborhoods to shape. Giuliano (1999) asserts that policy has limited power to affect auto travel, because land use changes are slow and driven by factors over which policy exerts little control, while Kenworthy and Laube (1999) contend that policy and planning tools may be useful in addressing excessive auto dependency and declining transit use and non-motorized travel.

Southworth (2005) describes six key aspects of the physical environment that may encourage mode-switching away from driving: connectivity of the street network, multimodal networks, finely mixed land uses, safe conditions, and the quality and larger context (surrounding activities and environment) of routes. Many of these characteristics are incorporated into the environmental representations modeled in this dissertation.

### *Environment and travel—Methodological issues*

Major research approaches to studying the interaction of physical environment and travel behavior include cross-sectional studies, and quasi-experimental designs that take advantage of urban design trends to compare traditional or recently built neo-traditional with conventional neighborhoods. A major review (Ewing and Cervero, 2001) included studies that match neo-traditional developments with conventional residential-only neighborhoods of large lots and limited support for walking, cycling, and transit. The neighborhoods typically are matched on characteristics such as household income, residents' age, neighborhood age, house size, neighborhood size, and access to services. Many studies have found higher pedestrian and/or transit travel in such neighborhoods (Cervero and Gorham, 1995; Cervero and Radisch, 1995; Friedman et al., 1994; Handy, 1996a; Khattak and Rodriguez, 2005; Kitamura et al., 1997; Lund, 2003) and lower auto travel (Cervero and Kockelman, 1997).

Plaut (2005) found mode choice to be associated not only with race, gender, education, and household income, but also with location (relative to the region) and neighborhood features. Moreover, studies suggest that travel times and/or distances are shorter in neo-traditional neighborhoods (Ewing et al., 1994; Khattak and Rodriguez, 2005; McCormack et al., 2001), although the more modest differences in travel times may relate to a travel time budget that is less responsive to urban form than are other measures of travel behavior (Ausubel et al., 1998; Rutherford et al., 1996). Golob et al. (1981) interpret the travel time and cost budgets in terms of economic utility, where expenditures can be taken as fixed in the short term but potentially variable in the long run under utility maximization. The disputed travel time budget has implications for both research and policy; if average daily travel time and cost budgets, as well as trip rates, are indeed relatively inelastic, even as auto ownership and VMT continue to grow, then the appropriate and effective focus of policy is more likely to be the quality of the journey than the quantity of travel (Metz, 2005).

Cervero (2002) calls for better specification of relationships between environment and travel mode, which may be more responsive to density and land uses than to design elements. Although mode choice is modeled after trip generation (the decision to make a trip) and distribution (choice of destination) in traditional 4-step travel demand modeling, some research suggests that new approaches are in order. Cervero and Duncan (2003) found that built environment factors exerted weaker (though statistically significant) effects on walking and biking than exogenous factors such as terrain, weather, crime safety, and darkness—suggesting the need for new approaches to studying non-motorized travel in the environment.

Self-selection often is cited as a concern with cross-sectional and quasi-experimental research. If residents choose a neighborhood based in part on preferred current or future travel patterns, lower auto ownership may signify a design that attracts and concentrates households with such preferences rather than a change in auto ownership and travel habits prompted by the environment. Modeling advances may be useful for testing claims of causality, and may inform policy that addresses both location and auto ownership decisions. For example, Bhat and Guo (2006) reported that household factors may be more important than the environment in auto ownership, while income is the dominant factor in residential sorting as well as a key factor affecting sensitivity to the environment, such that "ignoring income effects in car ownership (and by extension, other travel decisions) can lead to an inflated effect of the built environment and related variables on travel behavior decision."

Although many studies show reduced auto travel in neighborhoods characterized by higher density, mixed uses, and transit access, the direction of causality is not always clear. Using a quasi-longitudinal approach, Handy et al. (2005) found a small but significant association between travel behavior and built environment, although attitudes remained the dominant explanatory variables. The technique of seemingly unrelated regression applied to these data revealed a substantial influence of self-selected residential location on non-motorized travel, while attitudes about travel and residential location contributed less to auto and transit travel (Cao et al., 2006b). Using a longitudinal design, Krizek (2000) found an effect of neo-traditional design separate from a self-selection effect, as did Khattak and Rodriguez (2005), who used instrumental variables for qualitative questions in a study of a matched pair of conventional and neo-traditional neighborhoods. Self-selection may be less relevant from a policy perspective than in the research domain; as long as unsatisfied demand remains, as evident in the high price premium usually paid for these locations, such neo-traditional neighborhoods provide an environment that supports travel options for residents, whether they are new converts or self-selecters.

### *Environmental measurement*

Many studies to date have used starkly contrasting study sites to highlight differences in travel behavior. In reality, traditional and neo-traditional neighborhoods vary in the degree to which they express the design principles that characterize this approach—described by Cervero and Kockelman (1997) as the "3 Ds" of density, diverse land uses, and design. A typology of neighborhood designs, rather than an artificial conventional/traditional distinction, may permit a fuller look at the physical environment and travel behavior.

Although qualitative representations of neighborhood type based on historical reviews and visual interpretation of land use patterns may provide useful frameworks, advances in GIS capability and increasingly abundant data sources offer opportunities for quantitative approaches to classifying neighborhoods. Such efforts to characterize physical form are useful in the debate on urban growth management because they help organize and structure complex ideas, facilitate rigorous quantitative analysis, and support development, implementation and evaluation of public policy (Song and Knaap, 2007). These may be useful in behavioral research relating to, for example, residential location, auto ownership, or travel behavior.

A recent approach to emerge is the transect—a linear, cross-sectional progression of land uses along a gradient from rural to urban, within which various types can be distinguished in terms of physical design, social structure, and natural environment. While a potentially powerful tool for modeling, analysis, and policy development, transects present technical challenges, including boundary issues and choice of appropriately scaled units of analysis.

The transect approach advanced by Duany and others (Duany and Talen, 2002) is a geographical cross-section of a region that describes human habitats in terms of intensity of urban character, organizing the elements of the human environment—from buildings and lots to streets and neighborhoods. Inspired by the ecological process of natural selection, transect planning seeks to identify the most salient qualities of a local environment, whether rural or urban, and arrange them in the most effective pattern. Transects also serve as useful analytic tools, to discover and describe the range of habitats in a region (Duany and Talen, 2002).

Factor and cluster analysis are techniques used widely in urban planning, geography, and sociology (Bagley et al., 2002; Krizek and Waddell, 2003; McNally and Kulkarni, 1997; Song and Knaap, 2004). Cervero and Kockelman (1997) used factor analysis in their work describing the “3 Ds” of density, design, and land use diversity. Recent efforts to quantitatively describe the physical environment include techniques to operationalize such concepts as neighborhood accessibility as multiple dimensions of density, land use, and street design (Krizek, 2005). Such a refined classification of neighborhood types can illuminate the interaction of environment with auto ownership and travel.

This dissertation incorporates recent work by researchers who used the same dataset to reduce a set of 373 census block groups in the Charlotte (North Carolina) metropolitan area into seven neighborhood types. This typology serves as a set of independent variables in models that use residential location as explanatory variables for auto ownership and travel. The factor analysis employed here goes beyond some other studies by using not only built environment features, but also social measures such as property values and employment density.

### *Non-environmental measures*

Household and personal factors may interact with environmental. McDonald (2005) found a gender-specific effect of residential density on trips made by women with children. Another study (Clifton and Dill, 2005) showed men to be more responsive to walk-friendly environments than females, who are more sensitive to other factors such as family responsibilities. Gender differences in travel behavior also may relate to perceptions of the environment, including safety (Clifton and Livi, 2005). Helling (2000) found a stronger link between better accessibility to employment and travel (more but shorter trips) for employed men than for women. Sex as an explanatory variable for travel behavior may depend in part on life cycle, as women in particular move in and out of the labor market with the birth and aging of children. Women may be more willing to reduce auto use than men, partly because of environmental sensitivity and weaker auto habits (Matthies et al., 2002).

Age and school status likewise may be important in mode choice, including the bus vs. car decision, as well as in choosing active modes such as walking and cycling. One study found mode choice for kindergarten through 8th-grade students related to numbers and ages of children in the household, as well as household income and subjective measures of convenience and safety (Rhoulac, 2005). Mode splits differed in the morning and afternoon for schoolchildren (Schlossberg et al., 2006), suggesting that family factors like parents' work routines may be relevant in addition to environmental factors such as distance and sidewalks. Other factors, besides distance, may include traffic, weather, crime, and school policy (Martin and Carlson, 2005).

At the other end of the life cycle, Kim and Ulfarsson (2004) found that mode choice for the elderly (over 65) and retired is sensitive to neighborhood and trip characteristics, and personal and household factors. Although walking might reasonably be expected to decrease with advanced age, it also is an attractive mode for the healthy elderly, in part because of the personal freedom it offers; some individuals may find themselves making *more* trips with age because of more disposable time, freedom from a work schedule, a change in life cycle, or the desire to stay physically active. Thus, age-related differences in travel behavior may be more usefully described as life-cycle factors.

In travel behavior research, factors outside the strict transportation realm are relevant, e.g., social roles, institutions, and policy constraints (Bourgin, 1981). Pucher and Buehler (2006) report much higher bicycling activity in Canada than the U.S., despite a harsher climate, which they attribute not to history, culture, or resources, but rather to policy-relevant factors such as higher costs of auto travel, better infrastructure, and urban design factors (density and land use mixing). Using neighborhood clusters based on transit and pedestrian characteristics, urban design analysis, and household surveys to look at residential preferences, Levine et al. (2001) found significant differences in transit and pedestrian quality of two groups beyond what preferences could explain.

Attitudes and preferences may be under-studied determinants of travel behavior (Bagley and Mokhtarian, 2001; Clay and Mokhtarian, 2004; Kitamura et al., 1997; Schwanen and Mokhtarian, 2005), in part because of a mismatch between preferences and available options. The travel experience has not only a time component, but also associated desires, affinities, and attitudes not captured in models, which may hinder the success of public policy intended to reduce vehicle travel (Cao and Mokhtarian, 2005). Recent work suggests that attitudes and personality, as revealed by other (non-travel) choices, may be important in mode choice (Johansson et al., 2005) and vehicle type (Choo and Mokhtarian, 2004). At the same time, there is evidence of excess travel, where travelers do not always take advantage of opportunities to reduce travel (Krizek, 2003b; Mokhtarian et al., 2001; Salomon and Mokhtarian, 1998).

Thogersen (2005) used panel data to consider past behavior in choosing transit, and found non-car-owners are more sensitive to attitudes and perceptions about the adequacy of transit, while such attitudes were not important for those with access to a vehicle. Perceived mobility and personal preferences and attitudes toward travel are important attributes that may distinguish travelers and affect their receptiveness to various policies. Attitudes are social in origin—emerging from and embedded in social interactions (Wood, 2000), such that the study of attitudes should relate to both individuals and group influences, while accounting for processes specific to each.

### *Physical activity and travel*

A recent surge of research into physical activity and health, motivated largely by epidemic levels of overweight and obesity in the U.S. as well as increasing morbidity linked to air quality, has energized inquiry into non-motorized travel and the potential for the built environment to improve public health. Indeed, physical activity has been identified as a key research arena that can restore former close links between the disciplines of public health and urban planning (Frank and Engelke, 2001; Northridge et al., 2003). While some physical activity research is planted firmly in the health research literature, much of it is done by interdisciplinary teams from public health, planning, and policy. Because these fields may view physical activity differently (Sallis et al., 2004), the research done at this interface may involve new approaches, including interaction of psychosocial and environmental variables (Saelens et al., 2003a), policy analysis, and socio-ecological models. The latter can accommodate multiple scales (individual, household, neighborhood, and community) and the interaction of biological, behavioral, social and environmental factors over time (Baker et al., 2000; Sallis et al., 1998; Satariano and McAuley, 2003).

Physical activity research is relevant to this dissertation insofar as it looks for correlates of walking in the physical environment, among other factors, with implications for transportation planning and management. The Transportation Research Board and Institute of Medicine (both constituent members of the National Academies) jointly issued a summary report in January 2005 (TRB, 2005), which asked “Does the Built Environment Influence Physical Activity?” and called for a sound theoretical framework to support research that will uncover causal relationships and distinguish among personal attitudes, residential location decisions, and characteristics of the environment. This ultimately should generate practical guidelines for increasing physical activity and improving health. Scholars in the health sciences also have called for research to identify correlates of non-motorized travel and to integrate theory and practice across disciplines (Aronson and Oman, 2004; Bauman et al., 2002; Eyler et al., 2003; Humpel et al., 2002; King et al., 2002; Pikora et al., 2003).

Studies from the public health literature report correlations between walking (and other forms of physical activity) and such features as sidewalks and other facilities for non-motorized travel, scenery, terrain, land use mix, traffic, and age of homes—the latter to proxy the design paradigms of conventional versus traditional (pre-World War II) and neo-traditional (Addy and Wilson, 2004; Berrigan and Troiano, 2002; Brownson et al., 2001; Doyle et al., 2006; Frank et al., 2004; Huston et al., 2003; Kim and Kaplan, 2004; King et al., 2003; Owen et al., 2004; Troped et al., 2003).

Research already conducted into environmental correlates of non-motorized travel has generated somewhat mixed findings. Badland and Schofield (2005) found land-use mixing, density, and design to be relevant for physical activity. In highly walkable neighborhoods, with higher density, land use mix, connectivity, aesthetics, and safety, residents engage in more physical activity and have lower body-mass indexes (Saelens et al., 2003b). Moudon et al. (1997) found clear differences in pedestrian volumes in neighborhoods classified as urban and suburban according to residential density, with much higher pedestrian traffic in urban environments; still, they concluded that suburban residents would choose to walk more, given the opportunity. Sallis et al. (1997) found little contribution of physical environment variables to variation in physical activity of college students. Giuliano and Hu (2003) found only a limited effect of transit-supportive and mixed-use design on elderly travelers, while Burkhardt (1999) found a stronger relationship for that population.

The purpose of travel (recreational vs. utilitarian) may be relevant to the impact of the built environment on pedestrian travel (Cao et al., 2006b). Rodriguez et al. (2006) found that physical activity did not increase in a neo-traditional neighborhood compared to a matched conventional site, but that the location changed as residents substituted within-neighborhood utilitarian trips for physical activity trips outside the neighborhood. Troped et al. (2003) found the environment to be associated with utilitarian but not recreational physical activity.

Table 2 summarizes key research in the literature relative to the association between physical environment and travel behavior.

**TABLE 2 Key findings in the literature relating to environment and travel**

| Author and year | Type of study | Key findings |
|---|---|---|
| Boarnet & Crane, 2001b | Monograph focusing on trends and premises in urban design and transport planning | Travel behavior, modeling, travel planning: Can it work? Will/should it be implemented? |
| Cervero, 1996a | Mode choice relative to environment; American Housing Survey data | Residential density more important than mixed use for commute mode; services key for nonmotorized |
| Crane, 2000 | Review of studies of neighborhood design and travel behavior, methodology | Important for scholars and practitioners, but use of urban form to change travel behavior still tentative |
| Ewing & Cervero, 2001 | Review of >50 empirical studies of travel demand and built environment | Number trips more sensitive to household factors than urban form; mode choice sensitive to both |
| Handy, 2006 | Discussion of research on new urbanism and walking and driving | More walking doesn't entirely substitute for driving, which depends on external opportunities |
| Khattak & Rodriguez, 2005 | Quasi-experimental matched-pair study of neo-traditional/conventional neighborhoods | More internal trips and fewer external trips in neo-traditional; lower VMT |

## d. Current and future travel research

There remains substantial unexplored research territory at the interface of decision behavior, environment, and travel behavior. The spatial structure of the residential environment is important for explaining mode choice and other dimensions of travel behavior, with differential impacts depending on type of trip, and a role for personal variables (Meurs and Haaijer, 2001). Since the immediate decisions of daily travel are constrained by the environment and the transportation options it offers, as well as the availability of vehicles and the attendant costs, residential location is an area of interest to transportation researchers. At the same time, attitudes, beliefs, and values are likely partial determinants of travel behavior, along with habit and active choice processes.

Despite ongoing vigorous work investigating the influence of the environment on travel, as well as decision behaviors such as habit formation and the role of attitudes and beliefs, techniques to accommodate the many dimensions of human travel remain underdeveloped. Challenges include the need to account for habituation and intention formation (which suggests moving away from cross-sectional studies), and improving on "black-box" models with predictive variables to get at the underlying processes by which travelers make decisions. Attitudes, values and preferences—and how they relate to both socio-demographic and environmental factors—are hard to measure, while techniques for incorporating the environment into travel models are still developing.

To summarize, there is evidence that auto ownership and travel are sensitive to a range of factors, from urban form to household and personal characteristics. The literature on how the environment relates to auto ownership and travel is mixed, in part because of the complexity of both urban form and human behavior, even as techniques to measure the environment and model behavior continue to develop. Different approaches to measuring the environment may provide new insights into how household and individual travel responds to the local environment.

Given the accumulated knowledge about travel in the physical environment, and identified gaps in the literature, this dissertation considers how several quantitative representations of the environment perform in statistical models of travel behavior, and what these different approaches to measuring the environment can tell us about the importance of environment in travel behavior. Using a single dataset of households, travelers, and trips from a quantitatively described environment to examine household decision chains, this dissertation models the association of environment and travel, both direct and indirect mediated through auto ownership. Well-established relevant household and personal measures serve as control variables, and provide points of comparison with earlier work as well as grounds for discussing implications for policy and future research.

# 3. Conceptual Framework

Travel behavior modeling has progressed markedly in recent decades. Recent advances in geographic coding, simulation techniques and computing power, as well as more sophisticated conceptualization of travel, now bring within reach modeling goals that were earlier viewed as desirable but impractical (Koppelman, 2005).

At the same time, the practice of transportation modeling is not yet sufficiently refined and standardized to accurately describe and predict land-use scenarios with complex combinations of population and density levels, land-use mixtures, and design elements. Seldom are data about the built environment incorporated into regional travel models, and non-motorized travel is routinely ignored (Ewing and Cervero, 2001), with important consequences. For example, non-motorized travel includes precisely the type of trips that are likely to have concomitant positive health effects on travelers who have shown high sensitivity to variations in the local physical environment (Rodriguez and Joo, 2004). Mode choice models that exclude characteristics of the local physical environment may mis-state the importance of traditional attributes such as travel time and travel cost for mode choice (Cervero, 2002). Moreover, the traditional inclusion of mode choice after trip generation and distribution may mask important differences in how travelers choose whether and how to travel, given the greater sensitivity of walk trips to short distances and finer-grained urban design, compared to drive trips (Lee and Moudon, 2006; Shay et al., 2006).

Transportation planners have long recognized a role for the environment in travel behavior, although the most effective techniques for incorporating the environment into travel research remain an open and active area of inquiry. A clearer understanding of the link between the environment and travel may inform policy that has the potential to influence household travel behavior and reap tangible benefits in air quality, congestion management, fuel conservation, and more.

Figure 2 shows the conceptual framework for this dissertation, with the far right box (broken border) referring to the larger context that motivates the work. The core variables of household size and composition, home type and ownership, and income were chosen—on the basis of theory and earlier empirical research—for their likely relevance for relatively rare auto decisions, as well as the more frequent travel choices made once or more every day by most travelers.

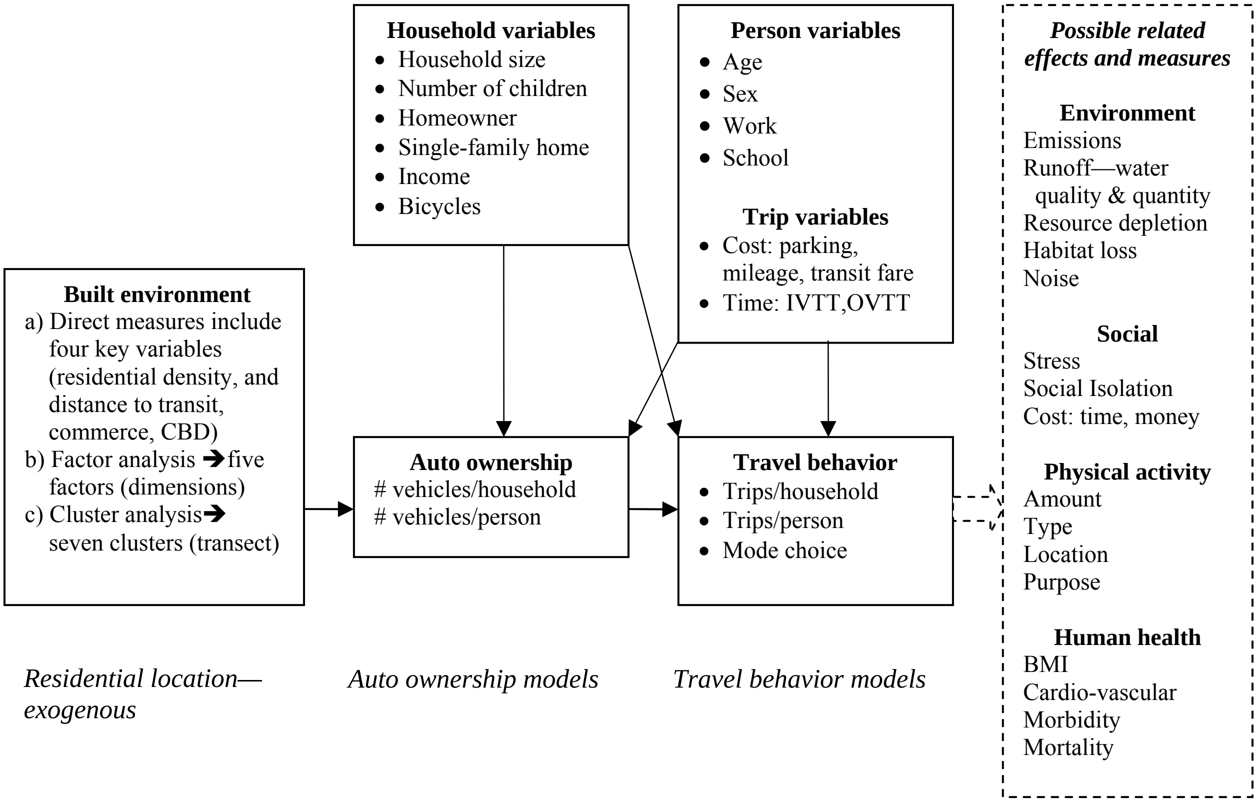


**Figure 2. Conceptual framework**

This research takes advantage of three different representations of environment as exogenous inputs to travel models. First is a neighborhood typology (transect), which captures such environmental qualities as density, connectivity, and streetscape. Two other environmental representations include 1) the factors used to generate the transect: walkability, accessibility, agglomeration, industry, and property values; and 2) a set of four direct environmental measures often used in travel modeling: residential density, and distance to transit, commercial uses, and the central business district—the latter a measure of regional access.

The more complex models for travel behavior (compared to auto ownership) are those relating to the most frequent decisions travelers make. Travel behavior is described in terms of number of trips (total household and personal, and by walk and drive modes), as well as personal mode choice. Modeling trip generation separately by modes makes it possible to consider the factors that shape mode of travel (including non-motorized), and better understand how accessibility and mobility are related in various environments.

Note that the increasing complexity of the models, moving from infrequent auto ownership to more frequent travel decisions, does not reflect complexity or simplicity of the decision processes they attempt to describe. Indeed, decisions about auto ownership may be more complex and energy-intensive than frequent travel decisions, because of the high stakes and substantial transaction costs involved. Rather, the complexity of, for example, the mode choice models in terms of number of independent variables reflects the accretion of independent variables that may  play a role in forming routine travel behavior, and follow from less frequent and less habitual decisions like household auto ownership. In reality, all these decisions are far more complex than the models used to approximate them.

For example, the household and environmental measures included in the models are not exhaustive, but rather were selectively chosen based on earlier empirical evidence suggesting their relevance. Moreover, attitudes and preferences are widely accepted as important in all these decisions, but are not included directly here, although they almost certainly contribute to and interact with the modeled measures. Attitudes and personal characteristics such as education and profession, which likely affect perceived costs of travel in both time and money, or views of the attractiveness of modes such as transit (often viewed as transportation for the poor), are beyond the capacity of these models to capture. The relevance of transportation for society and the environment, as well as human health (directly and through physical activity) is recognized (far right side of Figure 2) but not directly addressed.

### a. Hypotheses

The hypotheses for the linked decisions of interest follow:

$H_A$: Auto ownership, expressed as number of vehicles per household, varies across physical environments, as well as in response to household factors

$H_B$: Trip generation varies across physical environments, as well as in response to auto ownership and household factors

$H_C$: Mode choice varies across physical environments, as well as in response to auto ownership, and household and personal factors

### b. Expected Results

This research uses newly developed quantitative representations of neighborhoods, which are expected to be significant in models for auto ownership and travel behavior. However, the environments are complex, with many combinations of elements that may mask or amplify the effects of other factors, such that predictions about associations with outcome variables are difficult to make. The factor and cluster analyses (performed by other researchers) suggested combinations of environmental attributes potentially relevant to auto ownership and travel behavior. Generally, environmental measures (factors and clusters) are expected to be more relevant for travel (trips and mode) than for auto ownership, although they may reveal associations between environment and auto ownership that are difficult to see with earlier analysis techniques.

Auto ownership— The direct environmental measures (residential density, and access to transit, commerce, and regional center) are expected to be associated with auto ownership, as they relate to alternative modes, and number of and access to destinations, although the relationship may be weak; earlier research suggests that auto ownership is more closely tied to household size, income, and other personal and household traits than to environmental factors. Auto ownership may be lower in denser and mixed-use developments, both because of higher costs and greater constraints on parking typical in such environments, and because of the greater opportunity for mode substitution; however, it is difficult to predict how auto ownership relates to various environments, since they represent interactions of multiple dimensions (clusters) or indices of multiple measures (factors).

Home ownership and single-family residences (both typical of larger and wealthier households), as well as high income, are likely to be positively significant for auto ownership. The number of children may confound the household size effect; some households with unrelated adult housemates or multiple generations may have higher auto ownership than nuclear families with non-driving children, even as children increase travel demand without adding eligible drivers. Bicycles may relate to fewer autos, reflecting access to or preference for non-motorized modes.

Travel behavior—Many of the measures of trip-making are similar to auto ownership in their expected response to the chosen independent variables. That is, factors that increase auto ownership likely also will increase trips. Home ownership, single-family homes, and higher incomes are expected to be positively and significantly associated with trips, as are increasing household size and number of vehicles, as well as additional children. Environmental measures may be significantly associated with trips, but the sign is uncertain; within-neighborhood distances may be important.

Total household trips (of all modes) are expected to vary across neighborhoods, as well as in response to household factors, although the sign and magnitude are uncertain, as are differences among representations of the environment. Numbers of walk and drive trips are hypothesized to relate differently to environmental representations. Person-level trip generation is expected to show differences among modes, with walk trips more sensitive to environment measures than drive. This builds on recent research suggesting mode-specific sensitivity to urban form.

Finally, mode choice is likely to be sensitive to all these variables in different ways, such that predictions are difficult. Walkability and accessibility, expressed as shorter distances, good connectivity, pleasant walking conditions, and a variety of destinations, are associated with more walking, but the most effective and efficient combinations and thresholds of these design elements remain unclear. Earlier research suggests that mode choice may be more sensitive to the local environment than is trip generation, which is more closely tied to socioeconomic household and personal factors. In the mode choice modeling technique used here, the environment was incorporated first as dummy variables for identified walk and transit environments (derived from the clusters), and then as the same three environmental representations: clusters (which fall somewhere between nominal and ordinal variables), factors and direct measures. The expected positive effect of the environmental measures relates to the probability of the walk mode being chosen for any given trip.

Table 3 summarizes the expected relationships among environmental and household measures with the outcome measures of autos, trips, and mode choice. These are hypothesized net effects, accounting for indirect effects of autos on travel outcomes of trips and modes, which may either dampen or amplify the direct effect of environment on the respective travel behaviors.

**TABLE 3 Summary of expected relationships, with expected sign (positive or negative)**

| Hypotheses | Clusters: more urban | Factors | | | | Household | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Walk | Access | Industry | Prop value | Autos | HH size | Kids | Income | Own home | SF | Bike |
| Environ/autos | - | - | - | - | - | | + | + | + | + | + | - |
| Environ/trips | + | + | + | + | + | + | + | + | + | + | + | - |
| Environ/ non-motor modes | + | + | + | + | + | - | - | - | - | | | |

The modeling approach is detailed in Chapter 4 (research design); results of modeling are presented in Chapters 5 (autos and trips) and 6 (mode choice), and further discussed in Chapter 7 in terms of expected outcomes and relevance to policy and future research.

# 4. Research Design and Methods

This research was conducted as part of a large multi-institutional research project that seeks to understand how various alternative development patterns (e.g., neo-traditional, compact development, new urbanism, etc.), applied regionally over a planning horizon of 50 years, affect travel patterns and ultimately influence the spatial distribution of emissions from mobile sources. The inter-disciplinary team of social scientists, physical scientists, and engineers involved with this regional forecasting project used a cross-sectional land-market equilibrium model, commercial truck model, residential location model, and vehicle technology forecasts, together with the models developed for this dissertation, to support emissions modeling and risk analysis.

Two existing datasets provide raw data that describe households, travelers, and trips. The cross-sectional data were collected in 2001 in the Charlotte, North Carolina metropolitan area; survey design, data collection, and quality control are described in detail in the following section. Environmental measures at the block group level, provided by researchers who generated the neighborhood typology, were tied to household locations and trip origins and destinations to enrich the auto and travel models.

Three sets of models were estimated to represent interrelated household decisions, starting with relatively rare decisions about auto ownership, expressed as numbers of autos per households. More frequent (often daily) travel choices were modeled as trip generation (number of trips taken by households and individual travelers) and personal mode choice. The three different series of models (autos, trips, and mode choice) have in common a concise set of independent variables that theory and prior empirical research suggest may be significant, as well as additional independent variables specific to the decisions of interest.

Auto ownership models include the three separate sets of environmental measures described in section b, and control household variables. Trip generation models at the household level follow the same model structure, with the addition of number of household autos as a control variable, while person-level trip generation models include additional personal variables, and decompose trips into walk and drive models. The mode choice models include trip-level data describing trips by origin and destination, mode choice, and household and personal characteristics, as well as environmental characteristics of the residential location and trip origin. The very few transit trips in the sample were enriched with data from a survey of bus riders, as described below.

### a. Data Sources and Study Site

The secondary data used here were provided by the Charlotte and Mecklenburg County Departments of Transportation, and the Mecklenburg-Union Metropolitan Planning Organization (MPO), the transportation planning body that represents 14 municipalities in two counties in the Charlotte, North Carolina metropolitan region. See Figure 3 for a general view of the region. The data come from a travel survey conducted in 2001 in the greater Charlotte region as part of a cooperative effort between the departments of transportation of North Carolina, South Carolina, and Charlotte. The travel survey collected information on travel in the region for all modes of travel, with the express purpose of supporting the design, estimation, and calibration of a set of region-wide travel demand models used to project future demand for four MPOs, as well as several small non-MPO areas.

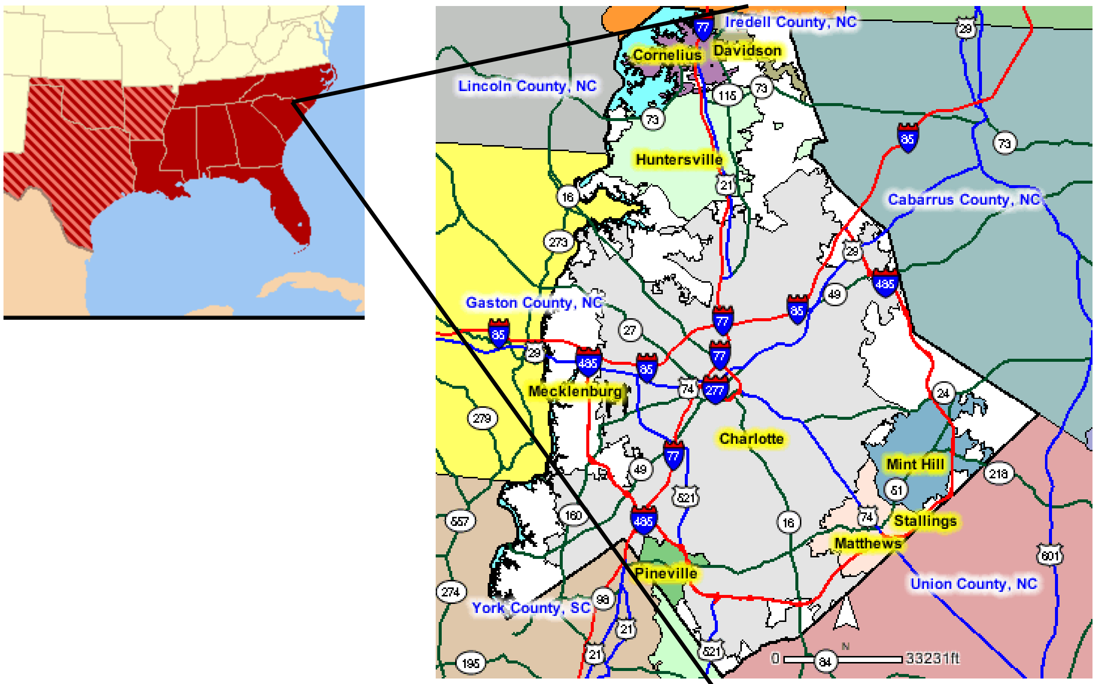


**Figure 3. Overview of study area. Source:** ***http://gischamber.co.mecklenburg.nc.us/website/chamber/***

The survey used computer-assisted telephone interviewing (CATI) to gather household- and person-level travel data, including the number, length, and purpose of trips, as well as mode and time of day, for all members of the sample households over the age of five years during a specified 24-hour travel day. In addition, household- and person-level demographic information was collected. The survey was piloted in November of 2001, with the full survey effort of over 3300 households initiated the following month. Telephone interviews ran from January through May, 2002; eligible travel days were Mondays through Thursdays, excluding holidays.

The household data were augmented by environmental data to characterize the area surrounding each household and trip end in the sample. These variables include measures of street design, density, land use mix, accessibility, transportation alternatives, natural environment, and socioeconomic traits such as population density, home ownership, household size, home vacancy, and employment density. Factor and cluster analyses identified block groups with similar land use and transportation attributes. First, factor analysis applied to a set of 34 select environmental measures generated a set of five of factors representing different dimensions of the environment. Then, cluster analysis yielded a typology of neighborhoods that could be arranged along an urban-to-rural transect. Each of the three different environmental representations (direct measures, factors, and clusters) comprises a different and mutually exclusive set of environmental measures; these are used, sequentially, as independent variables in the auto ownership and travel models.

Because environmental measures are available only for Mecklenburg County, with less than half (45.3%) of the households included in the behavioral survey (n=3333), the households with and without environmental measures were compared for statistically significant differences in means of household and travel measures; no significant differences were identified. In addition, select descriptive statistics for the study area were compared to Census data for the MSA (see Chapter 5, section a).

The households in Mecklenburg County comprise the sub-sample for which Census and environmental measures were collected, and provide the data for this research into the association of environmental and socio-demographic factors with household decisions about vehicles and travel. The Mecklenburg County sub-sample was further divided to ensure inclusion of 30 households each from two zipcodes in heavily urbanized central Charlotte. A list-assisted random-digit-dial approach improved access to unlisted telephone numbers and decreased the share of non-residential numbers, to improve coverage. Response was encouraged with a multi-step approach, with a pre-contact informative letter followed by an initial phone call to recruit households and obtain household-level information. A second call served to collect and check (against mailed travel diaries) travel data, and to reconcile and clarify responses. Late addition of households corrected for under-representation of certain households, including those with zero vehicles, more than four members, or urban zip codes. On-line data processing reconciled inconsistent responses, resolved missing data values, and corrected entry errors. Post-processing included geo-coding of locations (home, work, and school locations, and trip destinations), and weighting of data to adjust for selection probability, non-response bias, and stratification. Because this dissertation uses only the households in Mecklenburg County to test variation within the sample, the sampling weights were not applied.

### b. Characterization of the physical environment

A transect—a typology of neighborhood types—was developed by other investigators as part of the larger research effort within which this work fits. This transect used census data at the block group level to develop a quantitative typology of regional development that organizes all relevant elements of the built environment on a continuum from rural to urban. Each point along the continuum has distinctive unifying characteristics—reflected in the land use and transportation options in each zone—that were selected based on prior theory and available empirical evidence (Ewing and Cervero 2001; Boarnet and Crane, 2001a; Cervero, 2002; Krizek and Wadell, 2003; Rodríguez and Joo, 2004). This improves on earlier attempts to classify neighborhoods at two polar extremes of conventional (low-density, residential-only development hostile to non-auto travel) and traditional/neo-traditional (moderate density, pedestrian- and bicycle-supportive design with mixed land uses), presenting a more complex range of development types across a range from intensely urban to suburban to sparsely populated rural, with distinctly different neighborhood types containing a variety of partially substitutable features that locate them on the transect. This makes it possible to include the environment in auto and trip models as a household location choice, expressed as a neighborhood that differs from other alternatives along several distinct dimensions.

The key steps used for classifying the neighborhoods in the data set were: 1) identification of relevant attributes of physical form, such as street design, density, land use mix, access, transport alternatives, natural environmental features, and socioeconomic characteristics; 2) factor analysis of the raw measures to derive major dimensions; and 3) cluster analysis to group together neighborhoods that are most similar in terms of the factors.

The 34 direct measures were chosen based on the literature as well as availability of data. Through factor and cluster analysis, this large set of measures was distilled into three mutually exclusive representations of the environment, each allowing parsimonious modeling, interpretation, and comparison when applied to the dependent variables of auto ownership, trip generation, and mode choice.

Data were collected at the block group level—a unit of analysis chosen to tie into related analysis of residential and business location. To avoid problems with multi-collinearity and to keep the model size manageable, four measures were selected for direct inclusion in models, chosen both for their familiarity to travel behavior researchers as commonly recognized environmental measures, and for their relevance as key components of the factors they represent. The direct measures (calculated by block group) are:

*Resdensity*—number of single-family residential parcels per acre
*Bus*—median distance (1,000 ft) of all parcels to nearest bus stop
*Comm*—median distance (1,000 ft) of all parcels to nearest commercial outlet
*Cbddist*—median distance (1,000 feet) of all parcels to the central business district

Factor analysis reduces redundancy and condenses variables into more compact and efficient sets. As a second environmental representation, two separate factor analyses (using the Bartlett and Ward methods) on the 34 simple environmental measures generated five and eight factors, or dimensions, respectively. Factors were scaled such that means and standard deviations equal zero and 1, respectively. These results were used to generate preliminary cluster analyses with seven and eight clusters, which were mapped by block group, then shared with municipal and regional planners and researchers who are deeply familiar with the study area. Their input, as well as a review of the different techniques and of aerial photographs, prompted the selection of the five-factor structure, which used a subset of the original environmental measures to generate eight clusters with good correspondence to actual land use and urban form on the ground; see Table 4 for factor loadings.

## Table 4 Loadings for five factors

| **Factor loadings** | **Walkability** | **Accessibility** | **Agglom-eration** | **Industry** | **Property value** |
|---|---|---|---|---|---|
| Acres of commercial land | -0.6567 | | | | |
| Acres of tree canopy | -0.7797 | | | | |
| Intersections—count | -0.9353 | | | | |
| SFR parcels—count | -0.9119 | | | | |
| Miles of roads | -0.9293 | | | | |
| Acres of SFR land | -0.7685 | | | | |
| SFR parcels <¼ mile to commercial use | -0.7099 | | | | |
| Bus stops—count | | 0.6078 | | | |
| Miles of roads per square mile | | 0.6090 | | | |
| Median area of all SFR parcels | | -0.6840 | | | |
| Median age of SFR parcels | | -0.6243 | | | |
| Median distance to: | | | | | |
| commercial land use | | -0.7258 | | | |
| park | | -0.6078 | | | |
| primary road | | -0.5449 | | | |
| bus stop | | -0.6409 | | | |
| centroid of the CBD | | -0.7000 | | | |
| gas station | | -0.6775 | | | |
| supermarket | | -0.5234 | | | |
| Median building/total value ratio | | | -0.4813 | | |
| Total employment per acre | | | 0.4471 | | |
| Other business districts | | | 0.5516 | | |
| Acres of industrial land use | | | | 0.6041 | |
| Median area of all parcels | | | | | 0.6221 |
| Median heated area | | | | | 0.9717 |
| Median total value of all parcels | | | | | 0.9709 |

**Factor scores below |0.40| not shown**

Factors were given labels chosen to reflect the qualities of the physical environment they are intended to capture; these names are labels of convenience, and should not drive the interpretation.

Finally, cluster analysis of these five factors was used to identify block groups that cluster on these dimensions to yield eight neighborhood types, or clusters, such that variation is minimized within clusters and maximized between clusters (Figure 4).

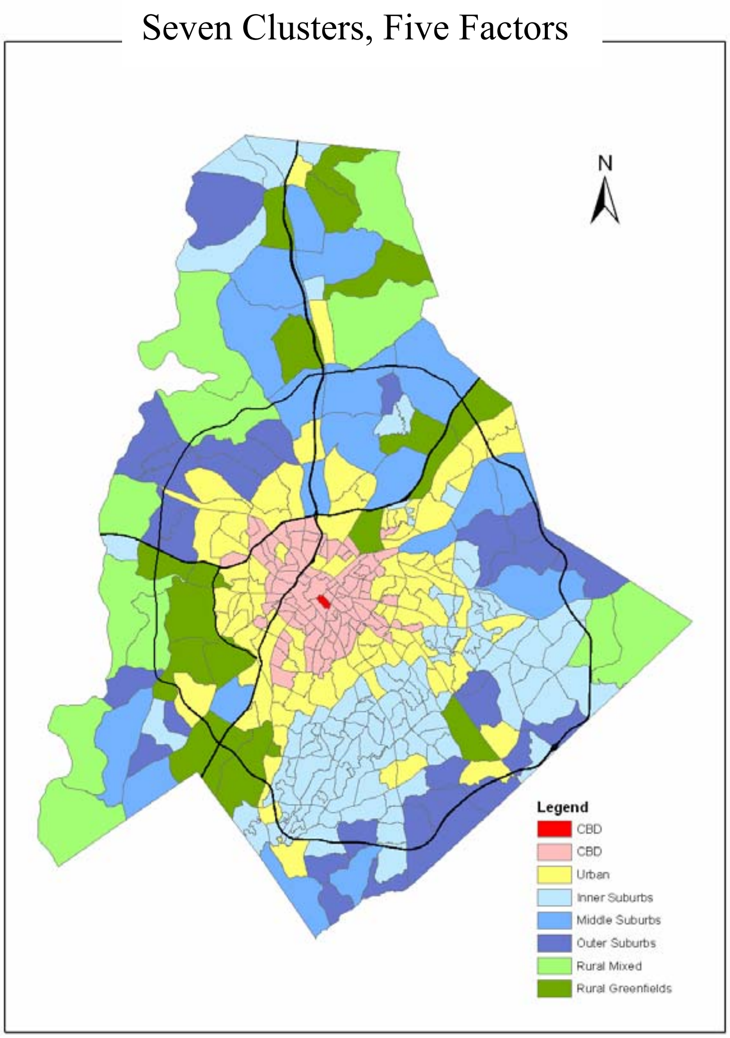


**FIGURE 4. Map generated by cluster analysis of five factors for the Charlotte metropolitan region (provided by B.K. Wilson, UNC—Chapel Hill)**

The cluster containing only a single block group comprising the central business district (CBD) and no residences was folded into the city center cluster, for a total of seven clusters, labeled CBD (hereinafter referred to as “city center”), urban, inner suburban ring, middle suburban ring, outer suburban ring, rural mixed and rural greenfields. As with factors, names for clusters are subjective labels of convenience intended to facilitate analysis, but should not be granted the status of definitions, lest they disappoint in interpreting results. Descriptive statistics for environmental measures appear in Table 7.

### c. Data preparation

The household survey was delivered in the form of CDs with data in Excel spreadsheets, SAS tables, and TransCAD data files, along with a data dictionary and summary report. The desired variables for each set of models (auto ownership, trips, and mode) were copied over to new tables. Data were preserved at the trip level for mode-specific person-level trip generation and mode choice modeling, and aggregated up to the person and household levels for household trip models. Data management and storage followed all Institutional Research Board protocols.

The IDs for trips, persons and households are cumulative. That is, the trip ID is built from a unique 6-digit household ID, a 2-digit person ID, and a 2-digit trip number signifying the 1st, 2nd, etc. trip by a given person. Thus, trip ID 245680101 represents the first trip (01) taken by person ID 2456801, who is the first person (01) in household ID 24568.

In the household file (n=3333), variables were renamed, edited, or recoded as necessary. Binary dummies represent home ownership and single-family homes, while household size, household trips, and autos are count variables. Variables in the original person file (n=7418) were edited, renamed, or recoded as necessary. Binary dummies represent student status (any age, full- or part-time) and worker status (full- or part-time). Both household and person files were edited to remove records from outside Mecklenburg County, retaining only those household (n=1508) and persons (n=3213) for which environmental measures are available.

### *Auto and trip models*

Quality control included preliminary modeling to uncover data problems such as missing or faulty values. Several variables missing a few (<10) values were imputed; two-way t-tests showed that the imputed values were not significantly different from reported values. Age and income were missing, respectively, ~1% and 17% of values; these were imputed and tested for significant differences, both in two-way t-tests and simple auto and trip models with household variables. All controls for imputation were dropped from final models for lack of significance.

In addition to household trip generation, the available data made it possible to model person-level trip generation with inclusion of both personal measures and environmental descriptors of the residential location and trip origins and destinations. Trips were sorted by mode, aggregated to the person level, and tied into the person file, which included traits such as sex, age, and work or student status. Likewise, household characteristics, such as number of household members and autos, as well as neighborhood type, were tied into the person file by household ID to produce a file with a single record for each traveler with values specific to that person, as well as household traits that apply to all persons in the same household. The 12,637 trips in the sample were taken by 3213 people in 1508 different households; they include 11,572 drive trips and 405 walk trips. The sample included 530 people in 1508 households who took no trips at all.

The control variables are household size, number of children, home type (1 for single-family detached homes), home ownership (1/0 for own/rent), income, and number of household autos and bicycles to represent access to and preference for different modes. Household income was reclassified from 14 income categories to three, to conform with related business and residential location models using the same dataset. The models use binary dummy variables for mid-income (MIDINC, \$30,000-\$75,000) and high-income (HIGHINC, over \$75,000) households, with 0-\$30,000 (LOWINC) serving as the reference category.

Preliminary modeling replaced the household size with four components that completely constitute household composition: numbers of children, working adults, non-working adults, and persons over 65 years of age. Because all these variables behaved nearly identically to household size, they were dropped and replaced with household size in the interest of parsimony. However, the number of children was retained, as a measure of a particular kind of travel demand non-driving children make on adults.

The zero-distance values for 260 trips were replaced with .01 mile, justified by the presence of apparently valid departure and arrival times for these short trips (1-10 minutes), and the very small or zero values derived by calculating the relative location of origins and destinations (i.e., O latitude – D latitude, O longitude – D longitude). All but 13 of the 260 trips showed nearly identical origin and destination geocodes, with differences at the 5th-6th decimal—smaller than the O/D differences in latitude and longitude for the smallest trips, which had the value 0.01 miles.

Early model runs included measures of spatial autocorrelation to capture possible interactions of households with each other and the environment; the autocorrelation variables used X (relative latitude, measured as the absolute difference between the household and the mean) and Y (relative longitude) in the following forms: X, Y, XY, $X^2$, $Y^2$, $X^3$, $Y^3$, $X^2Y$, and $XY^2$. All spatial auto-correlation variables proved not to be significant, and were dropped.

Extraneous variables were removed, and trips aggregated to the person and household levels to support trip generation models. Trip-level data were preserved for mode choice models.

### *Mode choice*

The mode choice modeling involved two data sources: the trip, person, and household files from the Metrolina survey (described above), and a 2003 bus rider survey of Mecklenburg County. The person and household files for Metrolina were tied together on PERSONID to get all desired variables, while the bus survey data already included all the necessary household data. The bus rider survey data (n=2823) were edited to produce new10-digit trip IDs starting with “1” and ending “01”; by contrast, Metrolina survey trip IDs start with “0” and end with the trip number.

Variables were edited and new dummies were created where necessary to make the two data sets consistent. This included creating, for the Metrolina trips, age groups of <25, 25-64, and >64 (youth, adults, and elders, respectively), and trip purposes of home-based work (one trip end each at work and home, in either direction), home-based other (one trip end at home, no trip end at work), and non-home-based trips (neither end at home). Modes were reconciled for the two data sources, and dummies created for drive-alone, carpool, walk and transit modes. Another dummy was created to indicate bus survey trips (1=bus survey; 0=Metrolina).

The Metrolina and bus survey trip files were intersected with spatial data to retain only trips originating in Mecklenburg County, for which environmental measures are available, with separate files for trip origins and destinations. Environmental measures were tied to each trip origin and destination on the block group ID; these included values for 34 direct environmental measures, five dimensions resulting from factor analysis, and binary dummies for seven neighborhood types resulting from cluster analysis. Thus, each trip end was characterized by different simple measures, factors and clusters, with labels that distinguish between origins and destinations. The files were merged to produce a single file with each trip originating in the study area, and separate columns for environmental measures at the origins and destinations. Trips to external destinations (with no attached environmental measures) were assigned a destination cluster value of 99999, and dropped from mode choice models. The trip files were examined for faulty values, such as multiple destinations or incomplete trips, and reconciled where necessary by returning to the raw trip data.

After trips with missing values for age, sex, work and student status, household size, autos and income were removed, the bus traveler sample totals 722 trips. Each trip in the bus rider survey represents a different person, because of the nature of data collection via an on-board survey. Metrolina survey trips in the mode choice model include 10,291 trips by 2913 travelers

Travel skims provided by the Charlotte Area Transit System contained travel times and costs for trips between origin and destination travel analysis zones (TAZs), broken out by drive and transit. These skims were used to create travel time and cost variables for each trip in the file. All trips had time and cost variables for drive-alone, carpool, and walk; only trips for which the origin and destination TAZ pair shows up in the transit skim were assigned travel variables for transit. Drive-alone and carpool used identical values for in-vehicle travel time (IVTT); an out-of-vehicle travel time (OVTT) of 5 minutes was assigned to drive-alone and 10 minutes for carpools, the latter to account for drop-off/pick-up time for the predominantly 1-passenger (in addition to driver) carpools in the sample. Values for IVTT and OVTT for transit came from the transit skims. Walk time (OVTT) was calculated from the distance between TAZ origins and destinations, assuming 3 mph; zero IVTT was assigned to all walk trips. Cost is a composite variable. It includes, for drive-alone and carpool modes, both parking (median parking based on destination TAZ, from the Metrolina survey) and a mileage-based cost ($0.10 and $0.05 per mile for drive and carpool) to capture the cost of gasoline, without including fixed costs of auto ownership such as car payments, insurance, or major repairs. Walk trips were assigned a zero cost, while transit cost came from TAZ-based fares from the transit skim.

For nested logit modeling, each trip is represented by multiple rows in the trip table—one for each travel mode option for the given origin/destination TAZ pair. All trips have drive-alone, carpool, and walk options; trips with origin/destination pairs in the transit skim also have a fourth row representing the transit option. Each trip has a value of 1 in the "CHOICE" variable for only the mode chosen. The trip table was broken down into home-based work (HBW), home-based other (HBO), and non-home-based trips (NHB).

To incorporate environmental measures, first the travel environments of interest (walk and transit) were identified with new dummy variables. Transit environments were defined as those with trip origins in urban or city center clusters, while walk environments are the same, but are limited to trips of less than 2 miles (40 minutes). These admittedly coarse definitions are intended as a pilot of the modeling technique, and ignore known transit trips in the rural mixed clusters and possible walk trips in clusters outside the city center and rural neighborhoods. Interactions were created for variables expected to relate differently to various modes: female, youth, and elder (interacted with non-driving modes of walk and transit); middle and high income, household size, and autos (interacted with the drive modes of drive-alone and carpool); alternative-specific constants (dasc, casc, and wasc for drive-alone, carpool and walk, respectively, with transit as the reference); and transit and walk environments (interacted with transit and walk modes, respectively).

Later refinements included using the three environmental representations as separate sets of independent variables added to the mode choice models, followed by restricted models using those environmental measures found to be statistically significantly associated with mode choice. For these models, the environmental measures were interacted with the walk mode, to observe changes in walking in relation to the other modes along the transect of clusters, and with select factors and direct measures.

The trip data were weighted to reflect mode shares in the population, by dividing sample mode shares into population shares. Sample mode shares are broken out (Table 5) by trip purpose. The HBW population mode split of 79.2, 12.5, 1.4, and 2.6 (from the Mecklenburg County journey-to-work Census data) was adjusted for the modes not considered here (4.3% other and telecommute) by dividing each by 95.7, to get an exhaustive choice set for the four modes in the mode choice model: 0.827, 0.131, 0.015, 0.027. Thus, the weights for HBW trips for drive-alone, carpool, walk and transit trips are, respectively, 1.17, 2.22, 1.00, and 0.12. Using the NHTS mode shares as population values, NHB trips are weighted as 0.93, 1.10, 1.76, and 0.35. Flawed bus survey data for home-based other trips were dropped, for a new sample mode split of 44.9, 50.5, 3.6, and 1, and weighting on HBO trips of 1.11, 0.77, 2.5, and 2.

**TABLE 5 Mode shares for trip sample and population**

| Share of total sample | Drive-alone | Carpool | Walk | Transit | Total |
|---|---|---|---|---|---|
| HBW | .705 | .059 | .015 | .221 | 1.00 |
| HBO | .422 | .466 | .037 | .075 | 1.00 |
| NHB | .538 | .354 | .051 | .057 | 1.00 |
| All | .521 | .342 | .037 | .100 | 1.00 |
| Population—HBW* | .827 | .131 | .015 | .027 | 1.00 |
| Population—HBO, NHB** | .500 | .390 | .090 | .020 | 1.00 |

*** The population modal split for HBW comes from the Census Profile of Select Economic Characteristics 2000 for Mecklenburg County (Table DP-3)**
**** The population modal splits for HBO and NHB come from 2001 NHTS mode shares for all trips combined**

## d. Model Specification

Models for autos and travel behavior are complementary, with the household trip models building on the auto model. Person-level trip and mode choice modeling include select personal factors in addition to the household factors from household autos and trips.

Autos and trips are modeled with negative binomial regression, to avoid the bias common in ordinary least squares regression when the outcome variable is a positive ordered count variable of relatively rare events. Because ordered probit does not account for the meaningful interval in the dependent variable (numbers of cars or trips increase in units of one), negative binomial is preferable here, particularly given the relatively normal distribution of the dependent variable. Further, the person-level trip generation models account for interaction among household members in decision-making (after White, 1980).

Mode choice was modeled at the person level, with household and personal factors as well as environmental measures. Conditional logit modeling accommodates discrete choices among the nominal categories that constitute the choice sets for travel mode.

*i. Autos*

With a dependent variable of number of household autos, the auto model is specified:

$$\text{AUTOS} = \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_3\text{*OWNER} + \beta_4\text{*SFHOME} + \beta_5\text{*BIKES} + \beta_6\text{*MIDINC} + \beta_7\text{*HIGHINC} + \beta_{14}\text{*}X_{14} \ldots \beta_{19}\text{*}X_{19}$$

where HHSIZE is number of people of all ages in the household, CHILDREN is number of children aged 5 to 17, OWNER is home ownership (as opposed to renting), SFHOME denotes single-family detached homes, BIKES is the numbers of household bicycles, and MIDINC and HIGHINC are dummies for the income ranges of $30-75,000 and over $75,000 (with a reference category of $0-30,000). The choice of neighborhood is represented by six clusters ($X_{14} – X_{19}$), each a dummy with its own coefficient, with the rural greenfields cluster (GREEN) serving as the reference category.

Two alternative models were estimated, where the neighborhood type (from cluster analysis) is replaced, first, by the five dimensions from factor analysis and, second, by the four direct environmental measures. All other variables are as defined earlier. Thus, the auto ownership model with five factors is specified:

$$\text{AUTOS} = \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_3\text{*OWNER} + \beta_4\text{*SFHOME} + \beta_5\text{*BIKES} + \beta_6\text{*MIDINC} + \beta_7\text{*HIGHINC} + \beta_{20}\text{*}X_{20} \ldots \beta_{24}\text{*}X_{24}$$

where household factors are as described for the previous model. The environment here is represented by five dimensions ($X_{20} – X_{24}$), using factor scores for, respectively, walkability, accessibility, agglomeration, industrial acreage, and property values.

The auto ownership model with direct environmental measures includes the same household variables, replacing the clusters or factors with four direct measures ($X_{25} – X_{28}$) of, respectively, residential density, and distance (in thousands of feet) to transit, nearest commercial use, and CBD:

$$\text{AUTOS} = \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_3\text{*OWNER} + \beta_4\text{*SFHOME} + \beta_5\text{*BIKES} + \beta_6\text{*MIDINC} + \beta_7\text{*HIGHINC} + \beta_{25}\text{*}X_{25} \ldots \beta_{28}\text{*}X_{28}$$

*ii. Trip-making*

Trip-making models (number of household and personal trips) include the same independent variables, with the addition of auto ownership. The model of household trips was run once each with the three environmental representations of, respectively, clusters ($X_{14}$ - $X_{19}$), factors ($X_{20} – X_{24}$), and simple environmental measures ($X_{25}$ - $X_{28}$):

$$\begin{aligned}\text{TRIPS} = \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_3\text{*OWNER} + \beta_4\text{*SFHOME} + \beta_5\text{*BIKES} + \beta_6\text{*MIDINC} + \\ \beta_7\text{*HIGHINC} + \beta_8\text{*AUTOS} \quad & + \beta_{14}\text{*}X_{14} \ldots \beta_{19}\text{*}X_{19} \\ & + \beta_{20}\text{*}X_{20} \ldots \beta_{24}\text{*}X_{24} \\ & + \beta_{25}\text{*}X_{25} \ldots \beta_{28}\text{*}X_{28}\end{aligned}$$

Person-level trip models include all household factors found to be significant for household trips, except bicycles. Personal characteristics were added to the models, with an outcome variable of total trips by all modes, specified thus:

$$\begin{aligned}\text{PERTRIPS} = \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_6\text{*MIDINC} + \beta_7\text{*HIGHINC} + \beta_8\text{*AUTOS} + \\ \beta_9\text{*FEMALE} + \beta_{10}\text{*YOUTH} + \beta_{11}\text{*ELDER} + \beta_{12}\text{*WORK} + \beta_{13}\text{*SCHOOL} & + \beta_{14}\text{*}X_{14} \ldots \beta_{19}\text{*}X_{19} \\ & + \beta_{20}\text{*}X_{20} \ldots \beta_{24}\text{*}X_{24} \\ & + \beta_{25}\text{*}X_{25} \ldots \beta_{28}\text{*}X_{28}\end{aligned}$$

where HHSIZE, CHILDREN, MIDINC, HIGHINC, and AUTOS are as specified in the household models, and FEMALE, WORK, and SCHOOL are binary dummies for females, work status, and school status; YOUTH and ELDER are binary dummies created from the continuous AGE variable, where youth are younger than 25, and elders 65 and older.

To further explore trip-making and the sensitivity of modes to the physical environment, trips by auto and foot were identified and modeled at the person level, with the same three environmental representations:

$$\begin{aligned} \text{DRIVETRIPS} = {} & \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_6\text{*MIDINC} + \beta_7\text{*HIGHINC} + \beta_8\text{*AUTOS} + \\ & \beta_9\text{*FEMALE} + \beta_{10}\text{*YOUTH} + \beta_{11}\text{*ELDER} + \beta_{12}\text{*WORK} + \beta_{13}\text{*SCHOOL} + \beta_{14}\text{*}X_{14} \ldots \beta_{19}\text{*}X_{19} \\ & + \beta_{20}\text{*}X_{20} \ldots \beta_{24}\text{*}X_{24} \\ & + \beta_{25}\text{*}X_{25} \ldots \beta_{28}\text{*}X_{28} + \end{aligned}$$

and

$$\begin{aligned} \text{WALKTRIPS} = {} & \beta_0 + \beta_1\text{*HHSIZE} + \beta_2\text{*CHILDREN} + \beta_6\text{*MIDINC} + \beta_7\text{*HIGHINC} + \beta_8\text{*AUTOS} + \\ & \beta_9\text{*FEMALE} + \beta_{10}\text{*YOUTH} + \beta_{11}\text{*ELDER} + \beta_{12}\text{*WORK} + \beta_{13}\text{*SCHOOL} + \beta_{14}\text{*}X_{14} \ldots \beta_{19}\text{*}X_{19} \\ & + \beta_{20}\text{*}X_{20} \ldots \beta_{24}\text{*}X_{24} \\ & + \beta_{25}\text{*}X_{25} \ldots \beta_{28}\text{*}X_{28} \end{aligned}$$

### *iii. Mode choice*

Finally, mode choice was modeled at the person level, using a concise set of household and personal characteristics chosen based on theory and earlier empirical evidence. Only factors that are expected to vary across modes are included as meaningful candidates for explaining mode choice. The mode choice model is specified as utility functions with measures that vary by mode:

$V_{drive} = \beta_1{*}HHSIZE + \beta_8{*}AUTOS + \beta_6{*}MIDINC + \beta_7{*}HIGHINC + \beta_{29}{*}IVTT + \beta_{30}{*}OVTT + \beta_{31}{*}COST$

$V_{carpool} = CASC + \beta_1{*}HHSIZE + \beta_8{*}AUTOS + \beta_6{*}MIDINC + \beta_7{*}HIGHINC + \beta_{29}{*}\ IVTT + \beta_{30}{*}\ OVTT + \beta_{31}{*}COST$

$V_{walk} = WASC + \beta_{30}{*}\ OVTT + \beta_9{*}FEMALE + \beta_{10}{*}YOUTH + \beta_{11}{*}ELDER + \beta_{14}{*}X_{14} \ldots + \beta_{19}{*}X_{19}$

$V_{transit} = TASC + \beta_{29}{*}\ IVTT + \beta_{30}{*}\ OVTT + \beta_{31}{*}\ COST + \beta_9{*}\ FEMALE + \beta_{10}{*}\ YOUTH + \beta_{11}{*}ELDER$

where CASC, WASC, and TASC are alternative-specific constants for, respectively, carpool, walk and transit modes (drive-alone is the reference mode); IVTT and OVTT are in-vehicle and out-of-vehicle travel time (minutes); COST (in cents) includes parking and mileage for drive modes and fare for transit; HHSIZE, AUTOS, MIDINC, and HIGHINC are household size, autos, and middle- and high-income (interacted with the drive modes of drive-alone and carpool); FEMALE, YOUTH, and ELDER are female, youth, and elder dummies (interacted with the non-drive modes of walk and transit); and $\beta_{14}{*}X_{14} \ldots + \beta_{19}{*}X_{19}$ are dummies for the six clusters (with rural greenfields as reference), interacted with the walk mode. As with auto and trip models, the mode choice modeling also replaced the clusters with factors and direct measures, in each case interacting them only with the walk mode.

Initial mode choice modeling used synthetic walk and transit environments, defining trips originating in city center and urban clusters as occurring in a transit environment; the same definition applied to walk environments, with the additional provision of destinations less than 2 miles away. While these models were a useful methodological exercise that produced plausible coefficients (compared with published models in use in other metropolitan areas), they added little new knowledge, but rather confirmed the increased probability of walk and transit travel in urban environments, as expected, while failing to capture some walk and transit trips known to have been made in other clusters. The creation of travel environments using clusters merits further work, as noted in Chapter 7, and should account also for the environment at destinations as well as intermediate stops in tours.

These utility functions and three data tables (one for each trip purpose) were used to model mode choice in LIMDEP. The resulting coefficients were interpreted in light of their p values and signs and magnitude of coefficients, and modifications made to improve model performance, specifically for nested logit modeling (Chapter 6).

Select socio-demographic variables used here are included in a person-level auto model to support path analysis of the direct and indirect relationships of environment and autos with personal mode choice. To that end, the following model was specified:

$$AUTOS = \beta_0 + \beta_1 * HHSIZE + \beta_6 * MIDINC + \beta_7 * HIGHINC + \beta_9 * FEMALE + \beta_{10} * YOUTH + \beta_{11} * ELDER + \beta_{14} * X_{14} \ldots + \beta_{19} * X_{19}$$

where all variables are as defined earlier. In addition to the clusters, person-level auto ownership (workers only, used with the HBW model) was modeled with factors and clusters:

$$AUTOS = \beta_0 + \beta_1 * HHSIZE + \beta_6 * MIDINC + \beta_7 * HIGHINC + \beta_9 * FEMALE + \beta_{10} * YOUTH + \beta_{11} * ELDER + \beta_{20} * X_{20} \ldots + \beta_{24} * X_{24} + \beta_{25} * X_{25} \ldots + \beta_{28} * X_{28}$$

**e. Path analysis**

Given the hypothesized direct and indirect (through autos) association of location with travel behavior, path analysis is employed to consider these relationships:

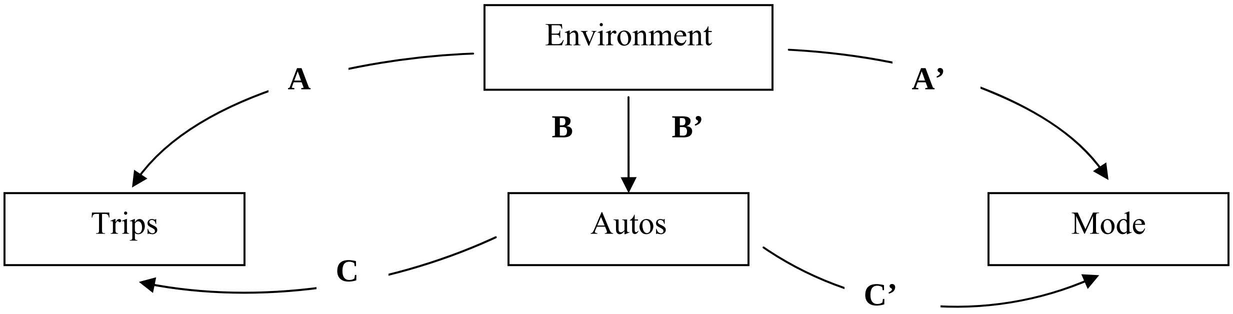


**Figure. 5. Path analysis**

This technique makes it possible to use output from one regression model (here, auto ownership) to determine an indirect effect in an outcome (e.g., trips) that includes the same measure as an explanatory variable. Working with the path in the center and left of Figure 5, the direct effect of environment on autos (B) multiplied by the direct effect of autos on trips (C) yields an indirect effect of environment on trips mediated through autos. This product (B * C) is added to the direct effect (A) to yield a total effect. These operations are done on marginal effects.

Path analysis is done for two paths: environment→autos→trips (A + B * C), and environment→autos→mode choice (A' + B' * C'). Note that the paths are different for the indirect association of autos with trips (B) and mode choice (B'). The former is a household-level model of vehicle ownership, and the latter a person-level model. Path analysis is presented separately in Chapters 5 and 6, following results for trip and mode choice models.

### f. Validity

Internal validity is limited by the cross-sectional data set. Some of the aspects of internal validity relevant to this dissertation include:

- Some selection bias is possible given the use of a telephone survey. Lower income groups may be under-represented, as might be those who are more likely to forego land lines in favor of cell phones, or those who vigorously screen calls.
- Although the address-based sample in the most urban zip codes may introduce sampling bias in the larger dataset (n=3333), this is of minimal concern because the Mecklenburg County subsample constitutes the data for all models.

- Non-response bias could be a problem if non-responders represent some particular part of the population or share some common trait. Comparison of survey households with Census data suggested this is a minor concern.
- There is little threat from history bias, as the data were collected in a relatively brief period, and the random calls moved around the metro area rather than working one geographic region at a time. With a large, cross-sectional sample, there is little threat from maturation.
- There is no change in instrumentation for this survey, nor is there repeated testing that might raise concerns about testing bias or statistical regression toward the mean.
- Missing data are very limited. Three of the 1511 households in the Mecklenburg County subsample were eliminated because of missing household- or person-level data. Income category was missing in 17% of the households, and imputed from other variables, but found not to be statistically significantly different. No other imputations or corrections were performed.

Construct validity is strong, as the carefully constructed survey uses well-known standard operational definitions for variables (e.g., household auto ownership, trips, mode choice) and builds on earlier surveys. The neighborhood typology (a transect constructed by researchers working on the related regional forecasting project) builds on extensive earlier work and itself will inform later research; the models using the transect included standard socio-demographic and land use measures already in heavy use in auto ownership and travel modeling. Statistical conclusion validity is strong, as the sample size of 1508 is generous and the alpha level for significance (0.10) is appropriate for models using a mix of established measures for the behaviors under study and new techniques for incorporating the environment.

External validity is limited, given the single study location, which hinders generalization of the findings to other areas. At the same time, the process is instructive on several fronts: looking at household-level decisions of different scales with the same dataset, integration of land use and transportation models to generate travel data appropriate for use as inputs in other land use and transportation models, and comparison of multiple model structures and statistical techniques.

Table 6 summarizes the models developed for this dissertation.

**TABLE 6 Models and measures**

| Outcome measure | Model | Dependent variables | Independent variables | Built environment attributes |
|---|---|---|---|---|
| Household auto ownership | Negative binomial count model | # of vehicles in household | Household size, owner, home type, income, children, bikes | • Neighborhood type: 7 clusters: city center, urban, inner/middle/outer suburbs, rural mixed, rural greenfields **OR**<br>• 5 factors: walkability, accessibility, agglomeration, industry, property values **OR**<br>• 4 environmental measures: residential density, access to transit, commercial use, CBD |
| Household trip generation | Negative binomial count model | # trips of all modes by all householders | Household size, owner, home type, income, children, bikes, autos | |
| Personal trip generation | Negative binomial count model | # trips, all modes, by person; walk and drive | Household size, income, children, autos, age, sex, work, school | |
| Mode choice | Nested logit choice model | Mode chosen for trip | Household size, autos, income, sex, age, travel time, cost | |

# 5. Auto Ownership and Trip Generation

For auto ownership modeling, household variables include household size, home type, home ownership, income, and numbers of children and bicycles. Trip models use the same household variables with the addition of auto ownership, modeled at both the household and person levels; the latter includes select personal characteristics. Environmental measures include three environmental representations, including built and natural features as well as select economic measures, comprising three separate sets of variables: clusters, factors, and direct environmental measures.

## a. Descriptive Statistics

Table 7 shows descriptive statistics for household, personal, and environmental measures. The household size of 2.3 compares to averages (2000) of 2.4 for Mecklenburg County and 2.6 for the U.S. (US Census, 2000). Income categories represent percentages, and sum to 1.0. The middle range claims 53% of households; 15% earn less than $30,000 and 32% exceed $75,000. By contrast, U.S. figures (1999) are 42% in the middle category, and 35% and 23% in the lower and higher categories, respectively (US Census, 2000), suggesting our sample is relatively affluent. Nearly 80% of sample households own their homes, compared to 60% for Mecklenburg County and 66% for the nation (US census).

Auto ownership (1.8) is slightly lower than the national 1.9 (NHTS, 2001)—a pattern familiar in large metro areas where household vehicle fleets are smaller than the national average (FHWA). Household trips (mean=8.4) include all trips made by all household members over the age of 5 on the travel day. Private autos were used for 93% of all trips, compared to 87% nationwide (40). Personal measures include female (52%), age (mean=40 years), and total trips per traveler (mean=3.9), including 3.6 drive and 0.12 walk trips.

### TABLE 7 Descriptive statistics for households and travelers

| **VARIABLES—name and type** | **Mean** | **St Dev** | **Min** | **Max** |
|---|---|---|---|---|
| **Household variables, n=1508** | | | | |
| AUTOS (number of household vehicles), count | 1.8263 | .8722 | 0 | 10 |
| HHSIZE (number of persons in household), count | 2.3203 | 1.2392 | 1 | 8 |
| CHILDREN (number of children in household), count | .3727 | .7565 | 0 | 4 |
| WORKERS (number of workers, full/part-time), count | 1.2334 | .8113 | 0 | 6 |
| BIKES (number of household bicycles), count | .8342 | 1.1342 | 0 | 7 |
| HHTRIPS (number of trips reported for travel day), count | 8.3899 | 6.1431 | 0 | 39 |
| MINUTES (total minutes household travel), continuous | 178.0968 | 158.2288 | 0 | 1846 |
| MILES (total miles household travel distance), continuous | 43.0534 | 49.7329 | 0 | 733 |
| Income (categories sum to 1.00) | | | | |
| LOWINC (income between 0 and $30,000), binary | .1512 | .3584 | 0 | 1 |
| MIDINC (income $30,000 -- $75,000), binary | .5265 | .4995 | 0 | 1 |
| HIGHINC (income above $75,000), binary | .3223 | .4675 | 0 | 1 |
| **Traveler variables, n=3213** | | | | |
| FEMALE, binary | .5213 | .4996 | 0 | 1 |
| AGE (years), continuous | 40.1512 | 19.6421 | 5 | 91 |
| WORK (work status, full- or part-time), binary | .5789 | .4938 | 0 | 1 |
| SCHOOL (student status, full- or part-time), binary | .2228 | .4162 | 0 | 1 |
| PERTRIPS (total trips by traveler on travel day, all modes), count | 3.9331 | 2.6467 | 0 | 15 |
| DRIVE (drive trips), count | 3.6016 | 2.7059 | 0 | 15 |
| WALK (walk trips), count | 0.1261 | 0.5524 | 0 | 7 |
| **Environmental variables** | | | | |
| Neighborhood (cluster, categories sum to 1.0), binary | | | | |
| GREEN—Rural greenfield | .0325 | .1774 | 0 | 1 |
| RURALMIX—Rural mixed use, including some industrial | .0424 | .2017 | 0 | 1 |
| OUTERSUB—Outer suburban ring | .1432 | .3504 | 0 | 1 |
| MIDDLESUB—Middle suburban ring | .1558 | .3628 | 0 | 1 |
| INNERSUB—Inner suburban ring | .2924 | .4550 | 0 | 1 |
| URBAN—Urban neighborhoods | .2009 | .4008 | 0 | 1 |
| CITYCENTER—Central business district and central city | .1326 | .3393 | 0 | 1 |
| Simple environmental measures (mean values) | | | | |
| RESDENSITY (single-family parcels/acre), continuous | 2.8216 | 4.0110 | .0073 | 51.4659 |
| BUS (distance to bus stop, 1000 ft), continuous | 3.8957 | 4.4093 | .2188 | 26.7004 |
| COMM (distance to commercial, 1000 ft), continuous | 2.1521 | 1.2657 | 0 | 7.1152 |
| CBDDIST (distance to CBD, 1000 ft), continuous | 42.6167 | 21.3014 | 2.1755 | 100.109 |

Neighborhood clusters sum to 1, with each household assigned to one cluster. Mean factor scores (not shown) are calculated for each case by taking that case's standardized scores on the component variables, multiplying them by the corresponding factor loadings, and summing the products. Factors may be interpreted in terms of a 1-unit increase in factor scores and the associated change in outcome variables (e.g., autos or trips), or as a larger change across the range of factors scores, for example, from the most walkable to least walkable environments—a range of 9.65 units. The four direct environmental measures are shown with mean values for residential density, and distance to the nearest commercial use, bus stop, and CBD—the latter a measure of regional access. The three sets of environmental measures are used, sequentially, as independent variables in auto and travel models.

Table 8 presents descriptive statistics for the 1508 households in the sample, broken out by cluster, for a general view of who lives in various neighborhood types. Auto ownership generally declines from rural to urban, with a high of 2.37 in the rural greenfields and a low of 1.51 in the city center. Household size likewise is greatest in the rural greenfields and lowest in the city center, but does not show a smooth drop along the transect, while the number of children per household is highest in the outer suburbs. Number of workers per household is highest in the middle suburbs and greenfields, and lowest in the city center—where the fewest household children also appear, perhaps indicating more single-person households.

Home ownership ranges from a low of 56% in the rural mixed cluster to 94% in the outer suburbs; single-family homes follow a similar pattern. These same two clusters have the lowest and highest trips per household, at 6.72 and 9.65 for rural mixed and outer suburban clusters, respectively.

Among personal characteristics, women account for an increasingly large share of the population, moving from rural clusters to urban and city center; mean age decreases from the rural greenfields in to the middle suburbs, then increases again toward the more urban clusters. The share of workers is highest in the rural mixed and middle suburban clusters, and lowest in the outer and inner suburbs, while student status is most common in the suburban and urban clusters. Daily person-trips increase in the rural-urban direction: lowest in the rural greenfields and highest in the city center, deviating from a smooth increase in the suburban clusters, perhaps reflecting trade-offs between distance to the city center and design elements that might induce trips (e.g., streetscape, connectivity, employment and commercial density).

### TABLE 8 Mean values for household and person variables by neighborhood type

| VARIABLES | **Rural green** | **Rural mix** | **Outer suburb** | **Middle suburb** | **Inner suburb** | **Urban** | **City center** | **Total** |
|---|---|---|---|---|---|---|---|---|
| **Household** | N=49 | N=64 | N=216 | N=235 | N=441 | N=303 | N=200 | N=1508 |
| AUTOS | 2.37 | 1.59 | 1.99 | 1.94 | 1.88 | 1.71 | 1.51 | 1.83 |
| HHSIZE | 2.63 | 2.00 | 2.56 | 2.56 | 2.29 | 2.29 | 1.94 | 2.32 |
| CHILDREN | 0.31 | 0.27 | 0.53 | 0.47 | 0.38 | 0.32 | 0.21 | .37 |
| WORKERS | 1.37 | 1.14 | 1.31 | 1.40 | 1.19 | 1.22 | 1.08 | 1.23 |
| OWNER | 0.92 | 0.56 | 0.94 | 0.90 | 0.83 | 0.72 | 0.65 | 0.80 |
| SFHOME | 0.88 | 0.53 | 0.92 | 0.85 | 0.77 | 0.73 | 0.64 | 0.77 |
| BIKES | 1.00 | 0.81 | 1.14 | 0.95 | 0.76 | 0.65 | 0.77 | .83 |
| HHTRIPS | 7.98 | 6.72 | 9.65 | 9.09 | 8.43 | 7.78 | 7.69 | 8.39 |
| MINUTES | 210.71 | 176.00 | 202.13 | 204.43 | 176.69 | 157.83 | 147.69 | 178.10 |
| MILES | 55.61 | 32.56 | 55.23 | 55.80 | 41.81 | 35.03 | 30.04 | 43.05 |
| LOWINC | 0.08 | 0.16 | 0.07 | 0.11 | 0.11 | 0.22 | 0.29 | .15 |
| MIDINC | 0.51 | 0.61 | 0.50 | 0.51 | 0.55 | 0.58 | 0.44 | .53 |
| HIGHINC | 0.41 | 0.23 | 0.43 | 0.39 | 0.34 | 0.20 | 0.28 | .32 |
| **Person** | N=112 | N=121 | N=511 | N=537 | N=947 | N=618 | N=367 | N=3213 |
| FEMALE | 0.50 | 0.45 | 0.51 | 0.51 | 0.52 | 0.54 | 0.56 | .48 |
| AGE | 40.52 | 39.27 | 38.71 | 36.30 | 42.87 | 39.60 | 41.88 | 40.15 |
| WORK | 0.60 | 0.60 | 0.55 | 0.61 | 0.55 | 0.60 | 0.59 | 0.58 |
| SCHOOL | 0.16 | 0.21 | 0.26 | 0.25 | 0.21 | 0.22 | 0.20 | .22 |
| PERTRIPS | 3.49 | 3.55 | 4.08 | 3.98 | 3.93 | 3.79 | 4.19 | 3.93 |
| **Factors—mean factor scores** | | | | | | | | |
| WALKABLE | -2.11 | -0.81 | -0.85 | -3.51 | 0.39 | 0.06 | 0.25 | -.61 |
| ACCESS | -2.17 | 0.30 | -1.08 | 0.71 | -0.71 | 0.33 | 1.29 | -.07 |
| AGGLOM | 3.53 | -0.66 | -0.43 | -0.96 | -0.69 | -0.43 | 1.08 | -.27 |
| INDUSTRY | 0.14 | 3.66 | -0.95 | -0.43 | -0.11 | 0.15 | -0.38 | -.10 |
| PROPERTY | -0.02 | 0.13 | 0.13 | -0.01 | 0.10 | -0.12 | -0.07 | .02 |
| **Simple environmental measures**—mean values for dwelling units/acre; distance (1000 ft) to bus, commerce, CBD | | | | | | | | |
| RESDENSITY | 0.7685 | 1.5214 | 1.2269 | 1.6560 | 1.8548 | 3.5415 | 7.8735 | 2.8216 |
| BUS | 15.4792 | 1.5610 | 8.6744 | 6.7913 | 2.3789 | 1.2411 | 0.6077 | 3.8957 |
| COMM | 3.0939 | 1.2399 | 3.2207 | 2.0001 | 2.7482 | 1.5671 | 0.8098 | 2.1521 |
| CBDDIST | 66.7946 | 57.1192 | 57.6483 | 55.0713 | 46.1930 | 30.7821 | 11.2276 | 42.6167 |

For the environmental measures, the factors show dramatic variation in descriptive statistics across clusters. For example, walkability ranges from a factor score of -3.51 for the middle suburbs to 0.39 for the inner suburbs, while access ranges from a low of -2.17 for the rural greenfields to a high of 1.29 for the city center. Likewise, industrial acreage is strongly represented in the rural mixed cluster (3.66), with a low of -0.95 in the outer suburbs.

The means for direct environmental measures show generally increasing residential density from rural (0.77 single-family parcels per acre) to urban (7.87), with a dip in the density in the outer suburbs. At the same time, the distance to transit and commercial activity decreases from the rural greenfields toward the center; an exception to this generally clear pattern is the rural mixed cluster, which has better access (shorter distances) to transit and commerce than both the rural greenfields and the three suburban rings.

### b. Auto Ownership

In order to answer questions about differences in auto ownership across the transect, autos were modeled as the number of vehicles held by the household, starting with household variables, then adding in, sequentially, three sets of variables comprising the three different environmental representations. Chapter 4 specifies the models and justifies use of negative binomial regression. Incident rate ratios (IRR) show the change in dependent variable as a value relative to unity.

Table 9 presents results of the auto ownership model. Variance inflation factors (VIF) for the restricted model (model 1) range from 1.2 to 2.6, all well below the standard threshold of 10, suggesting minimal concern about collinearity among independent variables. Clusters include a handful with VIFs ranging from 4 to 7, while factors and direct measures all have low values between 1 and 2.

All household factors (model 1) were found to be significantly associated with auto ownership. The negative sign on children may reflect children increasing household size without adding drivers, while simultaneously impacting the travel of adults in the household.

**TABLE 9. Household auto ownership, negative binomial regression**

| **Variables** | Model 1 | | | Model 2 | | | Model 3 | | | Model 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR |
| CONSTANT | **-.3891** | **.000** | **0.6777** | **-.2314** | **.069** | **0.7934** | **-.3594** | **.000** | **0.6981** | **-.4298** | **.000** | **0.6506** |
| HHSIZE | **.1596** | **.000** | **1.1730** | **.1576** | **.000** | **1.1707** | **.1588** | **.000** | **1.1721** | **.1593** | **.000** | **1.1727** |
| CHILDREN | **-.1475** | **.000** | **0.8629** | **-.1466** | **.000** | **0.8636** | **-.1479** | **.000** | **0.8625** | **-.1513** | **.000** | **0.8596** |
| OWNER | **.1862** | **.012** | **1.2047** | **.1754** | **.018** | **1.1917** | **.1668** | **.025** | **1.1815** | **.1680** | **.023** | **1.1829** |
| SFHOME | **.1777** | **.011** | **1.1945** | **.1783** | **.011** | **1.1952** | **.1680** | **.016** | **1.1829** | **.1642** | **.019** | **1.1784** |
| BIKES | **.0505** | **.003** | **1.0518** | **.0523** | **.002** | **1.0537** | **.0499** | **.004** | **1.0512** | **.0497** | **.004** | **1.0510** |
| MIDINC | **.3079** | **.000** | **1.3606** | **.2978** | **.000** | **1.3469** | **.2933** | **.000** | **1.3408** | **.2915** | **.000** | **1.3384** |
| HIGHINC | **.4282** | **.000** | **1.5345** | **.4172** | **.000** | **1.5177** | **.4110** | **.000** | **1.5083** | **.4074** | **.000** | **1.5029** |
| Cluster (GREEN is reference category) | | | | | | | | | | | | |
| RURALMIX | | | | -.1618 | .237 | 0.8506 | | | | | | |
| OUTERSUB | | | | -.1523 | .147 | 0.8587 | | | | | | |
| MIDDLESUB | | | | -.1464 | .160 | 0.8638 | | | | | | |
| INNERSUB | | | | -.1049 | .293 | 0.9004 | | | | | | |
| URBAN | | | | -.1468 | .156 | 0.8635 | | | | | | |
| CITYCENTER | | | | **-.2044** | **.064** | **0.8151** | | | | | | |
| Factors (indices) | | | | | | | | | | | | |
| WALKABLE | | | | | | | -.0080 | .521 | 0.9920 | | | |
| ACCESS | | | | | | | **-.0541** | **.007** | **0.9473** | | | |
| AGGLOM | | | | | | | .0020 | .900 | 1.0020 | | | |
| INDUSTRY | | | | | | | .0051 | .780 | 1.0051 | | | |
| PROPERTY | | | | | | | -.0150 | .850 | 0.9851 | | | |
| Simple environmental measures | | | | | | | | | | | | |
| RESDENSITY | | | | | | | | | | -.0023 | .703 | 0.9977 |
| BUS | | | | | | | | | | .0010 | .847 | 1.0010 |
| COMM | | | | | | | | | | **.0278** | **.084** | **1.0282** |
| CBDDIST | | | | | | | | | | .0006 | .614 | 1.0006 |
| **Summary statistics** | | | | | | | | | | | | |
| Number of obs | 1508 | | | 1508 | | | 1508 | | | 1508 | | |
| LR $\chi^2$ | 246.91 | | | 251.41 | | | 255.26 | | | 252.80 | | |
| P | 0.0000 | | | 0.0000 | | | 0.0000 | | | 0.0000 | | |
| Pseudo-$R^2$ | 0.0575 | | | 0.0585 | | | 0.0594 | | | 0.0589 | | |
| Log-likelihood | -2023.8682 | | | -2021.6223 | | | -2019.6964 | | | -2020.9277 | | |
| Likelihood ratio tests of restricted model (1) with each of the other model | | | | | | | | | | | | |
| LR $\chi^2$ | | | | 4.49 | | | 8.34 | | | 5.88 | | |
| Prob>$\chi^2$ | | | | 0.610 | | | 0.138 | | | 0.208 | | |

**Bold face denotes significance at p<0.10**

**Range of factor scores (units): walkable—9.65; access—8.46; agglom—8.49; industry—9.25; property—2.48**

The IRR values suggest 36.1% and 53.5% more autos for mid- and high-income households, compared to low-income. The significance and signs for the household variables persist across all models, and IRRs show only slight variation; the best-fit model (3) shows 34.1% and 50.8% more vehicles for mid- and high-income households, respectively.

When clusters are added as independent variables, with rural greenfields serving as the reference category (model 2), only the city center is significant, with an IRR suggesting an 18.5% drop in autos held by households living in the city center relative to rural greenfields.

Model 3 uses the five factors (each an index combining multiple simple measures) to represent various dimensions of the built environment; of these, only access is statistically significant (and negative), with an IRR indicating a 5.3% decrease in autos with a 1-unit increase in this factor. Given a range in factor scores in Charlotte of 8.46 (between minimum and maximum), the difference in auto ownership in the most and least accessible environments is substantial; that is, moving from residence in areas of low to high accessibility, households show a strong propensity to own fewer vehicles. Figure 9 in the Discussion (Chapter 7) shows both auto ownership and trips as they relate to increasing factor scores for access.

Of the simple environmental measures (model 4), only distance to commerce is significant, with a positive coefficient and an IRR suggesting a 2.8% increase in vehicles/household as distance to commerce increases by 1000 feet. Pseudo-$R^2$ values are low, but very similar across models—the appropriate use of this statistic, which is not a measure of explanatory power but rather describes how the models differ from one another.

Likelihood ratio tests compared model 1 (socio-demographic factors only) with each of the other three models; none significantly improved explanatory power over Model 1, which includes a concise set of household variables chosen because of their well-established relevance for understanding auto ownership. Nevertheless, the models with environmental measures are useful for advancing our understanding of how various quantitatively measured environments may relate to auto ownership.

Overall, the results for environmental measures conform to expectations of auto ownership being more responsive to household traits than to environmental measures. The exceptions are the distinctive access factor, which represents an index of measures that may dampen auto ownership, and location in the city center cluster or distance to commercial uses. These indicate that accessibility, as captured in three different environmental representations, is associated with decreased auto ownership. However, the declining auto ownership observed in the descriptive statistics (Table 5) along the transect from rural to urban clusters is not evident in clusters model, after controlling for other factors, except for the city center —characterized by the most extreme accessibility.

### c. Household trip generation

Household trip generation models start with the household variables used in the auto models, with the addition of number of household autos. Then three sets of variables comprising the three different environmental representations are added in separately and sequentially (Table 10). Compared to the auto models, the VIFs for trip models were similarly low—all below 3 for the restricted model and for factors and direct measures, with a handful of clusters ranging from 4 to 7; this suggests that collinearity among independent variables is not a concern.

In model 1 (household variables only), all variables except home ownership and single-family homes are significant and positive, with IRRs suggesting increased trips ranging from 2.8% (additional bicycle) to 27.2% (high income). The IRR on autos suggests that each additional auto relates to 10.8% more trips per household per day. Significance and signs of independent variables persist across all models, with only minor IRR changes.

**TABLE 10 Household trip generation, negative binomial regression**

| Variables | Model 1 | | | Model 2 | | | Model 3 | | | Model 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR |
| CONSTANT | **1.0928** | **.000** | **2.9826** | **.9482** | **.000** | **2.5811** | **1.0939** | **.000** | **2.9859** | **1.0453** | **.000** | **2.8443** |
| AUTOS | **.1029** | **.000** | **1.1084** | **.1062** | **.000** | **1.1120** | **.1081** | **.000** | **1.1142** | **.1054** | **.000** | **1.1112** |
| HHSIZE | **.1728** | **.000** | **1.1886** | **.1757** | **.000** | **1.1921** | **.1731** | **.000** | **1.1890** | **.1731** | **.000** | **1.1890** |
| CHILDREN | **.1908** | **.000** | **1.2102** | **.1919** | **.000** | **1.2115** | **.1919** | **.000** | **1.2115** | **.1958** | **.000** | **1.2163** |
| OWNER | .0682 | .183 | 1.0706 | .0792 | .124 | 1.0824 | .0774 | .133 | 1.0805 | .0818 | .112 | 1.0852 |
| SFHOME | .0496 | .311 | 1.0509 | .0454 | .354 | 1.0464 | .0482 | .326 | 1.0494 | .0518 | .291 | 1.0532 |
| BIKES | **.0273** | **.045** | **1.0277** | **.0264** | **.052** | **1.0268** | **.0253** | **.063** | **1.0256** | **.0276** | **.042** | **1.0280** |
| MIDINC | **.1541** | **.001** | **1.1666** | **.1679** | **.000** | **1.1828** | **.1458** | **.002** | **1.1570** | **.1656** | **.001** | **1.1801** |
| HIGHINC | **.2406** | **.000** | **1.2720** | **.2497** | **.000** | **1.2836** | **.2211** | **.000** | **1.2474** | **.2519** | **.000** | **1.2865** |
| Cluster (GREEN is reference category) | | | | | | | | | | | | |
| RURALMIX | | | | .0305 | .779 | 1.0310 | | | | | | |
| OUTERSUB | | | | .1088 | .214 | 1.1149 | | | | | | |
| MIDDLESUB | | | | .0840 | .334 | 1.0876 | | | | | | |
| INNERSUB | | | | .1139 | .173 | 1.1206 | | | | | | |
| URBAN | | | | .1122 | .192 | 1.1187 | | | | | | |
| CITYCENTER | | | | **.2218** | **.013** | **1.2483** | | | | | | |
| Factors (indices) | | | | | | | | | | | | |
| WALKABLE | | | | | | | **.0175** | **.059** | **1.0177** | | | |
| ACCESS | | | | | | | **.0380** | **.012** | **1.0387** | | | |
| AGGLOM | | | | | | | -.0044 | .727 | 0.9956 | | | |
| INDUSTRY | | | | | | | **-.0289** | **.032** | **0.9715** | | | |
| PROPERTY | | | | | | | **.1512** | **.008** | **1.1632** | | | |
| Simple environmental measures | | | | | | | | | | | | |
| RESDENSITY | | | | | | | | | | **.0094** | **.022** | **1.0094** |
| BUS | | | | | | | | | | -.0040 | .310 | 0.9960 |
| COMMERCE | | | | | | | | | | .0044 | .729 | 1.0044 |
| CBDDIST | | | | | | | | | | -.0001 | .925 | 0.9999 |
| **Summary statistics** | | | | | | | | | | | | |
| Number of obs | 1508 | | | 1508 | | | 1508 | | | 1508 | | |
| LR $\chi^2$ | 771.87 | | | 783.00 | | | 785.62 | | | 781.14 | | |
| P | 0.0000 | | | 0.0000 | | | 0.0000 | | | 0.0000 | | |
| Pseudo-$R^2$ | 0.0835 | | | 0.0847 | | | 0.0850 | | | 0.0845 | | |
| Log-likelihood | -4235.1527 | | | -4229.5854 | | | -4228.2757 | | | -4230.5183 | | |
| Likelihood ratio tests of restricted model (1) with each of the other model | | | | | | | | | | | | |
| LR $\chi^2$ | | | | 11.13 | | | 13.75 | | | 9.27 | | |
| Prob>$\chi^2$ | | | | 0.084 | | | 0.017 | | | 0.054 | | |

**Bold face denotes significance at $p<0.10$**

**Range of factor scores (units): walkable—9.65; access—8.46; agglom—8.49; industry—9.25; property—2.48**

When clusters are added (model 2) to represent built environment, only city center is significant (and positive), with an IRR indicating a 24.8% increase in trips in the urban neighborhoods compared to rural greenfields.

Among the factors (model 3), walkability and access are positively significant, with IRRs suggesting 1.8% and 3.9% increases in trips when the factor scores increase by 1. The range in walkability and access scores of 9.65 and 8.46 suggests that substantially more trips (17% and 33%) will be made in the most walkable and most accessible areas compared to the least, respectively. These results conform to expectations for increased trip-making with greater walkability and access. Industry is negatively significant, perhaps because this factor comprises a single measure (industrial acreage) that does not capture the mixed uses often present in traditional and neo-traditional development (including retail, services, office space, and public uses, among others). Property value is positively significant, relating to a 16.3% increase in trips with a 1-unit increase in this index, consistent with expectations for increased trip-making in areas of intense economic activity and high value of buildings and land. Note that the middle- and high-income variables capture the personal wealth of travelers, while the property value factor relates to economic intensity. Of the simple environmental measures (model 4), only residential density is significant, with an IRR suggesting <1% increase in trips with an additional single-family dwelling unit per acre.

Comparing across environmental representations in trip models, the clusters are not significant for household trips (except the city center, characterized by high density and connectivity), while most factors are. Property value has the largest effect, while the positive associations of walkability and access are smaller but still substantive, particularly when considered at the extremes. The walkability factor comprises measures that may encourage non-walking trips as well (e.g., short distances, density), and thus this factor expresses a similar trip-generating aspect of the environment. This may explain the significance of the city center cluster, which efficiently captures walkability, mixed used, and property value, and demonstrates how important such intensely urban subcenters may be. Figure 9 in the Discussion (Chapter 7) shows both auto ownership and trips as they relate to increasing factor scores for access.  Residential density is the only direct measure significant for trips trips—with a positive but very small association.

While the environmental measures did not improve explanatory power in the auto ownership models, all three improved performance of the household trip model, with likelihood $\chi^2$ values greater than the critical value ($\alpha = 0.100$). This is consistent with the apparently significant association between physical environment and trip-making, and with earlier research (e.g., Shay and Khattak, 2005) that found auto use sensitive to neighborhood type even where auto ownership was not.

### d. Path analysis—Trips

Path analysis is useful for estimating the total effect of environment on household trips, both directly as expressed in the coefficients for clusters and factors in the trip model, and indirectly through auto ownership. To estimate the total contribution of environmental measures to variation in number of trips made by households, the direct marginal effect (calculated from IRRs to show percentage change) of environment on trips is added to the product of the two segments of the indirect path (environment→autos→trips), from the auto and trip models. The total effect for each variable is A + B*C (Figure 6).

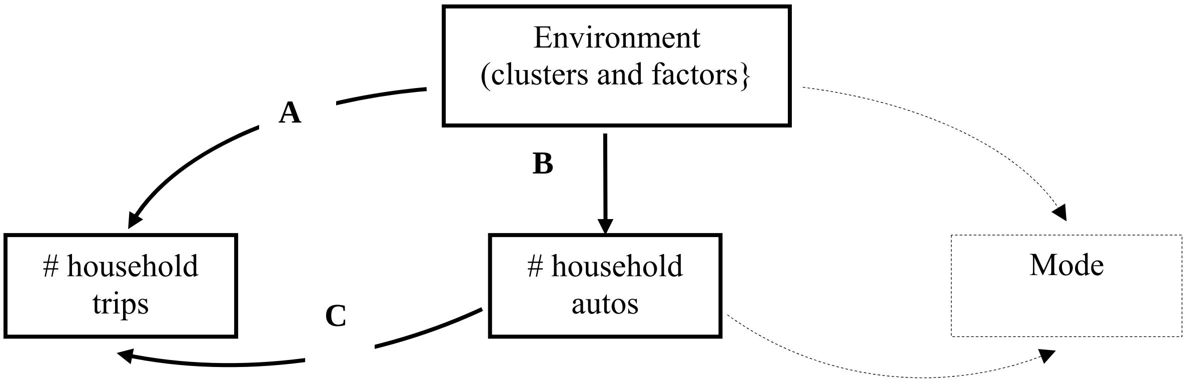


**Figure 6. Path analysis for environment→autos→trips chain**

Table 11 shows direct, indirect and total effects for the environment→autos→trips path, using clusters to represent the environment. The total effect of the city center (the only cluster significant for auto ownership) on trips is shown in the far right column. The 18.5% decrease (shown as an effect of -0.1849 in column B) in autos in the city center (compared to rural greenfields) is multiplied by the positive association of autos with trips (0.1120 in column C) to yield an indirect effect of -0.0207. This partially offsets the positive association of autos with trips (a 24.8% increase, or 0.2483 in column A), for a total effect of 0.2276, signifying a net 22.8% increase in trips in the city center.

The direction of the auto-dampening effect of environment, as represented by the city center cluster and its associated high walkability and access qualities, is as hypothesized, although the magnitude of the indirect effect was uncertain; here it appears to be modest compared to the larger positive association of the same environments with additional trips.

**TABLE 11 Path analysis of environment, autos and trips, using clusters**

| **Variables** | A) Direct, environ/trips | | B) Direct, environ/autos | | C) Direct, autos on trips | | Indirect, env/trips | Total effects |
|---|---|---|---|---|---|---|---|---|
| | % change | P | % change | P | % change | P | B*C | A + (B*C) |
| CONSTANT | **1.5811** | **.000** | **-0.2066** | **.069** | **0.1120** | **.000** | **-0.0231** | **1.5580** |
| HHSIZE | **0.1921** | **.000** | **0.1707** | **.000** | **0.1120** | **.000** | **0.0191** | **0.2112** |
| CHILDREN | **0.2115** | **.000** | **-0.1364** | **.000** | **0.1120** | **.000** | **-0.0153** | **0.1962** |
| OWNER | 0.0824 | .124 | **0.1917** | **.018** | **0.1120** | **.000** | 0.0215 | 0.1039 |
| SFHOME | 0.0464 | .354 | **0.1952** | **.011** | **0.1120** | **.000** | 0.0219 | 0.0683 |
| BIKES | **0.0268** | **.052** | **0.0537** | **.002** | **0.1120** | **.000** | **0.0060** | **0.0328** |
| MIDINC | **0.1828** | **.000** | **0.3469** | **.000** | **0.1120** | **.000** | **0.0389** | **0.2217** |
| HIGHINC | **0.2836** | **.000** | **0.5177** | **.000** | **0.1120** | **.000** | **0.0580** | **0.3416** |
| **Cluster (GREEN is reference category)** | | | | | | | | |
| RURALMIX | 0.0310 | .779 | -0.1404 | .237 | **0.1120** | **.000** | -0.0157 | 0.0153 |
| OUTERSUB | 0.1149 | .214 | -0.1413 | .147 | **0.1120** | **.000** | -0.0158 | 0.0991 |
| MIDDLESUB | 0.0876 | .334 | -0.1362 | .160 | **0.1120** | **.000** | -0.0153 | 0.0723 |
| INNERSUB | 0.1206 | .173 | -0.0996 | .293 | **0.1120** | **.000** | -0,0112 | 0.1094 |
| URBAN | 0.1187 | .192 | -0.1365 | .156 | **0.1120** | **.000** | -0.0153 | 0.1034 |
| CITYCENTER | **0.2483** | **.013** | **-0.1849** | **.064** | **0.1120** | **.000** | **-0.0207** | **0.2276** |
| **Summary statistics** | | | | | | | | |
| Number of obs | 1508 | | 1508 | | 1508 | | | |
| LR chi-square | 783.00 | | 251.41 | | 783.00 | | | |
| P | 0.0000 | | 0.0000 | | 0.0000 | | | |
| Pseudo-$R^2$ | 0.0847 | | 0.0585 | | 0.0847 | | | |
| Log-likelihood | -4229.5854 | | -2021.6223 | | -4229.5854 | | | |

**Bold face indicates p<0.10; bold face in total effects indicates significant along entire path**

Of the control household factors (all significant in the auto model; all but owner and single-family homes significant in the trip model), all have positive direct and indirect effects, so that the indirect effect of environment on trips (through autos) amplifies the direct effect. The only exception is children, positively associated with trips but negatively with autos, such that the negative indirect effect slightly offsets the positive direct effect.

Table 12 shows the same series of effects from environment and autos on trips, using factors instead of clusters as environmental measures. More of the factors showed significant associations with trips than did clusters, although only access is significant in both auto and trip models, yielding a negative indirect effect (environment→autos→trips) that partially offsets the positive direct effect. Although the net association of access and trips is modest, at 3.27%, this effect relates to a 1-unit change in factor scores, with 27.7% more trips in the most accessible compared to the least accessible. Figure 9 in the Discussion (Chapter 7) shows trips (direct effect from environment as well as net) and autos relative to increasing factor scores for accessibility.

**TABLE 12 Path analysis of environment, autos and trips, using factors**

| **Variables** | A) Direct, environ/trips | | B) Direct , environ/autos | | C) Direct, autos/trips | | Indirect, env/trips | Total effects |
|---|---|---|---|---|---|---|---|---|
| | % change | P | % change | P | % change | P | B*C | A + (B*C) |
| CONSTANT | **1.9859** | **.000** | **-0.3019** | **.000** | **1.1142** | **.000** | **-0.0345** | **1.9514** |
| HHSIZE | **0.1890** | **.000** | **0.1721** | **.000** | **1.1142** | **.000** | **0.0244** | **0.2134** |
| CHILDREN | **0.2115** | **.000** | **-0.1375** | **.000** | **1.1142** | **.000** | **-0.0157** | **0.1958** |
| OWNER | 0.0805 | .133 | **0.1815** | **.025** | **1.1142** | **.000** | 0.0207 | 0.1014 |
| SFHOME | 0.0494 | .326 | **0.1829** | **.016** | **1.1142** | **.000** | 0.0209 | 0.0703 |
| BIKES | **0.0256** | **.063** | **0.0512** | **.004** | **1.1142** | **.000** | **0.0058** | **0.0314** |
| MIDINC | **0.1570** | **.002** | **0.3408** | **.000** | **1.1142** | **.000** | **0.0389** | **0,1959** |
| HIGHINC | **0.2474** | **.000** | **0.5083** | **.000** | **1.1142** | **.000** | **0.0580** | **0.3054** |
| **Factors** | | | | | | | | |
| WALKABLE | **0.0177** | **.059** | -0.0080 | .521 | **1.1142** | **.000** | -0.0009 | 0.0168 |
| ACCESS | **0.0387** | **.012** | **-0.0527** | **.007** | **1.1142** | **.000** | **-0.0060** | **0.0327** |
| AGGLOM | -0.0044 | .727 | 0.0020 | .900 | **1.1142** | **.000** | 0.0002 | -0.0042 |
| INDUSTRY | **-0.0285** | **.032** | 0.0051 | .780 | **1.1142** | **.000** | 0.0006 | -0.0279 |
| PROPERTY | **0.1632** | **.008** | -0.0149 | .850 | **1.1142** | **.000** | -0.0017 | 0.1615 |
| **Summary statistics** | | | | | | | | |
| Number of obs | 1508 | | 1508 | | 1508 | | | |
| LR chi-square | 785.62 | | 255.26 | | 785.62 | | | |
| P | 0.0000 | | 0.0000 | | 0.0000 | | | |
| Pseudo-$R^2$ | 0.0850 | | 0.0594 | | 0.0850 | | | |
| Log-likelihood | -4228.2757 | | -2019.6964 | | -4228.2757 | | | |

**Bold face indicates p<0.10; bold face in total effects indicate significance along entire path**

Here too all of the control household factors are significant in the trip model and all but homeowner and single-family home in the auto model; at the same time, number of children shows the same negative sign in the auto model as seen in the clusters, such that a negative indirect effect partially offsets the larger and positive direct effect. Even with the moderating negative indirect effect of children dampening auto ownership, the total effect is large, with an additional child being associated with nearly 20% more trips. All the other control variables are positive for both autos and trips, such that the indirect effect amplifies the direct effect. Household size and mid-income variables have total effects of about 20% more trips, and high income with about 31%.

In general, walkability and access, expressed as the city center cluster and the walkability and accessibility factors, are associated with net increased trip generation. The trip-encouraging features that characterize the city center cluster and highly walkable and accessible areas are only slightly offset by the indirect negative association with auto ownership  The net association of environment and trips (a 3.3% increase with 1-unit increase in factor score), is smaller than the net association for all statistically significant household factors, except bicycles; these coefficients, all positive, range from 19.6% (children, middle income) to 30.5% (high income).

### e. Person trip generation by mode

Number of trips also is modeled at the person level, using select household variables (all those that were significant for auto ownership, except bicycles), as well as several personal characteristics: sex, age, and work and school status. Age was converted to two dummies of youth (under 25 years) and elder (65 and older), both for consistency with the person-level auto and mode choice  models, and to represent larger life-cycle patterns, which are more likely to show differences in trip-generating potential than single one-year increments over a range from young children to older adults. After person trips were modeled with socio-demographic variables, the same three sets of environmental variables were added, sequentially, to the person trip models (Table 13). The dependent variable is all trips taken by the traveler on the survey day, by all modes; travelers who made zero trips on the survey day are included. A robust cluster technique controlled for interaction among household members (after White, 1980), which yields a more conservative test.

Of the personal factors, female and worker are significant and positive, associated with 10.1% or 6.0% more trips, respectively, while youth relates to 16.4% fewer trips. All the household factors except autos are significant, and all but household size positive. The largest IRR, on high income, indicates high-income people making 23.4% more trips.

**TABLE 13 Person trips, all modes**

| Variables | Model 1 | | | Model 2 | | | Model 3 | | | Model 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR |
| CONSTANT | **1.2489** | **.000** | **3.4865** | **1.1150** | **.000** | **3.0496** | **1.2577** | **.000** | **3.5173** | **1.1870** | **.000** | **3.2772** |
| FEMALE | **.0958** | **.000** | **1.1005** | **.0939** | **.000** | **1.0985** | **.0945** | **.000** | **1.0991** | **.0950** | **.000** | **1.0997** |
| YOUTH | **-.1796** | **.001** | **0.8356** | **-.1788** | **.001** | **0.8363** | **-.1829** | **.001** | **0.8323** | **-.1806** | **.001** | **0.8348** |
| ELDER | -.0394 | .450 | 0.9614 | -.0406 | .436 | 0.9602 | -.0457 | .379 | 0.9553 | -.0453 | .387 | 0.9557 |
| WORK | **.0585** | **.092** | **1.0602** | .0558 | .108 | 1.0574 | **.0650** | **.059** | **1.0672** | .0564 | .103 | 1.0580 |
| SCHOOL | -.0346 | .509 | 0.9660 | -.0384 | .473 | 0.9623 | -.0277 | .603 | 0.9727 | -.0358 | .497 | 0.948 |
| HHSIZE | **-.0665** | **.000** | **0.9357** | **-.0657** | **.000** | **0.9364** | **-.0668** | **.000** | **0.9354** | **-.0665** | **.000** | **0.9357** |
| CHILDREN | **.1263** | **.000** | **1.1346** | **.1269** | **.000** | **1.1353** | **.1261** | **.000** | **1.1344** | **.1308** | **.000** | **1.1397** |
| AUTOS | .0200 | .288 | 1.0202 | .0238 | .202 | 1.0241 | .0241 | .207 | 1.0244 | .0226 | .232 | 1.0229 |
| MIDINC | **.1277** | **.009** | **1.1362** | **.1403** | **.006** | **1.1506** | **.1138** | **.024** | **1.1205** | **.1406** | **.005** | **1.1510** |
| HIGHINC | **.2101** | **.000** | **1.2338** | **.2194** | **.000** | **1.2453** | **.2110** | **.001** | **1.1984** | **.2230** | **.000** | **1.2498** |
| Cluster (RURALGREEN is reference category | | | | | | | | | | | | |
| RURALMIX | | | | .0203 | .851 | 1.0205 | | | | | | |
| OUTERSUB | | | | .1300 | .147 | 1.1388 | | | | | | |
| MIDDLESUB | | | | .1088 | .232 | 1.1149 | | | | | | |
| INNERSUB | | | | .1057 | .225 | 1.1115 | | | | | | |
| URBAN | | | | .1139 | .207 | 1.1206 | | | | | | |
| CITYCENTER | | | | **.2060** | **.030** | **1.2288** | | | | | | |
| Factors (indices) | | | | | | | | | | | | |
| WALKABLE | | | | | | | .0116 | .236 | 1.0117 | | | |
| ACCESS | | | | | | | **.0340** | **.026** | **1.0346** | | | |
| AGGLOM | | | | | | | -.0018 | .884 | 0.9982 | | | |
| INDUSTRY | | | | | | | **-.0276** | **.033** | **0.9728** | | | |
| PROPERTY | | | | | | | **.1759** | **.001** | **1.1923** | | | |
| Simple environmental measures | | | | | | | | | | | | |
| RESDENS | | | | | | | | | | **.0115** | **.009** | **1.0116** |
| BUS | | | | | | | | | | -.0025 | .495 | 0.9975 |
| COMMERCE | | | | | | | | | | .0076 | .561 | 1.0076 |
| CBDDIST | | | | | | | | | | .0002 | .836 | 1.0002 |
| **Summary statistics** | | | | | | | | | | | | |
| Number of obs | 3213 | | | 3213 | | | 3213 | | | 3213 | | |
| Wald $\chi 2$ | 144.27 | | | 153.69 | | | 163.42 | | | 156.33 | | |
| P>$\chi 2$ | 0.0000 | | | 0.0000 | | | 0.0000 | | | 0.0000 | | |
| Log pseudoLL | -7380.5754 | | | -7374.2233 | | | -7370.6828 | | | -7374.0771 | | |

**Bold face denotes significance at p<0.10**

**Range of factor scores (units): walkable—9.65; access—8.46; agglom—8.49; industry—9.25; property—2.48**

The p value of 0.288 on autos is surprising, particularly given the positive and significant association of autos with household trips; this may reflect collinearity with the household size variable, given the near saturation of the population with autos; descriptive statistics (Table 7, Chapter 5) showed that households average 2.3 people, including 0.4 children, and 1.8 autos.

The other household variables in the person-trip model are similar to the household trip model, particularly in terms of magnitude and sign for middle and high income; the IRR on children suggests a smaller effect on person-level trips (a 13.5% increase) than on household trips (21.0% more).  Household size relates to 18.9% more household trips but 3.4% fewer person trips with an additional household member, perhaps as householders share tasks that generate trips.

When environmental measures are added, the socio-demographic variables retain their sign and significance across all models, with only slight variations in IRRs. Of the clusters, only the city center is significantly associated with person trips, with an IRR showing increased trip-making (22.9%) similar to the 24.8% increase in household trips in this cluster, which likewise was the only significant cluster for household trips.

Person trips are sensitive to access, industry, and property values; of these, industry has a negative association, and the other two are positive. Property values have the largest effect (19.2%), compared to a 3.5% in increase in person trips with a 1-unit increase in the accessibility factor score. Compared to household trips, the person trips show a similar response to access (3.9%), but are insensitive to walkability, which had a positive, albeit small (1.8%) effect on household trips. The property value effect is similar for person and household trips (19.2% and 16.3%). The negative effect of industry on person and household trips is nearly identical, at 2.7% and 2.8%. Both person and household trips show a slight positive response (1.2% and 0.9%) to residential density increasing by 1 unit per acre.

When person trips of all modes (Table 14) are broken out into drive and walk modes, to consider how these two modes—one the overwhelmingly dominant mode and the other the primary non-motorized mode—relate to household and environmental factors, clear differences emerge. Only clusters and factors are shown, as direct measures are not significant, and household and personal factors are nearly identical in the restricted models to those with clusters and factors.

Drive and walk trips were modeled with the same socio-demographic variables (Table 14), adding first clusters (models 1 and 3) and then factors (models 2 and 4). All household and personal factors (except elder) are significant for person drive trips—including autos, which was not significant for all trips combined. As in the total person trips, youth and household size are negatively associated with person drive trips, with effects of 24.8% and 7.3%, respectively. Other household and personal factors are positively associated with person drive trips, with the largest effects for middle and high income: 24.5% and 32.5%, respectively. The same pattern holds for the model of person drive trips with factors.

Among environmental measures, person drive trips are sensitive only to the outer suburban and city center clusters, with positive effects of 19.2% and 20.8%, respectively. The city center effect is similar to that of total person trips (sensitive to only the city center cluster). Person drive trips are insensitive to access (significant and positive for total person trips), but are very similar to total person trips in sign and magnitude of the significant associations with industry and property value.

Walk trips, by contrast, are far less sensitive to personal and household factors and more sensitive to environmental measures. For the walk model with clusters, children and high income are associated with 35.3% and 111.3% increases in person walk trips, and an increase in household autos with a 35.5% decrease in person walk trips. Other personal and household factors are not statistically significant for person walk trips. By contrast, female, youth, work and school status, household size, and middle income all were significant for person drive trips.

Among clusters, both the urban and city center clusters are positively associated with person walk trips, with IRRs suggesting dramatic increases in walk trips of more than two- and five-fold, respectively, for people living in these clusters compared to the rural greenfields. For total trips, only the city center cluster shows a positive and significant effect for walk trips, while the drive trips are sensitive to not only city center environments, but outer suburban neighborhoods as well.

The factors show a strikingly different pattern for walk trips than for drive. The latter are sensitive to industry and property values. By contrast, walk trips have positive associations with walkability, access, and agglomeration, and IRRs indicating increased walk trips of 20.9%, 41.1%, and 25.4% with 1-unit increases in factor scores, respectively. Multiplied over the ranges of walkability and access factors, this translates to 2- and 3.5-fold increases in personal walk trips in the most walkable and accessible environments compared to least. These factors rise in areas with high residential, employment, and road density, and the attendant richness and diversity of destinations and range of goods, services, and activities found in areas of strong agglomeration.

For walk trips, environmental measures (urban and city center clusters, and walkability and access factors) have far larger effects than the few statistically significant socio-demographic factors. At the same time, the other neighborhood types did not show any differences—among themselves or compared to the reference category of greenfields—in numbers of trips, the only exception being outer suburbs, which showed 19% more drive trips but no statistically significant changes in total or walk trips.

**TABLE 14 Person trips by drive and walk modes, with clusters and factors**

| Variables | Drive, clusters | | | Drive, factors | | | Walk, clusters | | | Walk, factors | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR | Coef | P | IRR |
| CONSTANT | **.8362** | **.000** | **2.3076** | **.9952** | **.000** | **2.7053** | **-2.164** | **.002** | **0.1149** | **-1.218** | **.001** | **0.2958** |
| FEMALE | **.1178** | **.000** | **1.1250** | **.1179** | **.000** | **1.1251** | .1918 | .243 | 1.2114 | .2033 | .227 | 1.2254 |
| YOUTH | **-.2851** | **.000** | **0.7519** | **-.2935** | **.000** | **0.7456** | .3818 | .240 | 1.4649 | .4844 | .154 | 1.6232 |
| ELDER | .0156 | .774 | 1.0157 | .0100 | .853 | 1.0101 | -.4616 | .180 | 0.6303 | -.4532 | .192 | 0.6356 |
| WORK | **.1032** | **.006** | **1.1087** | **.1140** | **.002** | **1.1208** | -.1720 | .401 | 0.8420 | -.1660 | .427 | 0.8471 |
| SCHOOL | **-.1203** | **.053** | **0.8867** | **-.1049** | **.089** | **0.9004** | -.3797 | .248 | 0.6841 | -.4600 | .183 | 0.6313 |
| HHSIZE | **-.0760** | **.000** | **0.9268** | **-.0786** | **.000** | **0.9244** | -.1630 | .130 | 0.8496 | **-.2078** | **.040** | **0.8124** |
| CHILDREN | **.1117** | **.000** | **1.1182** | **.1115** | **.000** | **1.1180** | **.3023** | **.067** | **1.3530** | **.3649** | **.022** | **1.4404** |
| AUTOS | **.0863** | **.000** | **1.0901** | **.0854** | **.000** | **1.0892** | **-.4379** | **.001** | **0.6454** | **-.3901** | **.004** | **0.6770** |
| MIDINC | **.2192** | **.000** | **1.2451** | **.1901** | **.002** | **1.2094** | .1245 | .671 | 1.1326 | .0955 | .743 | 1.1002 |
| HIGHINC | **.2810** | **.000** | **1.3245** | **.2390** | **.000** | **1.2700** | **.7479** | **.015** | **2.1126** | **.6715** | **.031** | **1.9572** |
| **Cluster (RURALGREEN is reference category)** | | | | | | | | | | | | |
| RURALMIX | .0539 | .657 | 1.0554 | | | | .7853 | .237 | 2.1931 | | | |
| OUTERSUB | **.1754** | **.090** | **1.1917** | | | | -.1759 | .788 | 0.8387 | | | |
| MIDDLESUB | .1523 | .147 | 1.1645 | | | | .3563 | .547 | 1.4280 | | | |
| INNERSUB | .1326 | .187 | 1.1418 | | | | .8320 | .139 | 2.2979 | | | |
| URBAN | .1147 | .271 | 1.1215 | | | | **.9664** | **.096** | **2.6285** | | | |
| CITY CENTER | **.1890** | **.083** | **1.2080** | | | | **1.6259** | **.004** | **5.0830** | | | |
| **Factors (indices)** | | | | | | | | | | | | |
| WALKABLE | | | | .0033 | .764 | 1.0033 | | | | **.1896** | **.001** | **1.2088** |
| ACCESS | | | | .0200 | .241 | 1.0202 | | | | **.3444** | **.000** | **1.4111** |
| AGGLOM | | | | -.0170 | .231 | 0.9831 | | | | **.2266** | **.002** | **1.2543** |
| INDUSTRY | | | | **-.0318** | **.020** | **0.9687** | | | | .0556 | .451 | 1.0572 |
| PROPERTY | | | | **.1858** | **.002** | **1.2042** | | | | .4806 | .159 | 1.6170 |
| **Summary statistics** | | | | | | | | | | | | |
| Number of obs | 3213 | | | 3213 | | | 3213 | | | 3213 | | |
| Wald $\chi 2$ | 268.90 | | | 283.97 | | | 77.009 | | | 89.26 | | |
| P>$\chi 2$ | 0.0000 | | | 0.0000 | | | 0.0000 | | | 0.0000 | | |
| Log pseudo-ll | -7301.97 | | | -7295.8921 | | | -1011.5186 | | | -1011.0496 | | |

**Bold face denotes significance at p<0.010**

**Range of factor scores (units): walkable—9.65; access—8.46; agglom—8.49; industry—9.25; property—2.48**

Comparing across the trip models, person drive trips are similar to total person trips in the association with most household and personal factors, while walk trips are far less sensitive to these socio-demographic factors. Drive trips also are similar to total person trips in sensitivity to clusters and factors, while walk trips are responsive to different environments than drive trips—particularly walkability and access (to which drive trips are insensitive), and industry and property values (significantly associated with drive trips but not walk).

Across all travel models, autos are less sensitive to environmental measures than are trips. Clusters tell us little about auto ownership, except in the city center neighborhoods. The city center is the distinctive cluster—the only one with statistically significant differences in both auto ownership and trip-making, in opposite directions, such that a small negative association between city center and autos only slightly offsets the much larger positive association of city center with trips. This cluster likely is so dominant in these travel models not only because of the built environment it represents, but also because of its role as the center of the urban activity center. The factors provide more information, particularly through the walkability and access factors, with statistically significant negative associations with autos, and positive associations with trips. The mode-specific trip models demonstrate that even though increasing drive trips overwhelm the modest decrease in auto ownership in the city center neighborhoods, walk trips are very responsive to walkable and accessible environments.

Findings from auto and trip models and comparisons across environmental representations, including this path analysis, are discussed further in Chapter 7, along with results for other travel models.

# 6. Mode Choice

Mode choice is modeled with a nested logit structure that accommodates different and non-exhaustive choice sets for different travelers, based on a spatial network of trip origins and destinations with known travel conditions and environmental features.

## a. Nested logit mode choice modeling

Nested logit modeling avoids the problematic assumption inherent in multinomial logit (MNL) modeling of equal competition among alternatives. That is, the MNL approach reacts to changes in the utility of one mode (e.g., a new mode or improvements in the utility of an existing mode) by systematically adjusting the utility of all other alternatives. In travel mode choice modeling, this may be at odds with hypotheses that certain alternatives clump together, with more commonality and direct competition within a “nest” than with alternatives in other nests. For example, a change in transit service or introduction of a new transit mode, such as rail added where bus service exists, will not necessarily draw as many travelers from the drive-alone or walk modes as from bus.

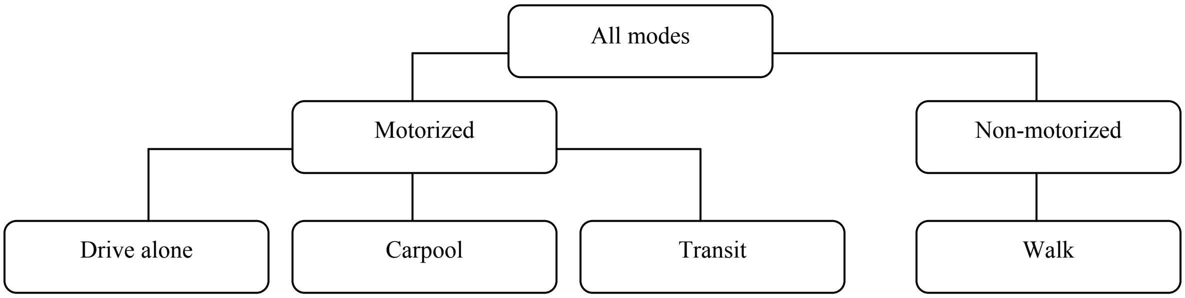
The Limdep statistics package was employed because it supports nested logit modeling with weighted data. After initial modeling of the data with a nonnested structure yielded problematic coefficients on key variables (including counter-intuitive signs and lack of significance), nested logit models were estimated to better observe the relationships of interest, particularly between the environmental factors and mode choice. The nested structure treats the choice between two or more branches first, before looking at secondary choices within branches. Inclusive parameters for branches falling between 0 and 1.0 indicate a nested structure that improves on the nonested structure, while a value of 1 suggests equivalence between the nested and nonnested. Negative values on inclusive parameters may indicate bad data or flawed model specification.

The auto and trip models sought to understand numbers of vehicles held and trips taken by households, without regard for types of trips. By contrast, because the mode choice modeling looks at individual choices for travel within given environments, where the activity or goal of travel is expected to influence mode choice, mode choice was considered by trip purpose: home-based work (HBW), home-based other (HBO), and non-home-based (NHB).

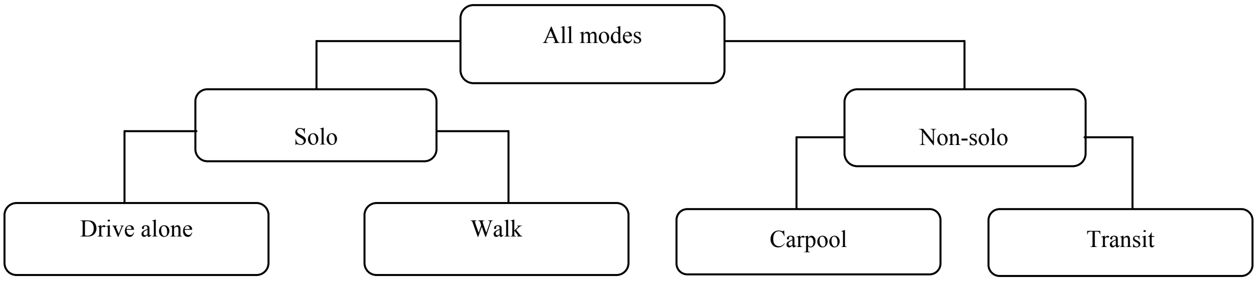
The models generate alternative-specific constants (ASC), which represent the average effect of all factors influencing mode choice but not included in the utility function, wherever there is more than one choice within a nest (for example, among the three motorized modes in HBW), leaving one reference mode. In addition, a nested model reports an ASC for nests; for example, the non-motorized nest in HBW (walk mode only) has an ASC, with the motorized nest as the reference.

Working with the three different trip types (HBW, HBO, NHB), various nesting structures were tested, including two- and three-level models. This process started with a list of likely nesting structures based on theory and earlier empirical evidence of which modes may nest together for various trip purposes. Instead of ceasing the search for nesting structures after the first successful outcome for a given trip type (i.e., $0<\theta<1$), all nesting structures initially deemed promising were tried. From among those models in which all inclusive parameters fell between 0 and 1.0, the best model for each trip type was chosen, based on number of iterations, and sign and significance of key variables: IVTT, OVTT, cost, alternative-specific constants, and environmental measures.

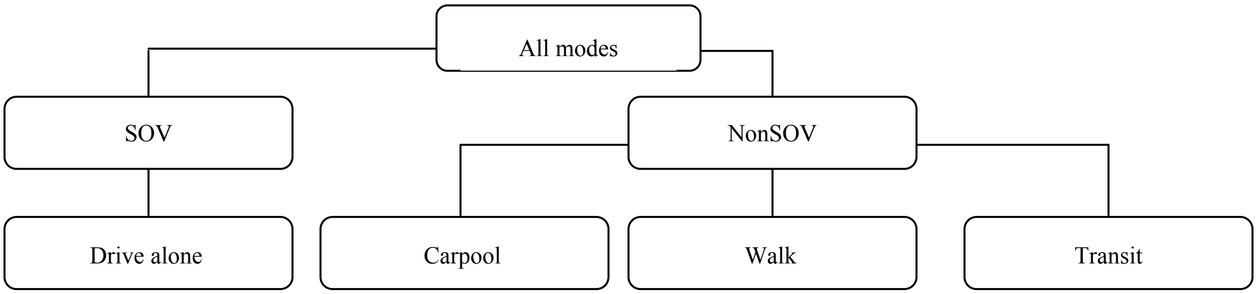
For HBW, the best model has a motorized/nonmotorized distinction (Figure 7a).



**a) HBW nest structure**



**b) HBO nest structure**



**c) NHB nest structure**

**Figure 7. Nesting structures for three trip purposes**

For HBO, the best model has two branches (solo, non-solo), shown in Figure 7b. In this model, one ASC is specified for each nest, as well as for the non-solo nest.

Finally, for NHB trips, the chosen model distinguishes between SOV (single-occupancy vehicles, or drive-alone) and non-SOV (Figure 7c). This model has ASCs for transit and carpool (in the non-SOV nest), with walk as the reference mode, and another for the non-SOV nest.

None of the models uses all the environmental variables, because of non-convergent or otherwise unsuccessful results. Rather, each of the models includes those environmental measures that are found in successful nested logit models, judging from the nesting parameters, significance and sign of independent variables, number of iterations, and other considerations.

The results of mode choice modeling (Tables 15 and 16) show trips broken out by purpose. Deeper analysis is devoted to HBW trips (Table 15), because of their prevalence in the literature, and because they are motivated by a specific purpose (access to employment) and represent a repeated behavior that may respond to similar factors across travelers. For these reasons, probability changes, which are expressed as marginal effects at the means of the independent variables, are presented for the HBW model, in addition to coefficients and p values; for any given variable, the marginal effects on the four modes sum to 0. The expanded model (i.e., with marginal effects) for HBW trips presents factors, for better comparability (with trips) in a later path analysis model. Only coefficients (and level of significance) are given for HBO and NHB, with substantive differences between these trips and HBW noted below.

The utility functions (Chapter 4) specify independent variables for the four modes:

Drive-alone: IVTT, OVTT, cost, household size, autos, middle income, high income
Carpool: IVTT, OVTT, cost, household size, autos, middle income, high income
Walk: OVTT, female, youth, elder, factors (alternatively, clusters or direct measures)
Transit: IVTT, OVTT, cost, female, youth, elder

Adjusted $R^2$ values for HBO and NHB, at 0.4277 and 0.2952, are lower than the 0.7123 for HBW. The log-likelihoods are in all cases substantially smaller than the restricted log-likelihoods that assume zero difference among modes. The θ values (inclusive parameters, also called logsum parameters or nesting coefficients) are significant and closer to zero (denoting perfect correlation) than to 1 (equivalent to the multinomial logit), indicating that the nested logit is the appropriate model here, implying non-zero correlation among modes in the nests. For home-based work trips (Table 15), the negative ASCs for carpool and walk suggest that these modes on average are less attractive to travelers than the reference (drive-alone). The ASC for transit is positive but not statistically significant.

For these models, IVTT and OVTT are significant, with the expected negative coefficient, although the slightly larger (i.e., more negative) IVTT for HBW trips is counter to the expectation of OVTT being more onerous than IVTT. By contrast, OVTT is larger (i.e., more negative) than IVTT for HBO and some NHB trips (Table 16). Faulty specification of OVTT for drive-alone and carpool may explain the contrary results for HBW. The 5 minutes of OVTT specified for drive-alone was based on an assumption of brief walking ends on drive trips; the doubled OVTT of 10 minutes for carpool drew from descriptive statistics showing most carpools to consist of one passenger in addition to the driver, and an assumption that this would double the OVTT. (Transit OVTT came directly from transit skims based on TAZs of origin and destination.) Cost has the expected negative sign only for NHB at $p<0.050$, but is not significant for HBW or HBO (with positive but very small coefficients). This may relate to incomplete data for parking costs, or faulty assumptions in assigned mileage costs—here set at \$0.10/mile for drive-alone, and \$0.05/mile for carpool, to capture marginal expenditures on gasoline but not the larger and more fixed costs of auto ownership, such as purchase or loan payment, insurance, and major repairs. Because carpools for HBW trips most often involve two people (drive and passenger) and may represent an established routine, carpoolers were assumed to share mileage costs, so that the carpool mode used half the mileage rate of drive-alone.

All travel time and cost variables are retained, despite lack of statistical significance for several. Variables chosen for likely significance and relevance, based on theory and earlier empirical evidence, need not be discarded (Koppelman and Bhat, 2006) as a low t-value may represent missing or limited data rather than a basis for exclusion from a model.

Cost, IVTT, and OVTT are assigned different values for the various modes, as described in Chapter 4. Variation in the other variables comes from their inclusion in the utility functions for some but not all modes. Thus, the relative probability of any given mode being chosen does not depend directly on the coefficients of the variables in the model, but rather on the composition of the utility functions of the mode, which include different combinations of the independent variables. The marginal effects (probability changes) are calculated as the expected change in probability of modes given a 1-unit change in a given independent variable, all others held constant. For example, the marginal effect for IVTT is the difference in expected probability of the four modes with average values for IVTT and the probabilities for modes when IVTT is increased by 1 minute for each mode.

The coefficient on IVTT indicates a negative effect of IVTT on the probability of the modes that include IVTT in the utility function (all but walk) being chosen. Focusing again on HBW trips as the prime example, the marginal effect of IVTT of -0.0066 for the drive-alone mode indicates that, if IVTT increases by a minute, the probability of drive-alone being chosen goes down by 0.7%. The IVTT marginal effects for carpool and transit are -0.0073 and -0.005, respectively, indicating that an additional minute of IVTT for the carpool and transit modes are associated with decreases in the probability of those choices of ~0.7% each, while the probability of walking goes up by 2.0% (0.0204).

### TABLE 15 Mode choice for home-based work trips

| Variables | HBW, with factors | | | | | | HBW, clusters | | HBW, direct | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coef | P | Changes in probability | | | | Coef | P | Coef | P |
| | | | D | C | W | T | | | | |
| $ASC_{carpool}$ | **-1.4163** | **.000** | | | | | **-1.4131** | **.000** | **-1.4175** | **.000** |
| $ASC_{walk}$ | **-1.5100** | **.001** | | | | | **-1.5647** | **.008** | **-1.1998** | **.005** |
| $ASC_{transit}$ | 0.3128 | .583 | | | | | 0.3049 | .588 | 0.3552 | .526 |
| IVTT | **-0.0817** | **.061** | **-0.0066** | **-0.0073** | **0.0204** | **-0.0065** | **-00813** | **.062** | **-0.0815** | **.061** |
| OVTT | **-0.0747** | **.002** | **0.0093** | **-0.0060** | **-0.0005** | **-0.0029** | **-0.0751** | **.001** | **-0.0745** | **.002** |
| COST | **0.0006** | **.051** | **-0.0183** | **0.0046** | **0.0276** | **-0.0139** | **0.0006** | **.050** | **0.0006** | **.052** |
| HHSIZE | **-0.7424** | **.000** | **-0.0344** | **-0.0206** | **0.0275** | **0.0275** | **-0.7493** | **.000** | **-0.7361** | **.000** |
| AUTOS | **2.1976** | **.000** | **0.0058** | **0.0042** | **-0.0050** | **-0.0050** | **2.1914** | **.000** | **2.2053** | **.000** |
| MIDINC | 0.3314 | .376 | 0.0410 | 0.0410 | -0.0410 | -0.0410 | 0.3306 | .378 | 0.3503 | .350 |
| HIGHINC | -0.1159 | .820 | -0.0145 | -0.0145 | 0.0145 | 0.0145 | -0.1133 | .824 | -0.1396 | .783 |
| FEMALE | -0.1062 | .717 | 0.0133 | 0.0133 | -0.0133 | -0.0133 | -0.1198 | .682 | -0.1285 | .659 |
| YOUTH | 0.5625 | .277 | -0.0685 | -0.0685 | 0.0685 | 0.0685 | 0.5181 | .314 | 0.5029 | .324 |
| ELDER | -2.0710 | .114 | 0.1940 | 0.1940 | -0.1940 | -0.1940 | -2.0993 | .111 | -2.1360 | .106 |
| **Clusters** | | | | | | | | | | |
| INNERSUB | | | | | | | 0.3019 | .845 | | |
| URBAN | | | | | | | 0.8295 | .581 | | |
| CITYCENTER | | | | | | | **32805** | **.056** | | |
| **Factors** | | | | | | | | | | |
| WALKABLE | **1.3977** | **.099** | **-0.1080** | **-0.1080** | **0.3242** | **-0.1080** | | | | |
| ACCESS | **1.4214** | **.040** | **-0.1100** | **-0.1100** | **0.3300** | **-0.2200** | | | | |
| **Direct measures** | | | | | | | | | | |
| RESENSITY | | | | | | | | | **0.1627** | **.050** |
| **Inclusive parameter** | | | | | | | | | | |
| MOTOR | **0.3850** | **.001** | | | | | **0.3652** | **.002** | **0.3667** | **.002** |
| NONMOTOR | **0.4166** | **.006** | | | | | **0.4214** | **.006** | **0.4322** | **.006** |
| **Summary statistics** | | | | | | | | | | |
| N trips (options) | 2518 (9112) | | | | | | 2518 (9112) | | 2518 (9112) | |
| $\chi2$ | 6357.587 | | | | | | 6356.724 | | 6351.953 | |
| $R^2$ | 0.7130 | | | | | | 0.7129 | | 0.7117 | |
| Adjusted $R^2$ | 0.7123 | | | | | | 0.7121 | | 0.7124 | |
| Log like-hd | -1279.404 | | | | | | -1279.835 | | -1282.221 | |
| Restricted LL | -4458.197 | | | | | | -4458.197 | | -4458.197 | |

**Bold face indicates $p<0.10$**

**Range of factor scores (units): walkable—9.65; access—8.46; agglom—8.49; industry—9.25; property—2.48**

Similarly, an increase in OVTT, also with a negative marginal effect, is associated with a changed probability of the choice of a given mode. The marginal effects suggest that a 1-minute increase in OVTT has a positive impact on the likelihood of drive-alone being chosen, with a nearly 1% increase, offset by negative impacts on the probability of the carpool, walk, and transit modes, with marginal effects suggesting decreases of 0.6, 0.1, and 0.3%, respectively. The negative marginal effects on cost for drive-alone and transit (-0.0183 and -0.0139, respectively) and positive for carpool and walk (0.0046 and 0.0276, respectively) are a mixed finding. While increasing cost can be expected to move travelers away from more expensive modes to, for example, walking, the positive marginal effect for carpooling is unexpected. The lack of significance and unexpected sign on cost coefficients may be related to incomplete parking data or weakly justified mileage costs attached to drive-alone and carpool trips.

Importantly, the mode choice models account for environmental effects through the same environmental representations used earlier for autos and trips, here interacted with the walk mode. For HBW trips (Table 15), a 1-unit increase in walkability at the trip origin is associated with a 32.4% increase in the probability of the walk mode being chosen, and a 10.8% decrease in the probability of each of the three non-walk modes. (Note that the nesting structure of non-motorized versus motorized distributes the decreased probability of the motorized modes evenly among the three.) Likewise, the accessibility factor has a marginal effect of 33.0% increased probability for the walk mode with a 1-unit increase in the factor sore, while the three non-walk modes have marginal effects of -0.1100, which collectively match the positive 0.3300 of walk. Given an initial walk share of 1.5% for HBW trips (Table 5, Chapter 4), this would denote a new walk share still at only 2%. Thus, even where walkable and accessible environments may have apparently large impacts on the probability of the walk mode being chosen, the mode split remains heavily motorized, because of the small initial shares of the non-motorized modes.

The variable for household auto is positively significant for drive and carpool (0.0058 and 0.0042, respectively), suggesting that as household autos increases by one, the probability of drive-alone and carpool modes being chosen increases by 0.6% and 0.4%, respectively. The negative effects on walk and transit (-0.0050 for both), which together equal the combined positive effect 0.010 of drive and carpool, indicate decreasing probability (0.5%) of each of these modes being chosen with the specified increase in auto ownership. The modest increase in probability of driving modes when auto availability increases reflects the nature of the variable. That is, auto ownership already approaches 1 vehicle/person, and increases in discrete increments of one vehicle. Beyond 1 vehicle/person, it has little power to change relative probabilities of mode choice, because only one vehicle can be consumed in the process of using a driving mode.

For HBW trips, the three environmental representations show similar results in terms of significance, sign and magnitude of coefficients on travel time and cost variables, and are similarly insensitive to household and personal measures. For the clusters model, only the city center is significant (and positive) for walk trips, suggesting walking increases in that cluster; residential density is the only direct measure significant (and positive) for walk trips.

Walkable and accessible environments, both significant and positive for the walk mode in HBW, are significant (and positive) for the probability of walking for NHB but not HBO trips (Table 16), perhaps highlighting the likely linking of many NHB trips to one end of a commute trip, while HBO trips are likely to be more spatially and temporally dispersed than the more routinized work-related routes, and may pursue a wider range of destinations for a variety of purposes. Moreover, the coefficient on walkability for NHB trips is smaller than for HBW, suggesting that walkability has the greatest impact on HBW trips.

## TABLE 16 Mode choice for home-based other and non-home-based trips

| Variables | HBO trips | | | NHB trips | | |
|---|---|---|---|---|---|---|
| | Factors | Clusters | Direct | Factors | Clusters | Direct |
| ASC$_{\text{carpool}}$ | 0.4949 | -0.0180 | 0.0119 | *** -0.8980 | *** -0.9851 | 0.1047 |
| ASC$_{\text{walk}}$ | *** 3.0752 | *** 2.7219 | *** 3.0874 | *** 1.8108 | * 0.9198 | *** 1.1836 |
| ASC$_{\text{transit}}$ | *** 1.7997 | *** 1.7857 | *** 1.8024 | 0.0696 | -0.2286 | **-1.0095 |
| IVTT | ** -0.0219 | ** -0.0241 | ** -0.0215 | ** -0.0372 | ** -0.0297 | ** -0.0383 |
| OVTT | *** -0.0456 | *** -0.0454 | *** -0.0455 | *** -0.0286 | *** -0.0236 | *** -0.0221 |
| COST | 0.0001 | 0.0001 | -0.0001 | *** -0.0007 | ** -0.0005 | ** -0.0005 |
| HHSIZE | | | | *** 0.4213 | *** 0.3743 | *** 0.3767 |
| AUTOS | | | | *** 0.2581 | 0.1795 | * 0.2161 |
| AUTOS/PERSON | *** 3.8352 | *** 3.9789 | *** 3.8313 | | | |
| MIDINC | *** 0.5304 | *** 0.5517 | *** 0.5162 | *** 0.8939 | *** 0.8331 | *** 0.9121 |
| HIGHINC | *** 0.4937 | *** 0.5422 | *** 0.4825 | 0.2377 | 0.3187 | * 0.3930 |
| FMALE | -0.0296 | 0.2126 | -0.0295 | 0.0498 | 0.0635 | 0.1035 |
| YOUTH | *** 0.9694 | *** 0.9815 | *** 0.9674 | -0.2939 | -0.0603 | -0.0377 |
| ELDER | ** 0.4351 | *** 0.5032 | ** 0.4310 | *** -2.0640 | *** -1.8020 | *** -1.8101 |
| **Clusters** | | | | | | |
| MIDDLESUB | | * 0.4053 | | | -0.4408 | |
| INNERSUB | | *** 0.6530 | | | -0.0439 | |
| URBAN | | -0.0557 | | | -0.3668 | |
| CITY CENTER | | *** 0.8369 | | | *** 1.3351 | |
| **Factors** | | | | | | |
| WALKABLE | 0.0602 | | | ** -0.1214 | | |
| ACCESS | 0.0346 | | | | | |
| **Direct measures** | | | | | | |
| RESDENSITY | | | 0.0129 | | | *** 0.1052 |
| COMM | | | 0.0298 | | | *** -0.3906 |
| BUS | | | | | | ** 0.0783 |
| CBDDIST | | | -0.0037 | | | |
| **Inclusive parameters** | | | | | | |
| Solo | *** 0.8556 | *** 0.8234 | *** 0.8653 | | | |
| Nonsolo | ** 0.2046 | ** 0.2022 | ** 0.2115 | | | |
| SOV | | | | *** 0.3469 | *** 0.3426 | *** 0.2924 |
| NonSOV | | | | *** 0.7961 | *** 0.8861 | *** 0.7743 |
| **Summary statistics** | | | | | | |
| N trips (options) | 4728 (16,383) | | | 3767 (13817) | | |
| $\chi$2 | 5600.981 | 5629.522 | 5602.176 | 2465.773 | 2593.009 | 2648.218 |
| $R^2$ | 0.4285 | 0.4307 | 0.4286 | 0.2639 | 0.2762 | 0.2822 |
| Adjusted $R^2$ | 0.4277 | 0.4298 | 0.4277 | 0.2627 | 0.2776 | 0.2834 |
| Log like-hd | -3735.597 | -3721.326 | -3734.999 | -3438.804 | -3375.186 | -3347.582 |
| Restricted LL | -6536.087 | | | -4671.690 | | |

***Significant at p<0.010

**Significant at p<0.050

*Significant at p<0.100

Range of factor scores (units): walkable—9.65; access—8.46; agglom—8.49; industry—9.25; property—2.48

For HBO trips (Table 16), the ASC for the walk and transit modes are significant, with unexpected positive coefficients. The ASCs for NHB show carpool to be less favored than the reference drive-alone mode, but the walk more favored—the latter an unexpected result.

The differences in the HBO trips (compared to HBW) include a negative coefficient on cost for NHB trips; recall that the positive coefficients on cost for HBW and HBO were contrary to expectations, but not statistically significant.

Although none of the control socio-demographic variables are significant for HBW trips, some are significant for other trip types (Table 16). Income, which is not significant for HBW, is significant and positive for HBO (both middle and high income) and NHB (middle income) for the drive-alone and carpool modes, perhaps relating to the greater discretion in making these trips than in commuting. The significant youth (HBO) and elder (HBO and NHB) coefficients suggest both are associated with more walk and transit HBO trips; elders are less likely to make NHB walking trips.

These models illustrate how the factors—both environmental and socio-demographic—that influence mode choice vary across trip types. The walkability and accessibility factors significantly and positively relate to home-based work and non-home-based trips; the former are home-to-work or work-to-home trips that are regularly repeated over the course of a traveler's tenure at a given work site, and thus may interact with long-term decisions such as residential location (captured in the trip origins for HBW trips) and auto ownership. The latter (NHB) trips often link to HBW trips as part of tours beginning and ending at home, and involve a work origin and non-home destination, such as restaurant, bank, or errand-related destination. The negative coefficient on the walkability factor is unexpected, and may relate to some aspect of these trips that neither begin nor end at home;

other models that suggest the walkability and accessibility factors affect the walk mode for NHB trips in opposite directions did not produce usable results.

At the same time, HBO trips are sensitive to most household and personal variables but insensitive to walkable and accessible environments; this likely is because these trips are motivated more by the attributes of the destination, which may offer goods, services, or activities that attract trips to widely dispersed destinations, and are made by travelers outside of the spatially and temporally constrained journey to work.

### b. Path analysis—mode choice

Path analysis for mode choice considers direct relationships, that is, walk and transit environments with mode choice, as well as the indirect relationship of walk and transit environments with mode choice, mediated through autos. This is illustrated in Figure 8, which focuses on the right-hand side of Figure 5 (Chapter 4):

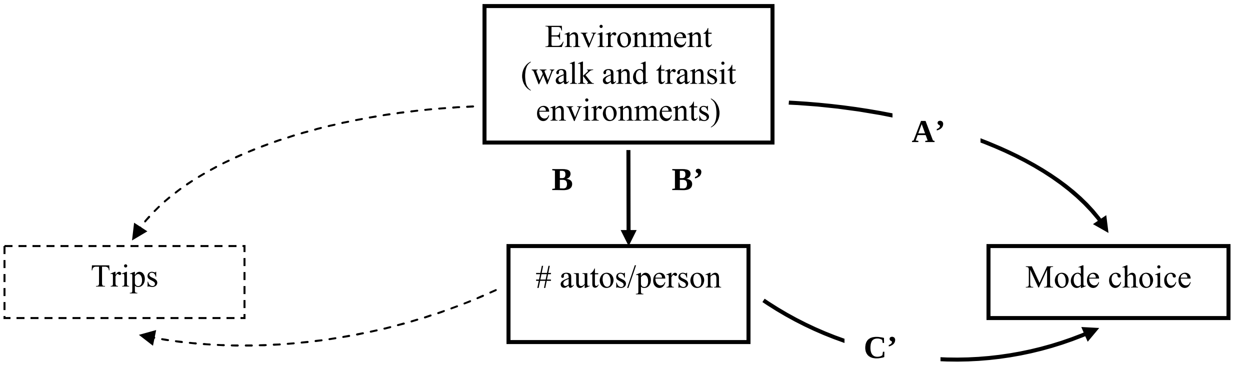


**Figure 8. Path analysis for environment→autos→mode choice chain**

To examine the paths by which environment relates to mode choice (directly, and indirectly through autos), an auto model was estimated at the person level, using the same independent variables included in the mode choice model. Because the mode choice path analysis uses HBW trips, the person auto model includes only individuals identified as workers, with an outcome variable of autos per household, and household size as a control in both the auto and mode choice models.  The same factors used in the mode choice model (walkability and accessibility) were included in the auto model, along with the same household and personal measures. The results of the negative binomial regression of person-level autos appear in Column B of Table 17, along with the marginal change in the dependent variable of autos. For example, the coefficients walkability and accessibility have IRRs of 0.9617 and 0.8954, which suggest decreases in autos of 3.8% and 10.5% as walkability and accessibility factors increase by 1 unit, respectively. These negative associations between autos and these two factors parallel the decreased auto holdings found in the household-level auto models for the same two factors.

For the path analysis presented in Table 17, Column A shows probability changes for variables relating to HBW trips from the mode choice model (Table 15), presented in separate columns for drive-alone and carpool modes (walk and transit are shown in Table 18). Column B shows the marginal change from the person-level auto model, representing the change in auto ownership with 1-unit changes in count variables or in the “1” states of the binary independent variables compared to the “0” state. Column C shows the probability changes for auto availability (from Table 15). Column D is the product of columns B and C (by drive-alone and carpool mode), yielding an indirect effect of environment on mode choice, mediated through autos. The total effects are calculated as the sum of columns A and D. The direct effects on auto ownership of walkability and accessibility yield a small negative indirect effect on the drive and carpool modes, which amplifies the larger direct negative effect of these two factors on the driving modes.

### Table 17 Path analysis of environment, autos, and mode choice for drive modes

| Variable | A) Direct, env/mode, mfx | | B) Direct, env/autos | | | C) Direct, autos/mode, mfx | | D) Indirect, env/mode | | Total effects | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Drive | Carpl | Coeff | P | mfx | Drive | Carpl | Drive | Carpl | Drive | Carpl |
| IVTT | **-.0066** | **-.0073** | | | | | | | | | |
| OVTT | **.0093** | **-.0060** | | | | | | | | | |
| COST | **-.0183** | **.0046** | | | | | | | | | |
| WALKABLE | **-.1080** | **-.1080** | **-.0391** | **.000** | **-.0383** | **.0058** | **.0042** | **-.0002** | **-.0002** | **-.1082** | **-.1082** |
| ACCESS | **-.1100** | **-.1100** | **-.1105** | **.000** | **-.1046** | **.0058** | **.0042** | **-.0006** | **-.0004** | **-.1106** | **-.1104** |
| HHSIZE | **-.0344** | **-.0206** | **.0908** | **.000** | **.0951** | **.0058** | **.0042** | **.0006** | **.0004** | **-.0338** | **-.0202** |
| MIDINC | .0410 | .0410 | **.8666** | **.000** | **1.3788** | **.0058** | **.0042** | .0080 | .0058 | .0490 | .0468 |
| HIGHINC | -.0145 | -.0145 | **1.1053** | **.000** | **2.0201** | **.0058** | **.0042** | .0117 | .0085 | -.0028 | -.0060 |
| FEMALE | .0133 | .0133 | -.0282 | .156 | -.0278 | **.0058** | **.0042** | -.0002 | -.0001 | .0131 | .0132 |
| YOUTH | -.0685 | -.0685 | .0319 | .604 | .0324 | **.0058** | **.0042** | .0002 | .0001 | -.0683 | -.0684 |
| ELDER | .1940 | .1940 | .0809 | .229 | .0843 | **.0058** | **.0042** | .0005 | .0004 | .1945 | .1944 |
| Constant | | | **-.5652** | **.000** | **-.4318** | | | | | | |
| **Summary statistics** | | | | | | | | | | | |
| N options (trips) | 9112 (2518 ) | | 1701 | | | 9112 (2518) | | | | | |
| $\chi$2 | 6357.587 | | | | | 6357.587 | | | | | |
| $R^2$ | 0.7130 | | | | | 0.7130 | | | | | |
| Adj $R^2$ | 0.7123 | | | | | 0.7123 | | | | | |
| Log-like. | -1279.404 | | | | | -1279.404 | | | | | |
| Restr LL | -4458.197 | | | | | -4458.197 | | | | | |
| Wald $\chi$2 | | | 395.68 | | | | | | | | |
| Prob>$\chi$2 | | | 0.0000 | | | | | | | | |
| Pseudo LL | | | -2299.4736 | | | | | | | | |

**Bold face indicates significance at p<0.10**

The direct and indirect effects for walk and transit modes follow in Table 18. The indirect effects again have very small coefficients for walkability and accessibility, in this case positive—suggesting that the probability of a given trip being taken by the walk or transit mode increases as these two factors increase. The small positive indirect effects of walkability and accessibility amplify the larger positive effect on the probability of the walk choice,and slightly offsets the negative direct effect of the walkability and accessibility factors on the probability of the choice of transit.

### Table 18 Path analysis of environment, autos, and mode choice for walk and transit

| Variable | A) Direct, env/mode, % change | | B) Direct, env/autos | | | C) Direct, autos/mode % change | D) Indirect, env/mode | Total effects | |
|---|---|---|---|---|---|---|---|---|---|
| | Walk | Trans | Coeff | P | mfx | Walk/trans | Walk/trans | Walk | Trans |
| IVTT | **.0204** | **-.0065** | | | | | | | |
| OVTT | **-.0005** | **-.0029** | | | | | | | |
| COST | **.0276** | **-.0139** | | | | | | | |
| WALKABLE | **.3242** | **-.1080** | **-.0391** | **.000** | **-.0383** | **-0.0050** | **.0002** | **.3244** | **-.1078** |
| ACCESS | **.3300** | **-.2200** | **-.1105** | **.000** | **-.1046** | **-0.0050** | **.0005** | **.3305** | **-.2195** |
| HHSIZE | **.0275** | **.0275** | **.0908** | **.000** | **.0951** | **-0.0050** | **-.0005** | **.0270** | **.0270** |
| MIDINC | -.0410 | -.0410 | **.8666** | **.000** | **1.3788** | **-0.0050** | -.0069 | -.0479 | -.0479 |
| HIGHINC | .0145 | .0145 | **1.1053** | **.000** | **2.0201** | **-0.0050** | -.0101 | .0044 | .0044 |
| FEMALE | -.0133 | -.0133 | -.0282 | .156 | -.0278 | **-0.0050** | .0001 | -.0132 | -.0132 |
| YOUTH | .0685 | .0685 | .0319 | .604 | .0324 | **-0.0050** | -.0002 | .0683 | .0683 |
| ELDER | -.1940 | -.1940 | .0809 | .229 | .0843 | **-0.0050** | -.0004 | -.1944 | -.1944 |
| Constant | | | **-.5652** | **.000** | **-.4318** | | | | |
| **Summary statistics** | | | | | | | | | |
| N trips (options) | 2518 (9112) | | 1701 | | | 2518 (9112) | | | |
| $\chi 2$ | 6357.587 | | | | | 6357.587 | | | |
| $R^2$ | 0.7130 | | | | | 0.7130 | | | |
| Adj $R^2$ | 0.7123 | | | | | 0.7123 | | | |
| Log-like. | -1279.404 | | | | | -1279.404 | | | |
| Restr LL | -4458.197 | | | | | -4458.197 | | | |
| Wald $\chi 2$ | | | 395.68 | | | | | | |
| Prob>$\chi 2$ | | | 0.0000 | | | | | | |
| Pseudo LL | | | -2299.4736 | | | | | | |

**Bold face indicates significance at p<0.10; bold for total effects indicate significance along entire path**

For all four modes, the only other variable significant along the entire path is household size, where a negative direct effect on drive modes is slightly dampened by a positive indirect effect, while the opposite is true for the probability of walk or transit: positive direct effect of household size slightly offset by a small negative indirect effect.

This and the previous path analysis (Chapter 5) are interpreted further in the following chapter (7), along with a general discussion of the auto and travel models, and their comparison across environmental representations, as well as the policy relevance of the results of these models, and implications for future travel behavior research.

# 7. Discussion

Planners draw on theory and empirical research findings to address complex urban and regional problems, often constrained by policy and statutory guidelines, as well as public support. The failure of much metropolitan planning practice to account for evolving urban form may relate both to the institutional and political challenges of absorbing such information into the decision-making process, and the still undeveloped theoretical basis for handling such complex and unruly interactions (Waddell et al., 2007). Quantitative techniques such as the transect used here may provide planners with analytic tools that express local conditions and resonate with the public.

The auto and travel models presented here provide useful insights into the relationship between physical environment and travel behavior, measured as auto ownership, trip generation and mode choice. The differences in how the three environmental representations relate to travel behavior likely will be of greater interest to researchers than practicing planners. The mode choice model, which found walkable and accessible environments (at the trip origin) to increase the probability of the walk mode, has coefficients comparable to those from studies for other metropolitan areas (US EPA, 2000), which planners use in estimating and forecasting travel demand.

The three environmental representations, while highlighting different relationships among variables, generally support the hypotheses that walkability and accessibility increase trips of all types, and that walking trips are more sensitive to the physical environment than are driving trips. Mode choice likewise is sensitive to the physical environment, with the probability of the walk mode being chosen rising in walkable and accessible environments. Residents of city center clusters and highly walkable and accessible environments own fewer vehicles; they make both more driving and walking trips, although the total effect on walking trips is more dramatic.

### a. Environmental representations compared

The three approaches to quantifying the physical environment relate differently to the modeled travel behaviors, as illustrated in Table 19. The clusters are generally less informative in these models than are the factors; both provide more evidence of relationships than the direct measures. At the same time, neither the clusters nor factors provide much information about auto ownership; only the city center cluster and accessibility factor are significant, and both are negatively associated with auto ownership. While the effect of the accessibility factor (5.3% fewer vehicles) relating to a 1-unit change in factor score is modest, the range of 8.46 units from the least to most accessible translates to a nearly 45% drop in auto ownership in the most accessible environments compared to the least; the city center cluster likewise has a large impact, with an associated 18.5% decrease in household autos compared to greenfields.

The association of walkable and accessible environments with decreased auto ownership is consistent with findings in other studies that environmental qualities such as residential and employment density or transit service are associated with high propensity of households to hold fewer vehicles (see, for example, Bhat and Guo, 2006). However, it is difficult to compare the results of this work directly with values in the literature, because of the wide variety of research designs and model specifications. For example, Hess and Ong (2002) modeled the probability of households owning zero vehicles, and found a 31% drop with a change from homogenous to mixed land uses—a parallel finding but not directly comparable because of their specific quantitative environmental description and different dependent variable.

**TABLE 19 Comparison of variables across models and environmental representations**

| **Environmental representations** | **Models** | | | | | |
|---|---|---|---|---|---|---|
| | **Autos** | **Household trips** | **Person trips, all modes** | **Person drive trips** | **Person walk trips** | **Mode (HBW)** |
| **Clusters** | | | | | | |
| **Rural greenfields—reference cluster** | | | | | | |
| Rural mixed | | | | | | - |
| Outer suburban | | | | * | | - |
| Middle suburban | | | | | | - |
| Inner suburban | | | | | | - |
| Urban | | | | | * | - |
| CITYCENTER | * | ** | ** | * | *** | - |
| **Factors** | | | | | | |
| Walkability | | * | | | *** | - |
| Accessibility | *** | ** | ** | | *** | - |
| Agglomeration | | | | | *** | - |
| Industry | | ** | ** | ** | | - |
| Property value | | *** | *** | *** | | - |
| **Direct measures** | | | | | | |
| Resident. density | | ** | *** | - | - | - |
| Access to transit | | | | - | - | - |
| Access to comm | * | | | - | - | - |
| Access to CBD | | | | - | - | - |
| **Mode choice environments for mode choice modeling** | | | | | | |
| Walk environment | | | | | | *** |
| Transit environment | | | | | | * |

*****Significant at p<0.010**
****Significant at p<0.050**
***Significant at p<0.100**
**- not tested**

For trip-making, only limited information again is provided by the clusters, except for the city center cluster, which proves to be significant and positive in all trip models; in addition, the outer suburban and urban clusters are positively significant for, respectively, person-level drive and walk trips. Compared to rural greenfields, city center households average increases in total household trips (24.5%), total person trips (22.8%), person drive trips (20.8%), and person walk trips (a five-fold increase). At the same time, walk trips are so rare in the rural greenfields that even a jump from 0.05 (the mean in the greenfields) to about ¼ trip per person (a five-fold increase) still is dwarfed by the overwhelming dominance of drive trips, which rise from 3.23 (mean in the rural greenfields) to about four trips per person in the city center cluster. Thus, while an increased share for the walk mode may be a desirable goal in many planning contexts, the increased access and density of such environments may also increase drive trips—a finding consistent with earlier work (Boarnet and Crane, 2001b). This is partially offset by the dampening effect city center clusters have on auto ownership, as discussed in the path analysis section.

The factors generally are more informative about trip-making than the clusters, with walkability significant for household trips, as well as for person-level walk but not drive trips. At the same time, the access factor is significant for all trip models except person drive trips. The magnitudes of factor coefficients are quite substantial, particularly when considered across the range of factor scores in the person-level trip models. For example, the 16.3% increase in trips with a 1-unit increase in property values translates to a 40.4% increase when multiplied by the range of extremes for this factor (2.5), while trips decline by 25.9% in the environments with the highest industrial acreage compared to the least. The latter does not necessarily represent an intervention opportunity for policy aimed at reducing travel, since industrial zoning and siting express other social and economic processes, but is interesting to note as it relates to the urban travel environment.

The sensitivity of travel to the physical environment shows up more dramatically in the person-level models, where the city center cluster is associated with a 20.8% increase in drive trips, but a 5-fold increase in walk trips compared to the rural greenfields. The relevant factor coefficients (on walkability and access) show 20.9% and 41.1% increase in walk trips with 1-unit increases in these factor scores, translating to 2-fold and 3.5-fold increases in walk trips in the most walkable and accessible environments compared to the least. At the same time, drive trips are insensitive to the walkability and accessibility factors.

Although factors were used in the detailed discussion of HBW mode choice and path analysis (below), in part to facilitate comparison with trip path models, it is interesting that the clusters were more informative for HBO mode choice than were factors, with three clusters (city center, and inner and middle suburbs) positively significant for the increased probability of the walk mode being chosen; city center was positive for NHB. At the same time, none of the factors were significant for HBO, and the walkability factor had an unexpected negative association with NHB.

These findings, and the mode choice model that found the walk mode for home-based work trips to be sensitive to environmental but not household and personal factors, echo the conclusions of a major review (Ewing and Cervero, 2001) that mode choice is more sensitive to urban form, and trips more sensitive to household factors.

Both the clusters and factors provide useful information about the underlying relationship between environment and travel. In addition to showing an association with many travel measures, the spatial factors may be relatively easily extended to other data, without the need to tie into a geospatial network. At the same time, the spatial clusters offer an interesting and promising model of classifying physical environments to support modeling of travel, and indeed other activities such as business location, with flexibility to edit, extend and enrich the classification.

The clusters that constitute the transect developed for this study area are consistent with the transect approach advanced by Duany and Talen (2002) and others. The clusters, which are spatially defined environments with distinctive common elements that distinguish them from other environments, may be ordered roughly from rural to urban. They provide an efficient vocabulary of human habitats that may facilitate discourse about human activity within the physical environment. The technique may be applied to other data to generate locally meaningful transects.

### b. Path analysis—direct and indirect effects

Path analysis makes it possible to consider household decision chains, to examine the relationship the physical environment has directly with trips and mode choice, and indirectly through auto ownership. For the environment→autos→trips path, the city center was the only cluster significant for both autos and trips—and in opposite directions. Thus, the negative association the city center cluster has with autos slightly offsets the larger positive association of city center with trips. Among the factors, only the accessibility factor is significant along the entire path; the negative association with autos slightly offsets the larger positive association with trips. In this way, the clusters and factors were consistent in showing that access (in which the city center cluster scored very high) is important in trip generation, despite a small negative indirect effect through autos. Thus, for this data set, even when auto ownership is dampened, such as in the city center clusters or walkable and accessible environments, the net effect of the environment on number of trips remains positive and substantial—with implications for policy intended to influence trip-making through urban form (see next section).

Figure 9 shows how increasing access, as reflected in the access factor score, is associated with decreasing auto ownership and increasing trip-making. The total effect (direct positive effect of increasingly accessible environments on trips, minus the indirect negative effect of reduced auto ownership) is shown in the dashed line, which trends just below the direct effect (solid line). The net effect is 28% more trips in the most accessible environments compared to the least.

Of the control factors, household size, children, bicycles, and income all are significant along the entire path. All except children are positively associated with both autos and trips, such that the indirect effect amplifies the direct effect. The negative indirect association of children and autos slightly dampened the positive direct association, for a net effect of 19.6% more household trips with an additional child..

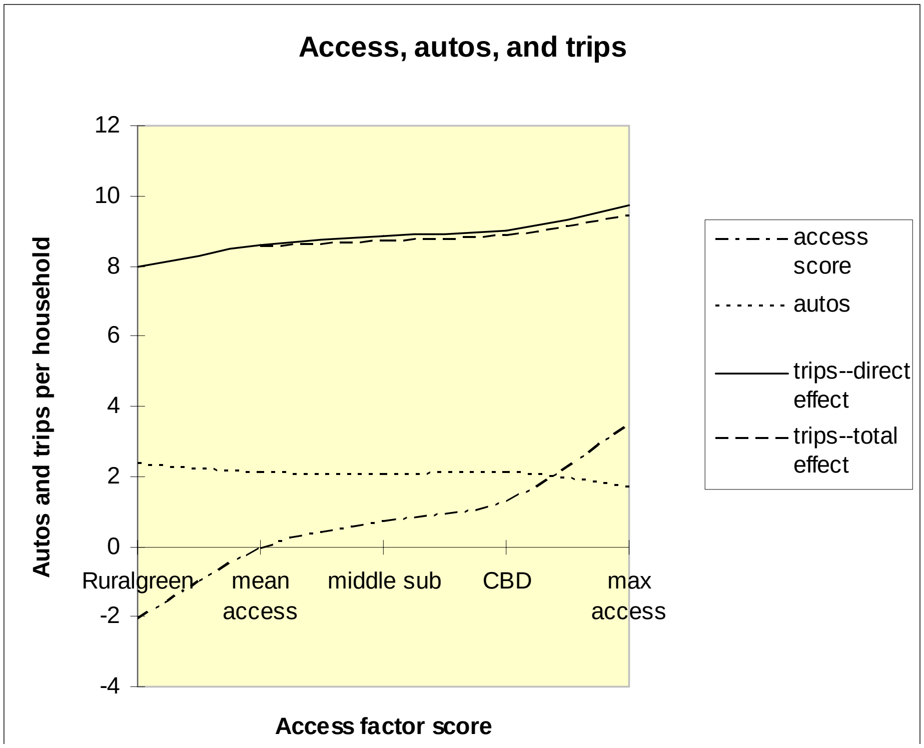


**Figure 9. Accessibility, autos and trips**

Figure 10 shows examples of a nonwalkable and walkable environment, generated from longitude and latitude of trips in this dataset identified as at the extremes of the walkability factor. The former is a conventional suburb, and the latter a residential neighborhood in a city center cluster.

**Figure 10. Residential neighborhoods identified as non-walkable (left) and walkable (right)**

For the environment→autos→mode choice path, the walkability and accessibility factors were significant along the entire path for HBW trips. The direct effect of these two factors on auto ownership, for workers whose trips constitute the home-based work sample, showed the same auto-dampening effect of these environments seen in the household-level auto models, with a negative indirect effect on drive modes and a positive indirect effect on walking and transit. The net effects suggest that the probability of a given trip being made by the motorized modes (drive-alone, carpool, or transit) drops by 11% each as walkability and accessibility increase by one unit, and that the walk probability increases by 33%.

By comparison, Cervero and Kockelman looked at HBO trips using a walking quality factor, and found only slight increases (several percentage points) in the probability of choosing a mode other than private auto. Cervero's 2002 mode choice study found statistically significant negative associations with several environmental measures and the probability of choosing drive-alone over carpool and transit, with elasticities (percentage change in probability with 1% increase in built environment factors) ranging from -0.141 (gross density at the origin) to -0.448 (sidewalk-to-road ratio at the destination). Direct comparisons are difficult, because of differences in factor development and trip type, among other modeling choices. For example, Rodriguez and Joo (2004) offer point elasticities for walk, bike and transit modes relative to four key environmental measures, most of which are not captured in the environmental representations here (largely for lack of available data); their study provides additional compelling evidence of the importance of the physical environment in mode choice decisions.

The coefficients produced by the mode choice model are comparable, in most cases, to those in use in travel demand models in other metropolitan regions (Table 20), in terms of sign and order of magnitude; some differences in magnitude may relate to changes in travel conditions since the data were collected. For example, the coefficient for IVTT produced by this research was -0.0817 for HBW trips, higher than published values; however, the -0.0219 and -0.0372 for HBO and NHB were closer to the coefficients reported elsewhere, which range from -0.0150 (New Orleans, 1960) to -0.0632 (Pittsburgh, 1978). The most recent coefficient (1997) of -0.0195 comes from Phoenix—a less monocentric city.

The OVTT coefficient of -0.0747 for HBW trips compares to a coefficients for OVTT (all trip types) from other metropolitan areas (U.S. EPA, 2000) ranging from -0.0219 (Albuquerque, from a 1992 model) to -0.1570 (Pittsburgh, 1978). The most recent coefficient

(-0.0257) comes from a 1997 Phoenix model. The OVTT coefficients for all trip types fall within the range of reported coefficients from other cities.

**Table 20 Comparison of mode choice model coefficients**

| **Travel demand models** | **Travel coefficients (factors)** | | | | | |
|---|---|---|---|---|---|---|
| | **IVTT** | | **OVTT** | | **Cost** | |
| **Metrolina** | -0.0817 | HBW | -0.0747 | HBW | | |
| | -0.0219 | HBO | -0.0456 | HBO | | |
| | -0.0372 | HBW | -0.0286 | NHB | -0.0007 | NHB |
| **Other models** | City and year of study | | | | | |
| Minimum | -0.0150 | New Orleans 1960 | -0.0219 | Albuquerque 1992 | -0.0018 | Tucson 1993 |
| Maximum | -0.0632 | Pittsburgh 1978 | -0.1570 | Pittsburgh 1978 | -0.0210 | Pittsburgh 1978 |
| Most recent | -0.0196 | Phoenix 1997 | -0.0257 | Phoenix 1997 | -0.0111 | Phoenix 1997 |

The cost coefficient produced by the mode choice model is not statistically significant for HBO trips. The NHB cost coefficient of -0.0007 is smaller (i.e., less negative) than those reported for other cities, which range from -0.0018 (Tucson, 1993) to -0.0210 (Pittsburgh, 1978). The IVTT coefficient for HBW trips is unexpectedly higher than OVTT, and also larger than values reported for other metropolitan areas. This may be related to data problems, such as a poorly specified cost variable, or to some unknown aspect of travel conditions or travel culture in the Charlotte area.

Taken as a whole, the coefficients from the mode choice model are plausible, given the range of values for travel demand models for other cities, the wildly varying age of those models and the elapsed time since the latest (even as trips and VMT generally have been growing across the nation), and the possibility of travel conditions specific to the Charlotte metropolitan area being reflected in model coefficients. Pending refinements in the mode choice model, such as travel environments that capture both origins and destinations, may yield better results. In the meantime, these results highlight differences in how trips of various types relate to both the environment and to household and personal factors, with possible policy implications (below).

### c. Policy relevance

Practitioners seeking guidance on urban design that supports planning goals of reduced auto use and greater use of walk and transit modes may find this research useful. The results are consistent with earlier empirical evidence of a link between the physical environment and travel behavior. In particular, the walkability and access factors, and the city center cluster (which scores very high in those two factors), show clear positive associations in these models with trip generation. In addition, the city center cluster and walkability and access factors are strongly associated with increased walking, and with moderate increases in driving trips. It is interesting to note that industry and property value are strongly associated (in opposite directions) with total trips and drive trips, but not with walk trips. The latter appear to be more sensitive to the elements of the environment that relate to the quality of the trip (distance, scale and density, connectivity, pedestrian support), while drive trips respond positively to the mix of destinations and economic intensity captured in property value, and negatively to industrial acreage, which may suppress trips by limiting auto access and passage, and by offering no destinations except for workers.

Understanding indirect as well as direct effects may illuminate intervention opportunities to address problems manifest in daily travel by influencing infrequent upstream decisions such as location or auto ownership, with cascading effects on more frequent travel choices. Changes in vehicle use are near-term adjustments to the factors that shape household demand, short of the longer-term strategy of altering the household vehicle fleet. This distinction presents two levels of attack for understanding—and, from a policy perspective, reducing—the dominance of private vehicles: reduced use (leaving autos parked at home) cuts VMT, congestion, and emissions (with possible positive impacts of increased physical activity, higher transit patronage, etc.), while reduced ownership has additional implications for urban sprawl and costs—to society and households—of parking capacity and lane miles.

Beyond identifying significant associations the environment has with travel behavior, it is important to understand the magnitude of any observed effect, since some statistically significant associations might suggest expensive interventions (e.g., sidewalks or other infrastructure) that are not justified by their very small potential effect. Policy interventions such as pricing or zoning may be preferable to more expensive and less adjustable physical design solutions. Even where apparent changes are large, such as a 33% increase in the probability of the walk mode in walkable environments, the effect on overall mode split would remain quite small, i.e., from 1.5% to 2.0% overall for HBW.

In these auto models, the city center cluster and accessibility factor have large associated IRRs, indicating an 18.5% decrease in household autos in city center clusters (compared to urban greenfields), and 44.8% fewer in the most accessible environments (compared to the least). While the auto-dampening effect of the access factor and the city center cluster may be relevant in addressing the problems created by heavy use of private autos, path analysis found this negative effect to only slightly offset the large positive association between such environments and number of trips. Thus, policies intended only to influence auto ownership by altering urban form are unlikely to be economical or effective at affecting the underlying behaviors of interest, particularly given the scale at which such interventions usually are mounted and the high attendant costs.

At the same time, depending on the local context, policy-makers may look for opportunities to promote such development, within the limits of public policy authority and scarce funding, particularly if such environments have other desirable qualities and the total effect (in terms of number and types of trips, as well as related effects such as parking demand) would be compatible with other planning goals. That is, transportation planning is not conducted in a policy vacuum. Planners generally pursue multiple goals, and thus may benefit from research that suggests a range of pressure points for influencing travel behavior, particularly where it overlaps with other planning concerns, such as affordable housing, impervious surface area, congestion, air quality, and related social and environmental concerns. Increases in walking or transit (which often includes a substantial walking leg of the trip) may have other benefits beyond reduced auto demand, such as physical activity, although such related effects may be difficult to measure.

The dramatic differences in the sensitivity of walk and drive trips to the physical environment may provide useful guidance for municipal planners. Policies focused on increasing walk trips without increasing drive trips (which often respond to the same environmental factors, such as connectivity, density, and compactness) may benefit from consideration of the composition of the factors, and the environments (clusters) that score high in these measures.

Because of the single study site, caution is in order in making any generalizations; nevertheless, some policy implications can be suggested for mid-size cities with a strong central core and a heavily auto-oriented transportation culture. For example, the city center cluster’s high visibility as an environment strongly associated with lower auto ownership but higher trip generation suggests that redevelopment opportunities in the city center may hold promise for reducing the auto mode share, particularly where policy or market solutions (e.g., parking fees, incentives for certain land uses) may increase non-auto trips without also increasing auto travel. The greater sensitivity of trips (compared to auto ownership) to walkable and accessible environments suggests that some travel behaviors may be responsive to interventions even where auto ownership remains static. Given the very small indirect effect on trips mediated by auto ownership, efforts to reduce auto ownership through urban form are not likely to be cost-effective strategies, except were it is part of a larger policy with other goals and benefits. The mode choice model presented here, highlighting how different trips relate to environment, suggests that home-based work trips—and the non-home-based trips frequently linked to one end of these—may be useful points for policy intended to alter mode choice, but that other trips (to and from home, for purposes other than commuting to work) are driven more by the characteristics of the traveler and household, and the goods and services that generate the trip.

Cluster analysis provides an interesting way to isolate or combine various dimensions of the environment, and may be an efficient representation of complex relationships and interactions to illustrate environments that have desirable traits and perform well in multiple dimensions. Other benefits may be associated with walkable and accessible environments, including social and environmental qualities that increasingly are viewed as valuable, but remain difficult to quantify or accommodate in public planning. Such qualities may include sociability, sense of safety, community cohesion, environmental stewardship, and others.

This is difficult policy territory, as claims of the power of physical design to create or enhance, for example, “sense of community” remain largely unsubstantiated (Talen, 1999), although empirical evidence of the association of certain designs with other measurable factors (e.g., low crime, frequent interaction of people in public spaces, etc.) may suggest new tools or planning approaches to be tested. Planning is a practice in transition, with both the professional corps and research community having recognized how conventional planning has produced a legacy of overly rigid prescriptive structures and tools that often are at odds with stated social objectives (Duany and Talen, 2002).

The effectiveness of using urban form to influence travel behavior, either directly or indirectly through auto ownership, is likely to be limited; expectations should be tempered by realistic assessments about the level of uncertainty in travel behavior modeling and unintended consequences of various interventions. Moreover, the U.S. public has limited tolerance for top-down initiatives that presume to know what best serves the individual citizen and the community as a whole, which may limit the planner's tool box to less coercive and more persuasive strategies for altering prevailing land use practices. Large-scale reorganization of the built environment is unlikely without strong public support for clearly articulated common goals, along with evidence of multiple benefits of the long-range plan (to both individuals and the community) and protection of personal rights.

### d. Travel and decision behavior research—current and future

Travel research grounded in decision behavior may support efforts to understand how and why travelers make daily choices, and how they may be induced to change their behavior, given the massive public investments into transportation systems—for both private and public modes—and the seemingly intractable problems of ever-increasing travel demand and attendant pollution, congestion, economic impacts, and threats to public safety. Many attempts have been made to reduce personal auto use in pursuit of social goals (reduced economic costs, pollution, noise, congestion), generally by imposing material and political costs on citizens and public servants (Bamberg, 2006). Empirical evidence of the potential success and failure of such measures may help decision-makers develop effective and efficient policy.

This dissertation builds on extensive earlier empirical work on travel behavior in the physical environment, and incorporates and compares several quantitative environmental measurement techniques. The results are presented in terms of commonly studied travel measures with well-established statistical techniques, and thus provide an example of how the techniques used here may be applied to other data sets. At the same time, other research fields may be usefully tapped for concepts and techniques, to enrich future travel behavior research.

Habit formation is particularly relevant for the frequent decisions relating to daily travel, which may be influenced by travel conditions and costs, as well as household factors. While households likely expend more effort in deliberating on the less frequent decisions such as auto acquisition and residential location, the influence those decisions may exert on lower-level (i.e., more frequent) decisions represents an intervention opportunity for policies that could usefully focus on influencing the infrequent decisions that constrain more routine choices.

Future research that accounts for the many dimensions of travel decision-making within a physical and social context may include, e.g., laboratory trials, simulations, surveys, panel data to capture habit; objective (geospatial) travel measures of activity space; and quantitative environmental representations. The neglected social environment merits attention as a spatially embedded influence on disaggregate travel behavior (McDonald, 2007).

Additional work planned for this dataset includes new environmental definitions accounting for both origins and destinations of trips, and tour-based models that describe the environment at each stop. Factors and clusters also may be combined and tested in travel models

Beyond this study, it will be interesting to apply the same environmental representations to travel research in other sites, to incorporate social environment measures, attitudes and preferences, and habitual travel choices. Such investigations will require additional refinements in research techniques.

# 8. Conclusions and Summary

This research employed quantitatively described environmental representations in auto ownership and travel models, to test several hypotheses.

*Hypothesis A:* Auto ownership, expressed as number of vehicles per household, varies across neighborhood types, as well as in response to household factors

Auto ownership was hypothesized (Table 3, Chapter 3) to be positively associated with household size, home ownership, single-family homes, number of children, and rising income, and negatively with environments characterized by density, connectivity, and other qualities associated with high walkability and accessibility.

Auto ownership was found to be sensitive to neighborhood type only with regard to the city center cluster, with an apparent 18.5% decrease in autos compared with the rural greenfields. Lower auto ownership also was found in areas that score high on accessibility; the apparent modest impact (5.3% with a 1-unit change in factor score) becomes substantial when multiplied across the range of factor scores. These negative relationships are as hypothesized (Table 3, Chapter 3).

Although auto ownership showed limited sensitivity to environmental measures, all of the control household variables are significant: household size, numbers of children and bicycles, home ownership and type, and middle and high income (compared to low income). All were positive, as hypothesized, except number of children—perhaps because children increase household size without adding drivers.

*Hypothesis B:* Trip generation varies across neighborhood types, as well as in response to auto ownership and household factors

Trip generation, hypothesized to increase with increasing urban character, was significantly associated with only the city center cluster, with an apparent 24.8% increase in trips compared to the rural greenfields. The 13.3% of households residing in clusters identified as city center (or 11.4% of the person sample), with distinctly higher trip generation despite lower auto ownership, are a large enough group to have a meaningful impact on regional travel demand. Note that some clusters labeled city center are in fact somewhat removed from the metropolitan center proper, and may represent neo-traditional environments that incorporate mixed uses and high density, along with design features that may encourage both motorized and non-motorized trips. Of the factors (all hypothesized to relate positively to trips), walkability, accessibility, and property values are positively associated with trips, with the latter having a much greater impact; industry is negatively associated with trip generation—perhaps because the single measure (acres of industrial land uses) does not reflect the kind of mixed use that might be expected to attract trips to a rich set of spatially co-located destinations, but rather comprises a single use that dampens trips.

All of the control household factors are significant for trip generation, except home ownership and single-family homes; all are positive, including children (negative for auto ownership), indicating increased trip-making with higher values for these measures. Number of bicycles, hypothesized to be associated with both lower auto ownership and fewer trips, is positively associated with both—suggesting that bicycles are a complementary rather than substitutive mode for driving.

When trips are broken out by walk and drive modes at the person level, the city center cluster (and outer suburbs) has the same positive association with drive trips despite lower auto ownership, illustrating the importance of the distinctive city center environment in shaping auto use, even though auto ownership is most closely associated with household and personal characteristics. At the same time, the walkability and accessibility factors, which are important for walking (with large and positive associations), have no statistically significant association with drive trips.

*Hypothesis C:* Mode choice differs across neighborhood types, as well as in response to auto ownership, household and personal factors

The probability of choosing the non-motorized (walk mode) was hypothesized to increase in areas identified as walakble or accessible, while numbers of children, autos, and household members as well as higher incomes were hypothesized to reduce nonmotorized travel.

For home-based work trips, walkable and accessible environments are associated with a higher probability of the walk mode being chosen. Additional autos are associated with higher probability of drive modes (drive-alone and carpool) being chosen, but other control socio-demographic variables are not significant. The same walk and transit environments were significant for non-home based trips but not home-based other trips. At the same time, home-based other trips, which likely are more discretionary, are sensitive to income and age but not physical environment.

Overall, the results for environmental measures conform to expectations of auto ownership being more responsive to household traits than to environmental measures. The exceptions are the distinctive accessibility factor, which represents an index of measures that may dampen auto ownership, and distance to commercial uses or residence in the city center cluster. This cluster consistently shows up as significant in travel models, likely not only because of its built environment features, but also because of its place at the center of the urban activity system. All these indicate that accessibility, as captured in three different environmental representations, is associated with decreased auto ownership. Given that socio-demographic factors are the primary drivers of auto ownership, and environment has relatively little impact, auto ownership is a less promising target of policy aimed at reducing auto use than other strategies.

The household models showed four factors but only one cluster (city center) to be significant for total household trips; the factors were similarly related to household- and person-level trips. Walk trips appear to increase significantly and substantially only in the city center cluster, with distinctly higher density and connectivity; the walkability and access factors provide additional evidence of the importance of urban form and its associated characteristics for walking. This suggests that dense, mixed-use neighborhoods with pedestrian-friendly features and high access are associated with fewer autos and more trips, although the increase in trips is more strongly shown than a decrease in autos, and the increase in walk trips is dramatically higher than the increase in drive trips. This is consistent with earlier empirical findings about the importance of urban form particularly for trip generation, and the mode-specific response to the physical environment, including distance and its effect on walking. Taken as a whole, these results are consistent with expectations, based on earlier empirical evidence, that trips are more sensitive to the environment than is number of household autos, and less sensitive to some household measures.

Path analysis showed the dampening effect of the city center cluster and access factor on auto ownership to only slightly offset the much larger positive association between these environmental measures and total household trips.

Mode choice modeling found walkable and accessible environments to increase the probability of the walk mode being chosen, and decrease the probability of the motorized modes (drive-alone, carpool, and transit).

These findings suggest that, where the built environment rates high on such measures as density, connectivity, pedestrian and transit facilities, and other features of highly walkable and accessible areas, people own fewer vehicles and make more trips. They also are more likely to choose non-drive modes. The local environment where people live, work and pursue other activities is key. For communities searching for ways to address the problems that come with heavy use of private autos—including environmental degradation, economic inefficiency, declining public health and inequities in access to goods and services, long-term planning that encourages such environments may provide some relief.

This dissertation considers a chain of household decisions relating to auto ownership and trip-making, using a dataset collected in a single place and time. This work makes several contributions to the field of travel modeling. Research to date on the decisions of interest here have been fragmented spatially and temporally, leaving subsequent research efforts to link relevant findings from studies conducted in different spatial and temporal contexts, with potential loss of comparability and generalizability. This work considers these travel decision chains jointly, using path analysis to consider both direct and indirect relationships between environment and travel behavior. Further, the travel models examine trip generation by mode to identify independent variables to which various travel modes respond differently. This dissertation also addresses environment-travel interactions by using environmental measures as inputs in models of auto ownership and travel, with multiple representations of the environment associated with each household location and each trip's origin and destination. Through the joint modeling of interrelated decisions, and the incorporation of quantitatively described environments in travel models, the author hopes to have contributed to the field of travel behavior research.

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